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Multi-perspective application selection: a method to identify sustainable applications for new materials using the example of cellulose nanofiber reinforced composites

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ABSTRACT

To date, technical and economic criteria have become the main benchmarks used in assessing the substitution potential of new materials. Sustainable product design uses multi-criteria decision methods to select the best material or process from a set of alternatives, requiring that the target product is already known. This paper follows a contrary approach by introducing the Multi-Perspective Application Selection, a method to support researchers and industrial practitioners alike in identifying and choosing the most promising and sustainable applications for new materials under development. This is achieved through combining and assessing technical, economic and environmental criteria covering the entire life cycle of an application. With this method, numerous possible applications can be screened during the early stages of material development when little information is available. The results help to narrow the selection of feasible products by excluding unpromising applications. The first step involves identifying and segmenting potential markets. In the second step, technical and economic aspects are assessed by employing user acceptance criteria. Finally, simplified life cycle assessment calculations are implemented in the third step to cover environmental considerations. Using an example of cellulose nanofiber reinforced composites, the authors illustrate the procedure whereby luxury consumer goods, specialty vehicles, industrial processing and furniture result as the most promising applications identified from this new method. The results give the researchers a more holistic understanding of their material and help to establish the requirements that the material must fulfill for the selected application. With that knowledge, the method can help enact development pathways in applied materials research.

1. Introduction

During the early research stages of a new material, the flexibility of the development pathways is still high and costs involved are comparatively low (Köhler and Som, 2014). While at the laboratory stage one can change the process with ease, this is not the case when a mini plant or even an industrial production plant is already in place. Estimates amount those costs to increase by a factor as high as 1000 from the laboratory scale to a production plant (Vogel, 2000). Hence, the later in the development process a change needs to be made, the more costly and inflexible it will likely be. Therefore, it is important to assess a new material from the different perspectives of sustainability, which involves economic, environmental and social aspects in combination with the time perspective (Lozano, 2008), in the very early stages of development in order to guide it in a promising direction. The technical properties of a material alone give little indication as to whether the material will be suitable for adoption and prolonged use in a specific application or market. Moreover, a number of factors determine whether a new material will be economically viable to enter the marketplace. With the environmental footprint of products increasing in importance

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for both regulatory control and consumer consciousness, it is crucial to take this factor into account as well.

The research of new materials and chemicals rarely focuses on choosing the most suitable application in a systematic manner. There are many aspects that need to be considered to find a suitable and sustainable application. Materials from renewable resources, for example, receive praise for having superior environmental performance. But this is not necessarily the case. For example when agriculture is involved in the production of natural fibers, such as cellulose nanofibers (CNFs), fertilizers, pesticides and other substances used may result in a high impact in the area of eutrophication (Corbière-Nicollier et al., 2001; Zah et al., 2007). When evaluating the environmental impact of a material, it is not only the production process that needs to be taken into consideration but also the specific application for which the material is used. For instance, a car body panel made from an environmentally friendly material that weighs more than a comparable standard panel may lead to an unfavorable environmental performance due to increased fuel consumption (Zah et al., 2007). It is therefore crucial that a material's whole life cycle is assessed before drawing conclusions as to how environmentally friendly a particular application is.

The fast-paced growth of the nanotechnology industry brings novel materials with distinct and unique properties into commercially available products on a frequent basis (Dang et al., 2010; Forster et al., 2011; Invernizzi, 2011; Piccinno et al., 2012; Rejeski, 2008). The example of CNFs has drawn a lot of attention due to their exceptional mechanical properties, their renewable nature and their biodegradability (Azizi Samir et al., 2005). Since the first description of CNFs as a reinforcement of composites (Favier et al., 1995), several application fields have been proposed. Cherian et al. (2011) discussed their use in medicine due to the biocompatibility with the human body. Additionally, excellent barrier properties make CNFs an attractive alternative for the use in food packaging (Azeredo, 2009; Lavoine et al., 2012). Their optical transparency lends itself to use the fibers in organic displays in the electronics device industry (Nogi and Yano, 2008). A composite material that is reinforced with CNFs can exceed the mechanical properties of glass fiber reinforced plastic (GFRP) (Kamel, 2007; Leung et al., 2013; Nishino et al., 2004). This, in combination with its low weight, makes it attractive for automotive or aerospace applications (Moon et al., 2011). While all these applications are feasible, they are a seemingly random selection of uses for CNFs and may not be the most exhaustive or appropriate applications in which to use this emerging material. Therefore, a systematic approach may help to minimize the potential of overlooking additional applications or inadvertently choosing applications which are not best suited to the material at hand.

Multi-criteria decision analysis is an approach to simultaneously assess alternatives from various perspectives. Especially in the context of sustainability to include environmental and/or social aspects it has been applied for various cases (Do et al., 2014; Gasafi and Weil, 2011; Matteson, 2014). In engineering and product development, the combination of technical, economic and environmental criteria in order to obtain sustainable products is increasing (Jahan et al., 2010; Ljungberg, 2007; Peças et al., 2013; Ribeiro et al., 2008; Zhou et al., 2009). Multi-criteria decision support methods are used on a regular basis in order to choose the most suitable material. Those studies focus on a known application and search the best alternative in terms of material or process for a given application. This means that it chooses from a set of alternatives the best solution based on predefined parameters.

Many tools and concepts to improve the sustainability for companies have been developed (Lozano, 2012). Among those, the concept of eco-design is growing in popularity. It is an approach to include environmental aspects in the product design and development of products (Karlsson and Luttropp, 2006). Various tools and methods have been developed for this purpose. Bovea and Pérez-Belis (2012) have reviewed those tools and found the three key factors for an eco-design tool as being (1) its early integration into product design, (2) the use of a life cycle perspective, and (3) the use of a multi-criteria approach.

However, in research and development, when a new material is developed, the opposite is often the case: a known material with certain properties is available and a suitable application has to be found. This step differs considerably from the product design as the material used for a product or application is under development as opposed to the product itself. To the knowledge of the authors, there is no literature available that addresses the development of sustainable products from this perspective. Therefore, this current manuscript closes this gap by proposing a method to identify the application fields that present the best opportunity to exploit the competitive advantages of a new material when entering a given market. The authors call this approach Multi-Perspective Application Selection (MPAS) because it aims at identifying suitable applications for a material using technical, economic and environmental criteria. The method covers each of the three key factors identified by Bovea and Pérez-Belis (2012) and differs from other multi-criteria selection and eco-design methods in various aspects. The approach of starting with the material and evaluating whether there are suitable applications results in a theoretically infinite number of alternatives. Therefore, the MPAS also involves a step to identify as many application fields as possible systematically. It is designed in a manner that it can already be performed at a very early stage of development based on the available knowledge and can be updated at a more mature research stage. The primary audience for the use of the method are researchers and industrial practitioners involved in the development to gain a better understanding and to direct their research efforts more efficiently. A case study on cellulose nanofiber reinforced polymers (CNFRP) exemplifies the applicability of the MPAS.

2. Multi-perspective application selection

To identify the most promising application fields for a new material, the MPAS decision scheme, which consists of three main steps, is applied (Fig. 1). The identification and segmentation of the application fields (Step 1) is followed by a selection based on technical and economic user acceptance criteria (UAC) (Step 2). Step 3 uses simplified Life Cycle Assessment (LCA) calculations for the environmental advantage score, being the third component of the MPAS score, to choose the most suitable applications for a given material.

Here, the methodical approach is presented step-by-step where a chapter is dedicated to each step. Further refinement is made with a practical example using CNFRP to illustrate its application. Both literature searches and surveys from key industrial players (material producers as well as consumers) helped to identify the case-specific user acceptance criteria for technical and economic feasibility of products. For the simplified LCA calculations of the example, the impact categories are limited to Global Warming Potential (GWP) calculated over a time interval of 100 years (Pachauri and Reisinger, 2007), Cumulative Energy Demand (CED) of non-renewable resources and ReCiPe Endpoint indicators (Goedkoop et al., 2008).

2.1. Step 1 – identification and segmentation of application fields

This step is crucial for the success of the MPAS as it is responsible for the identification of potential application fields. Hence, this is

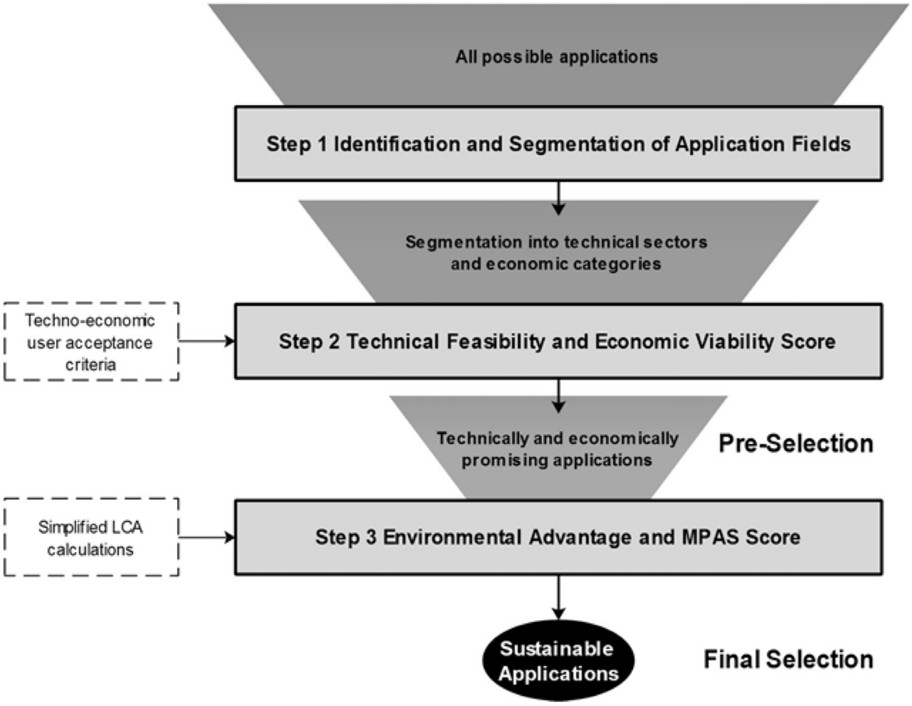


Fig. 1. Overview of the various steps and their in- and outputs in the MPAS method.

the limiting step given that an application that has not been identified cannot be selected. It is composed in such a manner to reduce the risk of overlooking potential application fields.

First, the varied application fields are segmented into groups with similar technological and/or economic benefits; aiming to create a balance between fine detail of material specific information and generalization of applications to create a practically useful dataset. If the material's main purpose is to substitute an existing material, the identification process of application fields can be based on the use of the current material that is being replaced.

Application fields have to be filtered into increasingly narrow classifications on three hierarchical levels to obtain a logical and structured segmentation (Fig. 2). The broadest grouping, or main function, on the highest level identifies the main functionalities for which the known properties of the material can be useful. Starting with such a broad grouping, reduces the risk of overlooking potential application fields. Next, sectors are defined within every main function based on technical criteria which are consistent with the material properties required for a given application; assuming that within a certain sector all applications require similar material properties. Hence, the first two levels of the identification and segmentation are based on technical properties. Following the technical segmentation of the first two, the subdivision of the sectors using economic criteria to obtain categories builds the third and final level of classification. The economic differentiation mainly focuses on the end-user (e.g. private vs. public vs. industry; luxury vs. low price etc.) and the degree of regulation for the specific category.

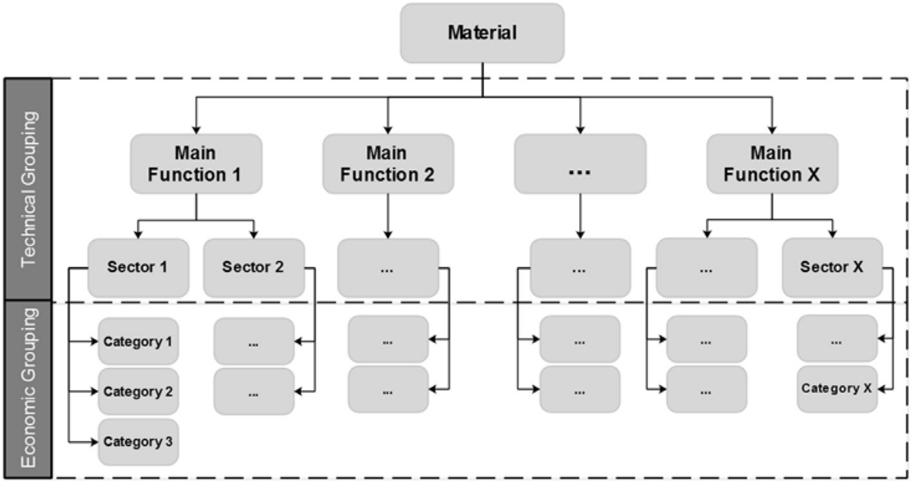


Fig. 2. The segmentation structure used to identify and classify potential application fields.

2.2. Step 2 — technical feasibility and economic viability score

Following the previous segmentation, this step selects the most suitable categories according to technical and economic user acceptance criteria (UAC). When focusing on the market entry of a new material, the following four UACs were identified to be the most important:

- *Material properties*. This is regarded as the most significant criterion as a new material must meet the specific material property requirements of an application. For a successful selection process, realistic estimates of the (achievable) properties based on current knowledge are crucial. The accuracy of this evaluation strongly depends on the material's development status. This UAC is split into sub-criteria consisting of the various material properties (e.g. modulus, density, water solubility etc.) that are case specific.
- *Quality and stability*. Quality means the uniformity and consistency with which a material can be produced. A material with high quality does not display any significant differences between different batches. The stability represents the alteration over time or a material's longevity. Quality and stability of a material become indispensable in applications where the consequences of material failure could result in huge financial loss or adversely affect human or environmental health (e.g. aerospace, construction or medical fields). Therefore, manufacturers and end-users will not take large risks and use a material without a proven track record of quality and stability in these high-risk applications. Industry needs to build trust in these new materials over time and it can take several years before a new material is fully accepted by the market.
- *Cost*. This is the most significant economic criterion, representing actual costs of the material and its production. It constitutes a critical factor for the acceptance of a new material. Cost is an especially important factor for low and medium technology applications where there is a high cost pressure. On the other hand, high-tech and luxury applications are not as price sensitive with a larger profit margin. New materials are rarely produced at cost efficient levels due to lack of technical experience and limited economies of scale. To assess the feasibility of a new material, the cost sensitivity of the market should be considered.
- *Regulation, legislation and certification*. This criterion can differ widely between applications, markets and geographical locations. The time and cost associated with testing and homologating a new material for use in highly regulated applications could represent a high barrier to entry into some markets. It is also important to consider that homologation and certification does not guarantee immediate adoption of a new technology. To contain start-up costs and be competitive immediately, the initial focus for emerging materials should be towards markets with low regulatory requirements and few barriers of certification. While this facet of the evaluation contains a technical component, it is regarded as an economic criterion for this study.

Although the differences are not always distinct, the first two criteria are defined as technical, whereas the latter two are economic criteria for the purpose of the MPAS. In general, the four elements listed above are the most important criteria for new materials to enter a market successfully and therefore they build the key UACs for the MPAS. However, depending on the specific case study, additional UACs might be defined to meet specific requirements. Those UACs might comprise soft factors, such as the affinity of the market for environmental friendly products, which are even more difficult to quantify. Ultimately, a new material must have a clear advantage over an existing material. Manufacturers and industrial end-users must recognize an advantage that gives the opportunity to make more profit.

The practical application of the UACs in this step consists of defining the requirements of the application fields investigated by giving them a qualitative value from low to high. Then, it needs to be verified whether the material can meet those requirements, resulting in a score from 0 (not possible) to 3 (good) as described in Table 1. A criterion that results in a competitiveness score of 0 automatically excludes that application. For the transparency of the selection, it is important to state the assumptions for the competitiveness of the material in relation to the requirements for each criterion.

Given that the segmentation of the sectors is based on technical characteristics, the appropriate sectors are selected in a first phase by using the technical UACs only in a selection matrix. Each of the two technical criteria — material properties and quality & stability — results in a score from (0) to (3). The average of the two criteria lead to the technical feasibility score of the respective sector, ranging from low to high (Table 1). Only sectors with a minimum score of medium will pass this phase. This filtering process eliminates sectors (and their underlying categories) for which the technical requirements the new material is unlikely to fulfill. This facilitates the subsequent investigation of the categories by excluding non-promising ones before applying the economic criteria. Within the selected sectors, the selection of the categories takes place in an analogous manner but in addition to the two technical UACs, also the economic UACs are applied. The reason why the technical assessment has to be performed again, is that there can be additional, more specific requirements for a category compared to its sector. As a result, one obtains a score for the technical feasibility of the category as well as its economic viability. In order for a category to be selected, it must have a medium–high (MH) or higher score for one of the two and at least a medium (M) score for the other. All categories that fulfill these requirements are selected for further analysis in Step 3.

2.3. Step 3 — environmental advantage and MPAS score

The last step of the MPAS assesses the environmental aspects of the selected categories with the help of a simplified LCA studies. Given that performing full LCAs for each of the chosen categories is too intricate and a very detailed knowledge of each case would need to be generated, this would go far beyond the scope of the MPAS approach here. Instead, simplified LCA calculations, which are semi-quantitative assessments of the product life cycle based on simplified and generalized assumptions, are used. This reduced analysis is helpful as a decision tool since it allows to quickly assess several different cases. In the majority of cases, the chosen categories represent a group of applications. For a simplified LCA calculation, the cases must be more specific. Since there are several varied applications within each category, a representative case as an example needs to be chosen. It should contain the definition of goal and scope, the inventory analysis, the impact assessment and the final interpretation of the results. The goal of the simplified LCA calculations is to evaluate in which applications the material might have environmental advantages compared to alternative materials, to detect the specific environmental advantages of the material, and to identify which factors are relevant for a competitive environmental performance in the context of various application cases. In order to keep the results of the simplified LCA calculations manageable but still comprehensive, the life cycle impact assessment (LCIA) can be reduced to a certain set of methods that are most appropriate for the specific case studies. In general, the ReCiPe endpoint indicator method is very useful for this purpose, as it

Table 1
Definition and weighting of the competitiveness scoring for the evaluation of the UACs.

Qualitative values for UAC requirements	Score for competitiveness of investigated material	Description	Weighting for average calculation	Technical feasibility and economic viability score (translation of average score)
High (H) Medium–High (MH) Medium (M) Low–Medium (LM)	0 = not possible	Material is objectively not able to meet the requirements (e.g. requirement water solubility); or if markets with certain requirements are wanted to be excluded (e.g. high risk market)	Excludes application	<1.25 = Low 1.25–1.74 = Low–Medium 1.75–2.24 = Medium 2.25–2.74 = Medium–High
Low (L)	1 = poor	It will be very difficult for the material to meet the requirement; or if there is not enough information about those material properties	Double weighting	≥2.75 = High
	2 = fair	The material should be able to meet the requirements.	Single weighting	
	3 = good	The material can easily meet the requirements.	Single weighting	

comprises various different impacts. This helps to highlight possible environmental benefits and/or drawbacks of a certain category. The relative difference in the LCA results between the examined material and the comparison material determines the environmental advantage score according to Table 2.

In the end, the sum of the scores for all the technical, economic and environmental aspects examined in Steps 2 and 3 results in the MPAS score. It indicates which applications seem to be the most favorable from all the three perspectives based on the proposed MPAS with the currently available knowledge and data (Table 2).

3. Case study: cellulose nanofibers as a polymer reinforcement

To illustrate the application of the MPAS, a case study using cellulose nanofibers as reinforcement of polymers is presented.

3.1. Step 1 — identification and segmentation of application fields

While CNFs have the potential to be employed in many applications, this case study focuses solely on their use as reinforcement in polymers where the combination of high strength and low weight properties are of key interest. Using the existing market for fiber reinforced composites as a base, it is helpful to review current uses for materials in this field including carbon (CFRP), glass (GFRP) and natural fiber reinforced polymers. Thus, the segmentation was made by reviewing the use of reinforced composites (Future Markets, 2012; Kalia et al., 2009; Roberts, 2011; Saxena et al., 2011; Visiongain, 2013) and by a survey among material scientists as well as industrial composite producers. Based on the material properties, ballistic protection (strength and modulus), fuel efficiency in transport (lightweight), carrying/structural function (strength and modulus), design and human body interaction (biocompatibility) emerged as the main functions. Table 3 illustrates the entire segmentation.

Table 2
Definition and values of the environmental advantage and MPAS score.

Average difference to comparison material	Environmental advantage score	MPAS score
>20% reduction	High = 3	≥8.25 High
11–20% reduction	Medium–High = 2.5	6.75–8.24 Medium–High
0–10% reduction	Medium = 2	5.25–6.74 Medium
1–10% increase	Low–Medium = 1.5	3.75–5.24 Low–Medium
>10% increase	Low = 1	<3.75 Low

3.2. Step 2 — technical feasibility and economic viability score

Industrial manufacturers helped to discuss the substitution potential of the developed new material in their manufacturing process, complemented by an analysis with potential customers to ascertain their acceptance requirements. A number of challenges exist concerning the material properties of CNFs. One disadvantage is that cellulosic fibers tend to absorb water and swell (Eichhorn et al., 2010; Siqueira et al., 2010). Even if this might be solved by suitable coatings and embedding of the fibers in a matrix material, this factor can nevertheless be important in specific applications. Another drawback is that cellulose degrades at high temperatures limiting both the potential application as well as its ability to be processed under such conditions, and hence reducing the compatibility with certain matrix materials (Azizi Samir et al., 2005; Kamel, 2007; Siqueira et al., 2010).

One concern with materials from renewable materials in general is their quality and stability. There is a perception in the market that the quality of bio-fibers can differ from one batch to another due to uncontrollable factors such as the climatic conditions that can alter the composition of the raw materials used for the production of such fibers (Dittenber and GangaRao, 2012). Another concern is the long-term stability of CNFs since there is no real life experience with this material so far, especially concerning durability (Hubbe et al., 2008). These uncertainties about material variability and stability are why high-risk markets should be avoided.

As a new material entering the market, the price of CNFs is expected to be non-competitive in comparison to existing low-cost fibers. This is due to smaller economies of scale and the industrial production processes which are not yet optimized during the introduction stage of a product life cycle. Consequently, it is very difficult for CNFRP to successfully enter a market with high cost pressure. An ideal market for CNFs should be cost insensitive. A cost related competitive advantage of CNFs is that their price is not related to the price of oil and the resulting lower price volatility is very attractive for industrial customers.

Composite manufacturers expressed the importance of the compatibility with a wide range of manufacturing processes. Ideally, CNFs should directly substitute existing fiber technology without the need to modify the existing manufacturing equipment and processes as manufacturers are reluctant to invest in new machinery in order to adopt a new and unproven material. Despite this, the manufacturing process was not taken into account in the selection process since it is very difficult to assess the processability of CNFs at this stage of development. However, as it is an important criterion, this issue will be revisited after the analysis for the chosen application cases in order to highlight which requirements have to be fulfilled. Based on the known and expected properties of cellulose nanofibers, for every requirement the competitiveness has been defined (Table 4).

Table 3
Results of the identification and segmentation of the application fields for cellulose nanofiber reinforced composites.

Main function	Sector (technical properties)	Category (economic)
Ballistic protection	Body armor	- Military - Private
	Vehicle protection	- Military - Private
Fuel efficiency (transport)	Aerospace	- Space - Passenger airplanes - Private airplanes
	Ground	- Mass transit - Automotive – regular cars - Automotive – high value sport cars - Automotive – specialty vehicles
	Marine	- Passenger boats - Private boats - Submersibles
	Packaging	- Single-use - Multiple-use
Carrying/structural function	Industrial	- Processing - Pipes, tanks, containers - Robotics
	Construction & infrastructure	- Buildings and bridges - Modular structures - Cladding
	Wind/energy	- Wind turbines - Water turbines
Design	Housing	- Sanitary ware - Furniture
	Consumer goods	- Regular products - Luxury products
Human body interaction	Sports & recreation	- Equipment - Protection
	Medical	- Prosthesis - Implants

Table 5 shows the selection process for the different sectors in a matrix in order to evaluate whether CNFs can be competitive enough to enter a market as a new material according to the two technical UACs. The upper row for each sector is the qualitative rating (from low = L to high = H) of the requirements that need to be fulfilled by the material, while the lower row evaluates whether CNFs are actually in a position to meet those requirements. Hence, for each requirement, a competitiveness score is given as defined in Table 4. Seven out of 13 sectors passed the selection using this procedure. The main reason for the dismissal of the other sectors was the high risk resulting from the uncertainty about quality and stability of CNFs. Being omitted from this selection process does not mean these sectors might not be suitable for CNFs in the future, but this must be reassessed once the material has been established in the market for some years.

In the next step, the seven sectors selected are subdivided into their categories identified in Step 1, and all four UACs are applied (Table 6).

At the end of Step 2, six categories from five different sectors remained (Fig. 3):

- *Specialty vehicles*. This appears to be a very attractive category since many of the regulations and technical requirements are relatively easy to achieve. It is not a high output market and the manufacturers are comparably small companies. Consequently, the market adopts new materials easier compared to the regular automotive market.
- *Processing*. The use of reinforced composites in tanks and pipes requires high levels of durability and must have specific mechanical properties depending on the exact application. This is not the case if the composite is only used during processing, such as cutting or transporting, and directly disposed of afterward.
- *Furniture*. Although the housing category is interesting for the use of CNFs, the current uncertainty and lack of data regarding the durability and its tendency to absorb water make it unsuitable for the use in sanitary ware. However, in another housing category, furniture, CNFs are able to meet the requirements.
- *Luxury products*. The consumer goods sector can be segmented by the price of the products, which directly translates into cost sensitivity. CNFs could only enter the market for high price products at this time.
- *Equipment and protection*. In the sports & recreation sector, two categories were selected: equipment and protection. The former may be slightly more favorable due to the reduced certification requirements of the final products.

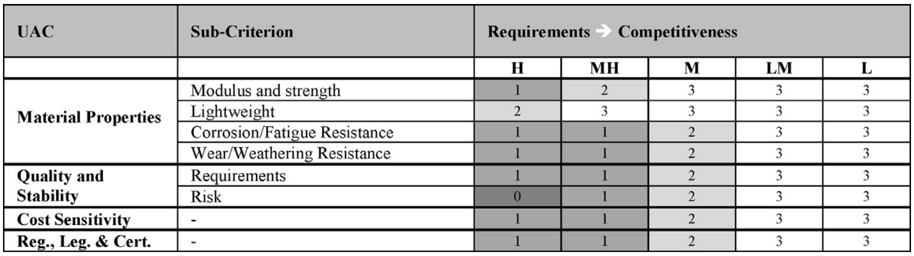
3.3. Step 3 – environmental advantage and MPAS score

The use of simplified LCA calculations will show whether the selected categories for cellulose nanofiber reinforced composites are still considered promising application fields when the environmental perspective is included.

3.3.1. Goal and scope of the simplified LCA studies

With the simplified LCA calculations, CNFRP are compared to other existing materials to see their potential for substituting said materials in terms of environmental performance. The impact assessment has been limited to GWP, CED of non-renewable resources (fossil and nuclear) and ReCiPe Endpoint indicators. An important assumption for this study is that CNFRP achieve all the technical requirements in each application. All data, with the exception of carbon fibers, was obtained from the ecoinvent database (ecoinvent Centre, 2010). The data for carbon fibers only

Table 4
Assumed competitiveness of CNFs for the various criteria in relation to the requirements.



UAC	Sub-Criterion	Requirements ➔ Competitiveness				
		H	MH	M	LM	L
Material Properties	Modulus and strength	1	2	3	3	3
	Lightweight	2	3	3	3	3
	Corrosion/Fatigue Resistance	1	1	2	3	3
	Wear/Weathering Resistance	1	1	2	3	3
Quality and Stability	Requirements	1	1	2	3	3
	Risk	0	1	2	3	3
Cost Sensitivity	-	1	1	2	3	3
Reg., Leg. & Cert.	-	1	1	2	3	3

Table 5
Selection matrix to evaluate the technical feasibility scoring of the sectors.

		Material Properties						Quality & Stability				
Main Function	User Acceptance Criteria / Sector	Modulus and Strength	Lightweight	Corrosion/Fatigue Resistance	Wear/Weathering Resistance	Other Properties	Score	Requirements	Risk	Score	Technical Feasibility of Sector	Selection
Ballistic Protection	Body Armor	H[a]	MH	MH	MH	-	1.3	H	H	0	L 0.64	-
		1[b]	3	1	1	-		1	0			
	Vehicle Protection	H	M	H	H	-	1.3	H	H	0	L 0.64	-
		1	3	1	1	-		1	0			
Fuel Efficiency (Transport)	Aerospace	H	H	H	H	-	1.1	H	H	0	L 0.57	-
		1	2	1	1	-		1	0			
	Ground	M	MH	M	M	-	2.5	M	M	2	M-H 2.25	✓
		3	3	2	2	-		2	2			
	Marine	M	MH	MH	H	water resistance	1.5	MH	M	1.3	L 1.42	-
		3	3	1	1	1		1	2			
	Packaging	LM	M	M	M	barrier properties	2.6	M	L	2.5	M-H 2.55	✓
		3	3	2	2	3		2	3			
Carrying/Structural Function	Industrial	M	LM	MH	M	-	2.0	M	M	2.0	M 2.00	✓
		3	3	1	2	-		2	2			
	Construction & Infrastructure	MH	M	H	H	-	1.5	H	H	0	L 0.75	-
		2	3	1	1	-		1	0			
	Wind/Energy	MH	MH	H	H	-	1.5	H	M	1.3	L 1.42	-
		2	3	1	1	-		1	2			
Design	Housing	LM	LM	M	M	-	2.5	M	L	2.5	M-H 2.50	✓
		3	3	2	2	-		2	3			
	Consumer Goods	LM	LM	M	LM	-	2.8	M	L	2.5	M-H 2.63	✓
		3	3	2	3	-		2	3			
Human Body Interaction	Sports & Recreation	M	MH	M	M	-	2.5	M	M	2.0	M-H 2.25	✓
		3	3	2	2	-		2	2			
	Medical	M	MH	H	M	biocompatibility	2.2	H	H	0	L 1.08	-
		3	3	1	2	3		1	0			

[a] The upper row indicates the requirements of the sector with: H=high, MH=medium-high, M=medium, LM=low-medium, L=low

[b] The lower row indicates the competitiveness score which is defined in relation to the requirements according to Table 4.

Table 6
Selection matrix to evaluate the technical feasibility and economic viability scoring of the categories.

Main Function	Sector		User Acceptance Criteria	Material Properties						Quality & Stability				Costs		Reg., Leg. & Cert.			
			Category	Modulus and Strength	Lightweight	Corrosion/Fatigue Resistance	Wear/Weathering Resistance	Other Properties	Score	Requirements	Risk	Score	Technical Feasibility of Category	Cost Sensitivity	Score	Regulation, Legislation & Certification	Score	Economic Viability of Category	Selection
Fuel Efficiency (Transport)	Ground	Automotive	Regular Cars/Motorcycles	M	MH	M	M	-	2.5	H	M	1.3	M 1.92	H	1	LM	3	L-M 1.67	-
				3	3	2	2	-		1	2			1		3			
			High Value Sport Cars	MH	H	MH	M	Temperature Resistance	1.7	H	MH	1.3	L-M 1.50	L	3	LM	3	H 3.00	-
				2	2	1	2	2		1	1			3		3			
			Specialty Vehicles	M	MH	M	M	-	2.5	LM	M	2.5	M-H 2.50	LM	3	L	3	H 3.00	✓
				3	3	2	2	-		3	2			3		3			
			Mass Transit	M	MH	MH	M	Fire Resistance	1.7	H	MH	1.0	L 1.36	H	1	H	1	L 1.00	-
				3	3	1	2	1		1	1			1		1			
	Packaging		Single-Use	LM	M	M	M	barrier; (biodegrad.)	2.6	L	L	3.0	H 2.80	H	1	LM	3	L-M 1.67	-
				3	3	2	2	3; (3)		3	3			1		3			
			Multiple-Use	LM	M	MH	M	barrier properties	2.2	MH	M	1.3	M 1.75	MH	1	LM	3	L-M 1.67	-
				3	3	1	2	3		1	2			1		3			
Carrying/Structural Function	Industrial		Processing	M	LM	M	M	(biodegrad-ability)	2.5	L	LM	3.0	H 2.75	M	2	L	3	M-H 2.50	✓
				3	3	2	2	(3)		3	3			2		3			
			Pipes, Tubes, Containers	M	LM	MH	MH	Resistance to chemicals	1.5	H	M	1.3	L-M 1.42	M	2	M	2	M 2.00	-
				3	3	1	1	1		1	2			2		2			
			Robotics	MH	MH	MH	M	-	1.8	H	M	1.3	L-M 1.57	LM	3	M	2	M-H 2.50	-
				2	3	1	2	-		1	2			3		2			
Design	Housing		Sanitary Ware	M	LM	MH	M	Resist. water/chemicals	1.7	H	L	1.7	L-M 1.69	M	2	L	3	M-H 2.50	-
				3	3	1	2	1		1	3			2		3			
			Furniture	LM	LM	M	M	-	2.5	LM	L	3.0	H 2.75	M	2	L	3	M-H 2.50	✓
				3	3	2	2	-		3	3			2		3			
	Consumer Goods		Regular Products	LM	LM	M	LM	-	2.8	LM	L	3.0	H 2.88	H	1	L	3	L-M 1.67	-
				3	3	2	3	-		3	3			1		3			
			Luxury Products	LM	LM	M	LM	-	2.8	M	L	2.5	M-H 2.63	L	3	L	3	H 3.00	✓
				3	3	2	3	-		2	3			3		3			
Human Body Interaction	Sports & Recreation		Equipment	M	MH	M	M	-	2.5	M	LM	2.5	M-H 2.50	LM	3	M	2	M-H 2.50	✓
				3	3	2	2	-		2	3			3		2			
			Protection	M	MH	M	M	-	2.5	M	M	2.0	M-H 2.25	LM	3	M	2	M-H 2.50	✓
				3	3	2	2	-		2	2			3		2			

[a] The upper row indicates the requirements of the category with: H=high, MH=medium-high, M=medium, LM=low-medium, L=low

[b] The lower row indicates the competitiveness score which is defined in relation to the requirements according to Table 4.

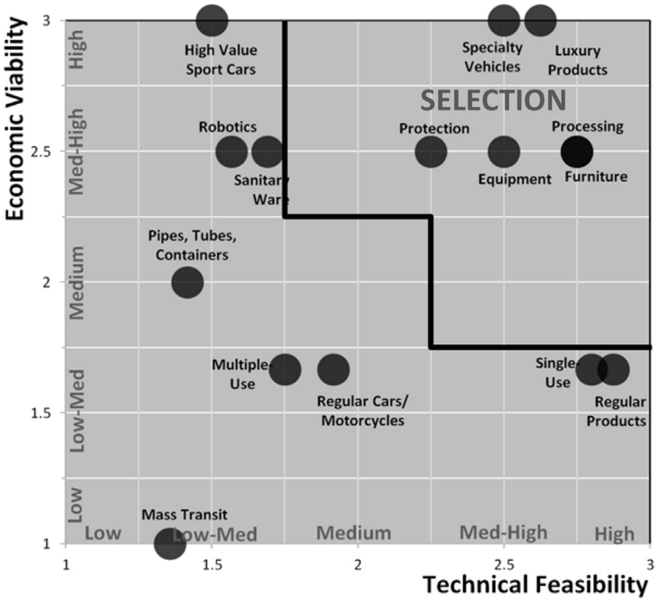


Fig. 3. Graph for the selection of the categories technical feasibility and economic viability selection graph of categories.

consisted of GWP and CED since no ReCiPe values were available (Das, 2011).

For each of the six categories selected in Step 2, the following is the selection of the representative examples for further analysis: motorhome sidewalls (for the category specialty vehicles), marble protection (processing), table (furniture), high-end loudspeakers (luxury products), surfboards (equipment), and motorcycle helmets (protection). In the following section, only the case for motorcycle helmets is presented in more details. Results for all other examples can be found in the Supplementary data. Motorcycle helmets were chosen as the representative example from the protection category. It appears to be a suitable example since it would compete with numerous different materials when manufacturers are designing a product. Compared to many other cases within that category (e.g. bicycle helmets, ice hockey protectors etc.) it involves a use phase where direct fuel consumption is included, which may be a relevant factor. To understand the impacts and implications in the non-fuel-consuming cases, the use phase can be omitted for the simplified LCA calculations.

3.3.2. *Inventory analysis*

The simplified LCA calculations consist of two different scenarios (A: 60% of GF and B: 80% of GF) of cellulose nanofibers production, serving as sensitivity analysis with the first representing the more optimistic one. The specific assumptions and data used in order to obtain life cycle inventory data of cellulose nanofibers from vegetable food waste can be found in the Supplementary data.

3.3.3. *Impact assessment – example: motorcycle helmets*

Categorizing full-face helmets made of traditional materials leads to three different groups according to the composition of its outer shell. The first type is made from non-reinforced polymer such as polycarbonate (PC) or acrylonitrile butadiene styrene (ABS), whereas the second type consists of glass fiber reinforced plastic. High-end helmets are commonly made of carbon fiber reinforced polymer. Besides these three groupings, there are a few models with mixed products combining the use of glass, carbon and kevlar fibers. The current case study excludes those mixed models. The different outer shell materials used in the helmets account for various differences in price, weight and performance; with the carbon fiber type being the lightest, best performing and most expensive helmet. Helmet weight differs by the specific model and size, so an average value for each of the three groupings has been defined (Table 7).

The outer shell of one helmet is the functional unit (FU). This leads to different weights of material per FU (Table 7). Besides the different scenarios A and B for the production of the cellulose nanofibers mentioned above, scenarios with different weight compositions of fibers and resin are used in this example by using 75, 80 and 85 wt% of CNFs in epoxy. The operation data of a scooter served as input to calculate the use phase. The system boundaries only comprised the production and the use of the helmet's outer shell. The end-of-life stage is excluded from this simplified LCA calculation.

Fig. 4 shows the results for the different impact categories. The helmet made from CFRP accounts for the highest values in all the impact categories due to its production phase. Weight had a larger impact during use than the production phase in all cases except for CFRP, yet since the weights of the helmet types varied by only 0.35 kg, the resulting impacts in the use phase are similar. This explains why the use phase is not the determining factor for the differences in the total LCA, but rather the variances are due to the unequal production phases of the materials. On one hand, the low values for the CNFRP result from the precondition of scenarios A and B, which by the assumptions made are lower than for GF. On the other hand, the higher weight ratios within the composite also improve the environmental performance given that epoxy is less favorable than the fibers. This shows that the reduction in weight is not very important from an environmental point of view in this application. Rather the resulting increased comfort of a lighter helmet might be a decision criterion for the end-user.

3.3.4. *Scoring of the simplified LCA calculations and final selection of applications*

Based on the simplified LCA calculations, a helmet made of CNFRP can have interesting environmental advantages and

Table 7
Assumptions for the production and use phase for the simplified LCA calculations of motorcycle helmets.

Name	Material	Weight of helmet [kg]	Weight of outer shell/composite = FU [kg]	Life expectancy = use phase	System boundaries
PC	Polycarbonate	1.6	1.4	19,500 km	Production and use of outer shell
GFRP	Glass fiber (50 wt%) in epoxy	1.5	1.3		
CFRP	Carbon fiber (50 wt%) in epoxy	1.25	1.05		
CNFRP XA	Cellulose nanofiber (75, 80, 85 wt%) in epoxy, scenario A	1.4	1.2		
CNFRP XB	Cellulose nanofiber (75, 80, 85 wt%) in epoxy, scenario B	1.4	1.2		

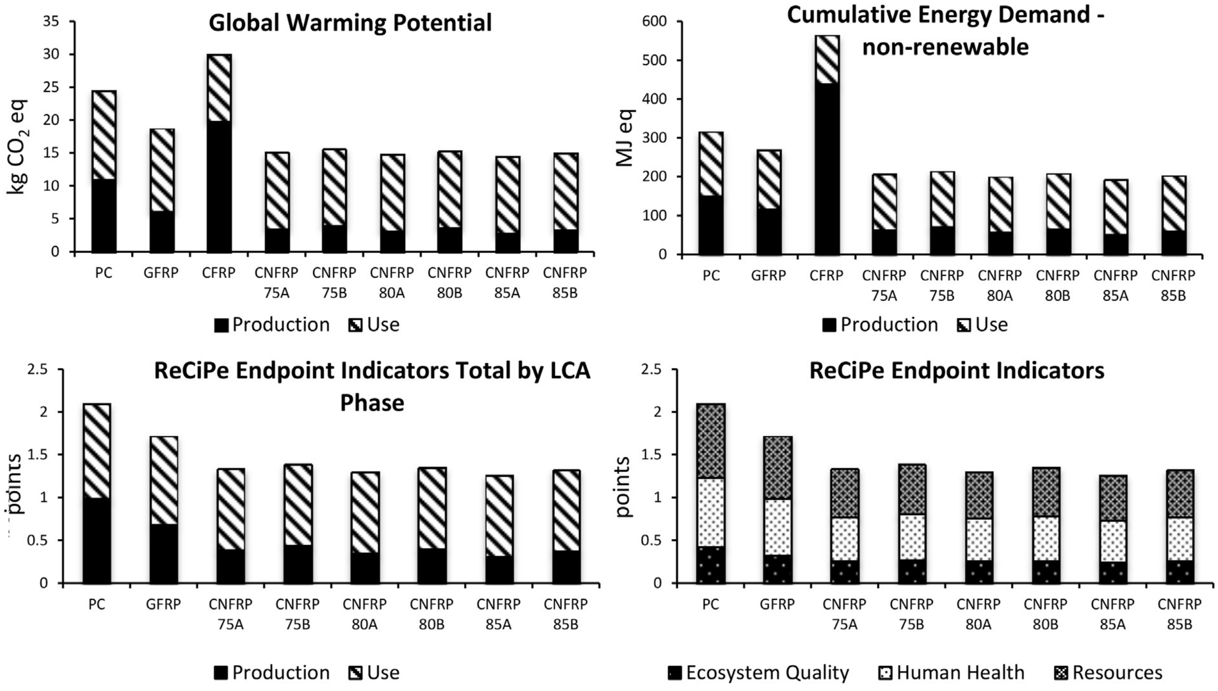


Fig. 4. Environmental impact of the production and use of motorcycle helmets with different material composition of the outer shell.

outperform all of the existing helmet types if its production phase can achieve favorable LCA values compared to GFRP and especially CFRP helmets. Given that the use phase is not the determining factor, those results are a good indication for the entire category of protection. The resulting reduction of the environmental impact compared to the alternative materials (PC: −37%; GFRP: −23%; CFRP: −57%) leads to a high environmental advantage score for the motorbike helmet – and therefore the whole protection category. The environmental advantage scores for the other examples are included in Table 8 (for more details, see Supplementary data).

Adding the results from the evaluations in Steps 2 and 3 together results in the MPAS score of CNFRP (Table 8). Four of the categories assessed have a high overall potential for CNFRP acceptance, whereas the other two categories have a slightly lower score. Luxury products (high-end loudspeakers), specialty vehicles (motorhome sidewalls), processing (marble protection) and furniture (table) achieved a high MPAS score and therefore seem to be the most promising applications for CNFRP.

4. Discussion

It often takes years for a new material to establish market acceptance because manufacturers are often risk averse and tend to prefer choosing materials with a tested market acceptance, known performance characteristics (longevity, safety, production processes) and low capital investment (in training employees and new equipment).

Increasing environmental awareness of end-users, in addition to more stringent environmental regulations in developed countries, suggests eco-friendly products will gain more and more attention in future. Therefore, the economic evaluation (regulation, legislation and certification) of the product should also look at mid- and long-term developments of the market. The longevity of the end products is very difficult to estimate in the early phases of development but has both environmental and economic consequences. In some applications, this is a crucial point and if there is a substantial difference in longevity between the materials assessed, it can change the outcome of the LCA. In many cases, a simplified LCA is sufficient to provide information about the minimum requirements of life expectancy that the material must achieve in order to be environmentally favorable.

The accuracy of the results from the Multi-Perspective Application Selection depends on the development status of the material and the respective assumptions made with the current knowledge. Therefore, it is important to understand the implications of those assumptions with high uncertainty, in which cases scenario

Table 8
Overview of the MPAS scores for the examined categories resulting from the technical feasibility, economic viability and environmental advantage score.

Sector	Category (LCA example)	MPAS score	Technical feasibility	Economic viability	Environmental advantage	Material to substitute
Consumer goods	Luxury products (high-end loudspeakers)	High (8.6)	Medium–High (2.6)	High (3)	High (3)	Carbon fiber
Sports & recreation	Protection (motorbike helmets)	Medium–High (7.75)	Medium–High (2.25)	Medium–High (2.5)	High (3)	Carbon fiber Glass fiber
Sports & recreation	Equipment (surfboards)	Medium–High (7)	Medium–High (2.5)	Medium–High (2.5)	Medium (2)	Glass fiber
Ground	Automotive – specialty vehicles (motorhome sidewalls)	High (8.5)	Medium–High (2.5)	High (3)	High (3)	
Industrial	Processing (marble protection)	High (8.25)	High (2.75)	Medium–High (2.5)	High (3)	
Housing	Furniture (table)	High (8.25)	High (2.75)	Medium–High (2.5)	High (3)	Glass fiber Aluminum

analyses in Step 2 as well as Step 3 are helpful. The best option, however, to monitor the accuracy is by updating the results from the MPAS on a regular basis or whenever more accurate/new data is available. With that measure, one can identify with ease whether the results diverge from selections made at an earlier stage. In a more advanced stage, researchers have a more accurate understanding of the material in terms of technical properties, related costs as well as the production processes. However, even in the mature stages of development, it remains important to verify and understand the degree of inaccuracy and uncertainty. One source of uncertainty involves predictions about the market, such as changes in consumer preferences and requirements, affinity for eco-products, price development of raw materials, development of alternative competitive products, etc. which are very difficult to measure. Those soft factors can be included as additional UACs and it is important to address these issues in the early stages of development before a lot of time and resources are used in product development. While the results of the MPAS have a subjective component in evaluating and weighting requirements and competitiveness of the material, it is still useful as it creates awareness, which helps to take advantage of the opportunities and minimize the risks identified through use of the method. In other words, the selection of an application with the MPAS does not guarantee its success in the market but increases the likelihood. Because of that subjectivity, different users of the MPAS may end up with results that deviate from each other. Those differences should be regarded as an added value since it opens the possibility of discussing and involving important aspects of material development.

The example of CNFs showed that it can be possible for new materials to enter niche or high-end markets that have considerably lower outputs and price sensitivity faster than the bulk of applications. This step could give the material an opportunity to establish itself in the market and build a track record. If cellulose nanofibers are used, for example, to produce designer furniture, it could become vogue by attracting attention from both industry and consumers due to its unusual source as food waste. Another economic advantage, which would interest industry, is the low dependency of CNFs on crude oil price, which makes better price competitiveness in the future seem reasonable.

It is interesting to point out that the results obtained from the case study include applications that were not initially mentioned by researchers involved in the materials development or found in the literature as potential applications for cellulose nanofibers. Therefore, those probably would not have been identified without a systematic procedure. Only after performing the MPAS those emerged as the most suitable applications underlining the importance of such an assessment. The researchers can now look more into the detailed requirements of the selected categories to see what exactly the cellulose nanofibers must achieve. For example, for the motorhome case it is important that there is a weight reduction, otherwise the high environmental advantage score cannot be achieved.

5. Conclusion

The MPAS is a simple and powerful method to simultaneously evaluate several possible application fields and to make predictions about their suitability for adoption of new materials. With a systematic and transparent reasoning of the selection of applications, many uncertainties concerning where new materials can best be implemented can be mitigated. A key strength of the MPAS is that it couples different perspectives (technical, economic and environmental) to obtain a sustainable application and successful product. Besides evaluating the environmental performance, the involvement of both technical and economic aspects enhances the probability of market acceptance. It is designed to be applied at a very early research state (before the application is even known), uses a multi-criteria selection and includes simplified LCA calculations and, thus, meets the three key factors for an eco-design tool, as defined by Bovea and Pérez-Belis (2012).

New and otherwise unforeseeable applications can be identified and evaluated, minimizing the risk of overlooking promising, sustainable uses of the material.

The presented method helps to guide researchers and industrial practitioners to cope with the many relevant technical, economic and environmental questions. Additionally, it builds up an awareness and understanding of these factors, which otherwise would be neglected, when choosing where to use new materials.

It is already applicable at an early point of development and is flexible in the level of detail involved depending on the information available as well as the knowledge and preferences of the MPAS user. Once the suitable application fields are identified, focus can then be shifted to R&D in the relevant direction by defining specific criteria (e.g. material properties, costs, longevity etc.) that the new material must fulfill in order to suit a given application. This approach therefore optimizes (research) time and resources, which may result in additional cost savings to developers.

The practical applicability of the method proved very helpful in the evaluation of cellulose nanofibers. New application fields were identified and luxury consumer goods, specialty vehicles, industrial processing and furniture emerged as the most promising. These results can be adopted by researchers and industrial practitioners in order to meet the requirements of those applications.

However, the MPAS method only serves as a preliminary assessment to make a pre-selection of promising applications and should be considered as a continuous process to be updated and re-evaluated whenever new or more accurate data is available. The Multi-Perspective Application Selection is therefore a starting point for the development of sustainable products by creating awareness and understanding as well as initiating discussions.

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Appendix A. Supplementary data

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