

Article

Circular Technology Roadmapping (TRM): Fostering Sustainable Material Development

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Abstract: To design more sustainable products often means improving the sustainability of materials. Currently, sustainable innovation calls upon materials to not only minimize environmental impacts but also to become circular. That requires efforts to keep materials functional for longer, avoid early disposal, and re-entering the cycle via recycling and other feedback processes. Those emerging challenges for materials development and the Circular Economy (CE) are especially critical in the case of polymers. How to develop strategies to preserve the value of polymers remains a question that mobilizes both researchers and practitioners. Technology Roadmapping (TRM) is a tool traditionally used for planning innovation processes and has supported the development of sustainable materials and other sustainability-related projects. This study tests TRM's potential to assist with the planning of new circular polymers solutions and proposes the Circular TRM method. This proposition results from the case study of the development of waste-based fiber-polymer materials and strategies for getting them into the market. Our case study demonstrates how it would be possible to differentiate the various polymer material technologies and determine the most circular strategy path.

Keywords: technology roadmapping; TRM; technology development; circular economy; sustainable material



Citation: Cobra, R.; Sanvezzo, P.; Branciforti, M.; Mascarenhas, J. Circular Technology Roadmapping (TRM): Fostering Sustainable Material Development. *Sustainability* **2021**, *13*, 7036. <https://doi.org/10.3390/su13137036>

Academic Editor: José Ignacio Alvarez

Received: 3 May 2021
Accepted: 2 June 2021
Published: 23 June 2021

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1. Introduction

The productivity of a company is not only dependent on its operational effectiveness but is also directly associated with its strategic positioning. While the operational effectiveness measures process efficiency, the strategy defines how the business can maintain a chain of well-coordinated processes that secure profit and protect the business from destructive competition [1]. Similarly to management practices that support the improvement of operational performance, there are approaches dedicated to strategic planning. One strategy method is Technology Roadmapping (TRM), which aims to identify, define, and map strategies, objectives, and actions related to innovation [2]. The TRM method's popularization is credited to Motorola Company in the 1970s, motivated by the need for alignment between technology development and product planning [3]. However, scientists recently traced TRM's origins to high technology organizations in the United States in the 1960s, such as NASA [4]. TRM application necessarily culminates in a graphical representation with the time in the horizontal axis and the strategic elements (e.g., markets, products, and technologies) in the vertical axis [5]. Workshops are helpful to gather all the information for preparing the TRM's output and its graphical representation. This entire process brings together different stakeholders and fosters learning, sharing information, and ultimately communicating and disseminating the strategy built collaboratively [5,6].

Despite the benefits of TRM, the academic literature highlights some limitations and states that it can be: more normative than exploratory; difficult to disseminate; tough to evaluate and assess business value; challenging to express the business attractiveness of

R&D outputs; hard to express a business system or operation model; difficult to customize; encourages linear and isolated thinking; provides few guidelines; lacks focus and clear boundaries; and lacks reliability and objectivity [7]. In this case, linearity does not oppose circularity, but disregards the multiple pathways of technology development, such as jumps to different solutions and direction changes [8]. There is still room for proposing branched strategy paths in TRM. Even though there are limitations to applying the TRM method, the literature reports numerous successful applications in a great variety of contexts [7,9]. Among the customizations of the TRM method, adaptations for promoting sustainability remain scarce. Some authors reported a need for more research for expanding technology management to sustainability [10]. Despite the low priority, the literature presents some attempts at roadmapping for sustainability that target specific contexts [11–13]. Table 1 brings a non-exhaustive compilation of TRM sustainability applications, indicating what was customized and the sustainability integration. In the first column of Table 1, customization relies on more detailed information on sustainability aspects of interest and the use of support tools such as scenarios, tables, and frameworks. Next, the second column of Table 1 shows sustainability can also be supported by proxies such as indicators, decision criteria, and representations.

Table 1. Review of TRM’s applications to sustainability.

Reference	Focus	Main Customizations for TRM	How Is Sustainability Integrated?
[8]	Metal manufacture	Association of TRM and scenario method.	The method is not particularly tailored for sustainable applications. However, the study presents a pilot application in the definition of clean production strategy for metal manufacturing.
[11]	Multinational Italian fashion company	The method uses three macro layers in the vertical axis: products, processes, and organization. Each layer is divided into sub-layers and projects as distributed inside them. Projects displayed in the roadmapping are clustered. The method includes the preparation of three sub-roadmaps: empowerment of stakeholders, increasing efficiency, and the creation of new performance criteria, models, and measurements.	It uses indicators for evaluating project proposals of TRM: people engagement, waste management, and energy efficiency.
[14–17]	European manufacturing industry	The information on the roadmaps is summarised in a table and in a framework. The roadmapping has 3 phases: pre-implementation, implementation, and post-implementation and combines with guidelines and project management.	Sustainability is a decision criterion.
[12,18,19]	Enterprise resource planning systems	The authors combine TRM with the Sustainable Value Analysis tool that assists the identification of sustainable value.	Considers sustainability according to the value-chain perspective and the management of the companies’ sustainability portfolio.
[13,20]	Generic [20]. Additive manufacturing [13].	The method proposed by the authors has three layers: drivers, business opportunities, and enablers.	The method includes a sustainable vision proposition. This lifecycle approach is incorporated into the method. The triple bottom line is part of the Sustainable Value tool combined with TRM.

Whereas sustainability is a much broader concept, the emergent Circular Economy (CE) has a more focused agenda. It aims at building a “regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops” [14]. For both sustainability and the CE, system change and innovation are at the core, while, at the same time, they face similar technological related difficulties [14]. Those two challenges coincide with issues that TRM addresses by design. Up to the submission of this work, the authors did not identify any roadmapping initiatives connected to the CE. While not considering CE during roadmapping, a business may lose opportunities in two ways. First, by having CE initiatives resumed to the micro-level of operational effectiveness [15]. Second, by ignoring the economic and environmental benefits that technology management and innovation processes could provide [14].

Materials development is both a significant driver for TRM applications [16] and a focus of “closing the loop” initiatives in the CE [15]. Innovations in materials sciences may take long to reach the market, however, this span might be reduced with the adoption of TRM [16]. From the CE perspective, improvements in materials used can either extend the product lifecycle or improve recycling opportunities at the end of life [15]. Tackling both the need to promote materials innovation and the CE should motivate the inclusion of new elements when customizing classical TRM workshops.

In summary, the main contextual opportunities identified are (a) the lack of multi-strategy paths in the TRM, (b) the need to expand technology management to incorporate sustainability, and (c) the possibilities that the CE brings for extrapolating the operational domain and reaching the strategic level, thus achieving a superior economic, environmental, and social performance. This study aims to present a proposition of a circular TRM method for technology push applied to the development of a waste-based fiber-polymer composite material. The pilot application of the Circular TRM brings an insight into materials development that is relevant for both technology management and the circular economy.

After this introduction, the paper has four sections beginning with the materials and methods, which shows how the case study aligned to the peculiarities of this research. Later, the results section brings the method proposal and the outcomes of its empirical application, followed by the discussion. Finally, the conclusion section closes the text with the highlights, insights, limitations, and final remarks.

2. Materials and Methods

Towards the development of the Circular TRM for the production of innovative materials, the research team sought a company that met the following criteria: (i) having an industrial waste composed of polymers that could be recycled; (ii) having the strategic goal of finding better solutions for this waste; (iii) being capable of providing samples of the waste; and (iv) willing to participate in the TRM workshops and work collaboratively. After establishing a partnership with a carpet manufacturer in São Paulo state, Brazil, the researchers began designing a solution to incorporate an industrial waste composed basically of jute and polypropylene (PP) fibers, Figure 1a [21]. This collaboration was motivated by the massive amount of fiber-polymer waste generated and discarded. Approximately 150 tons of the jute-PP material was going to waste every year solely from this carpet manufacturer. Specifically, the automotive carpet production is responsible for most of such fiber-polymer waste generation. Therefore, we can assume this waste can be produced in several carpet manufacturers in the automakers’ supply chain. Unfortunately, while no better alternatives are available, the material remains landfilled or incinerated, resulting in environmental impacts and costs for covering transportation, treatment, and disposal.

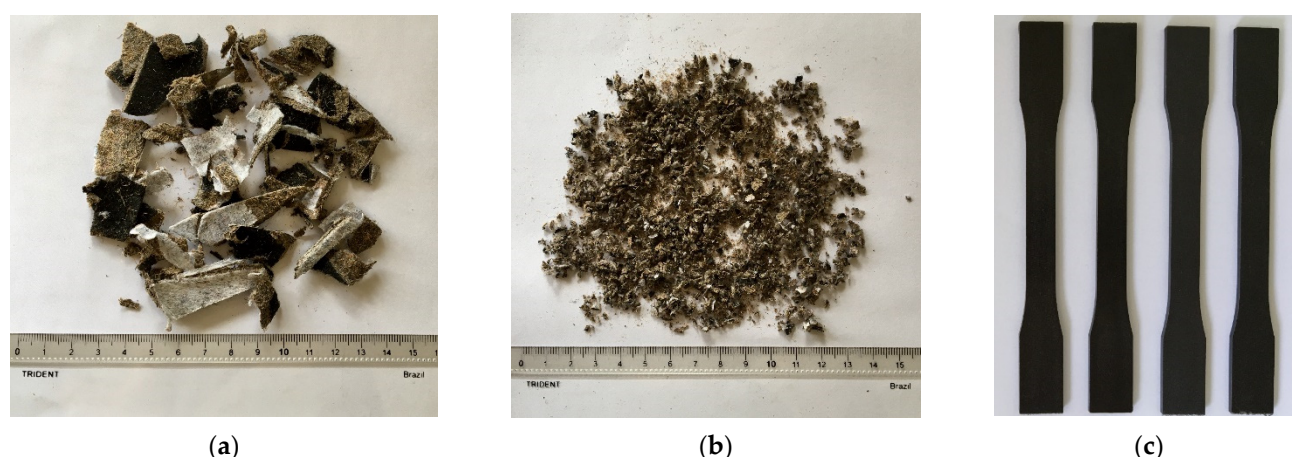


Figure 1. (a) jute-PP waste, (b) shredded jute-pp waste, (c) M1–M4: new materials specimens. Adapted with permission from [21]. Copyright 2021 Elsevier.

The development of the initial material concepts and TRM customization required approximately a 6-month stage. This stage was split into four steps: (1) materials characterization; (2) manufacturing; (3) characterization of the new materials; and (4) develop and apply the circular TRM. In the first step, the waste was characterized simultaneously with all the other raw materials used. Fourier-transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), optical microscopy, and selective dissolution were some of the methods used to characterize raw materials. Manufacturing included shredding, extrusion, and injection molding. Tests examined the new materials' specimens (Figure 1c) mechanical properties, density, permeability, and degradation (mechanical, photo-oxidative, and thermal) [21]. Finally, TRM aimed to go beyond developing waste-based materials and offer complete strategies to utilize those materials and achieve circular goals. This proposition considered the technical and circular goals of the specific carpet manufacturer carefully. For this reason, the collaboration resulted in technical and circular metrics that translated the aspirations and the ambition to return the material back into the cycle.

3. Results

The design of the Circular TRM methodology focuses on helping companies, especially those dedicated to new materials, to plan the development of technologies and products, giving priority to circular options beginning with the early stages. Some possibilities for applying the method are using it during the strategic planning in companies' internal processes and supporting circular initiatives, such as reusing industrial wastes. In any case of TRM application, this work reinforces that, independently of product or technology development planning, it should consider the circular attributes of materials, products, and markets.

The proposed method uses the classical TRM structure based on T-Plan [5] with the technology push approach. Its differential lies in the supporting elements designed to assist discussions of circular aspects during the workshops. This information added to the TRM process ensures the team has enough information to stimulate creativity towards a circular mindset.

Figure 2 shows the circular TRM divided into three main steps: preparation, workshops, and assembly. The former involves both development of the supporting elements and workshop planning, whereas the second addresses the classification and ranking of the technologies, products, and markets, according to general and circular aspects. The latter gathers the final roadmapping and identifies the better-ranked circular options.

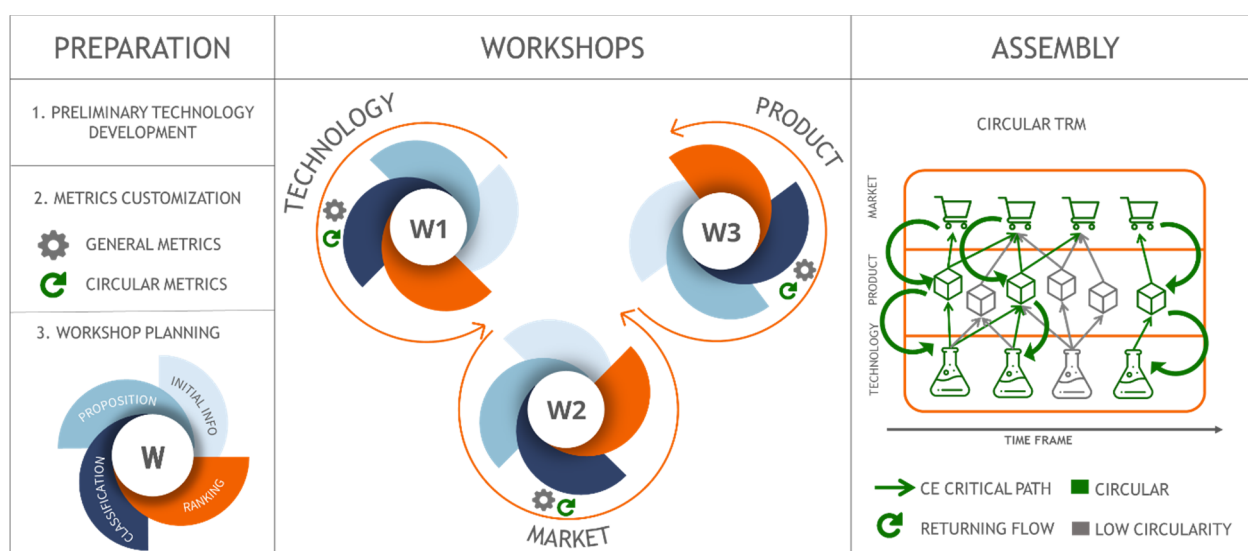


Figure 2. Circular TRM method.

In the following subsections, the paper details the circular TRM method and the pilot application results.

3.1. Preparation

The preparation step requires the previous development and selection of new technologies the company desires to introduce into the market; this appears as the “preliminary technology development.” This step lasted six months during the pilot application and resulted in four different technologies (M1, M2, M3, and M4). First, the industrial waste was shredded and processed by extrusion with PP, a mineral load, and a compatibilizer, followed by forming the specimens. Characterizations provided information about the materials that was summarized and prepared for presenting to specialists.

Next, the “metrics customization” step aims to assist the team in making the best decisions and classifying the technologies, markets, and products proposed during the workshops. For making this classification, it is first necessary to select general and circular metrics that can then support the assessment of technologies, markets, and products. There is no “one size fits all” set of metrics, nor is there a standard criterion for choosing them. Consequently, their selection responded to the particular technical performance parameters and the circular metrics that better fit the company’s strategy. Using these metrics, the Circular TRM enables comparison through a matrix that differentiates the options and helps with the contrasting of one material against the other.

In the “workshop planning” stage, the facilitators established the group activities and their sequence for the three workshops: technology, market, and product. In addition, it is necessary to prepare the support materials, for example, cards with technical specifications and non-disclosure agreements (NDAs).

In the workshop step of the method, all three workshops elapse according to four phases:

1. Initial: aims at sharing preliminary information used as input for discussion or emerged from a previous workshop (e.g., preliminary technology development, technical details, potential markets description);
2. Proposition: has the goal of making the team use the initial information to create new options for technologies, markets, and products;
3. Classification: has the objective of evaluating the options according to general and circular metrics;
4. Ranking phase: aims to prioritize the options and select some according to predefined and strategically selected, circular, and general criteria.

Towards the fiber-polymer circular solution design, the facilitators and the carpet manufacturer selected the general and circular metrics for each workshop and defined all activities, as shown in Table 2. Adding to the metrics and activities, at this step, the group also chose six initial markets to be explored in the market workshop: construction, automotive, naval, acoustic applications, domestic utensils, and sports.

Table 2. General and circular metrics and activities in each workshop of the fiber-polymer circular material development.

Workshops	Activities	General Metrics	Circular Metrics
Technology	Proposition of new components and compositions, manufacturing processes; classification of technologies according to metrics.	Modulus, elongation, impermeability, density, price	Durability, Recyclability
Market	Proposition of potential markets for both initial and proposed technologies; classification of markets according to metrics	Value added, market size	Sustainability appeal
Product	Proposition of potential products in the markets selected; classification of products according to metrics	Value added, interest in starting a business	Servitisation

The workshop participants or specialists invited formed a heterogeneous group of engineers, managers, material technology entrepreneurs, researchers from different institutions, and design experts. Individual competencies guided the participants' selection for each workshop. Both background and capacity to contribute to the discussions were decisive for determining the best combination of expertise. Even though some participants were present at every workshop, technology, market, and product specialists supplemented the team and enriched the discussions.

3.2. Workshops

The first workshop of the Circular TRM focused on "Technology", since the method adopts the technology push approach. It should begin with the initial information about the materials to be introduced into the market, followed by the propositions of improvements to these materials, e.g., new components, compositions, and changes in original manufacturing processes. Materials development specialists were, therefore, included for enabling discussions on materials technologies. Finally, the participants classified the technologies according to general and circular metrics. After the workshop, the facilitators ranked and selected the technologies, which were part of the inputs for the second workshop.

During the Circular TRM pilot application, this workshop culminated in new components to the materials, different combination of components, and alternative manufacturing processes, using the four initial technologies from the development stage (M1–4) as a starting point. Table 3 shows the five new materials proposed at the workshop (M5–9) and the four initial ones. While M1 to M4 technologies were manufactured in a corotational twin-screw modular extruder, the specialists suggested using a single-screw extruder, since it is cheaper and more employed in Brazilian industries. For forming the products, the specialists proposed pressing, roto-molding, lamination, and thermo-molding.

Afterwards, through group dynamics, the specialists classified, collaboratively, the nine technologies. Subsequently, the facilitators ranked all technologies through a seven-point Pugh matrix (Table 4) using the classification outputs.

Table 3. Initial technologies (M1–4) and proposed technologies (M5–9).

Technology	Matrix	Loads	Compatibilizer
M1	Recycled PP	Industrial waste	-
M2	Recycled PP	Industrial waste	-
M3	Recycled PP	Industrial waste	Calcium nanocarbonate
M4	Recycled PP	Industrial waste	Calcium nanocarbonate
M5	Polyamide	Industrial waste	Carbon fiber
M6	Polyamide	Industrial waste	Calcium nanocarbonate
M7	Polyamide	Industrial waste	Acrylonitrile butadiene styrene
M8	Polyethylene	Industrial waste	Glass fiber
M9	Copolymer PP	Industrial waste	Calcium nanocarbonate

Note: ¹ MAPP: maleic anhydride grafted polypropylene; ² MAMMA: maleic anhydride-methyl methacrylate; ³ MAPE: maleic anhydride grafted polyethylene.

Table 4. Ranking of the technologies by the Pugh matrix method according to circular (*) and general metrics.

	Weight	T1	T2	T3	T4	T5	T6	T7	T8	T9	Total	Rank
Modulus	1	1	1	1	1	3	2	−1	2	1	11	2
Elongation	1	−1	−1	−1	−1	−3	−2	−1	−3	−1	−14	6
Impermeability	1	0	0	3	3	1	2	−1	1	3	12	1
Density	1	3	3	−3	−3	−2	−3	1	−3	−3	−10	5
Price	1	3	1	2	1	−3	−2	−2	−1	1	0	4
Durability	1	−1	−1	0	0	3	2	2	2	0	7	3
Recyclability	1	−1	−1	−1	−1	−3	−1	−2	−3	−1	−14	6
Total	-	4	2	1	0	−4	−2	−4	−5	0	-	-
Rank	-	1	2	3	4	7	6	7	9	4	-	-

According to the Table 4, it is possible to notice that the team did not give higher priority to any criteria and considered all nine material technologies viable minding their unique traits. Two criteria, namely durability, and recyclability, represent the target circularity expected from the new materials. Even though many other metrics could help to assess circularity qualities, those two embody the peculiarities of both case and materials. While durability measures how long the material could maintain its properties without degenerating, recyclability measures how suitable to recycling the material was. Consequently, more durable materials would contribute to making long-lasting products, and more recyclable materials would minimize the need for producing raw materials.

Next, the “Market” workshop aims to classify the potential markets for the technologies selected in the previous workshop according to another set of general and circular metrics. Firstly, the facilitators presented the initial markets that commercialized similar technologies towards a brainstorming activity on proposals of potential markets. At the end, the facilitators conduce another ranking dynamics and select some markets for the next workshop.

Adding to the initial markets selected in the preparation step, the specialists included other potential markets that could use the material technologies. This discussion resulted in 13 potential markets that were classified and ranked according to the pre-selected criteria. The smaller market size was considered a positive characteristic; therefore, the company could guarantee enough waste to incorporate into the new materials. Figure 3 shows a bubble chart ranking, where the bubble size represents the market size metric. Furthermore, participants distributed markets on the vertical axis according to the perceived appeal of sustainable solutions, and on the horizontal axis according to the perceived value of the solutions. Particularly in this step, sustainability replaced circularity. Sustainability

appeal represents the way the participants considered the markets would respond to more sustainable solutions. Therefore, the higher the sustainability appeal score, the more sensitive the market is to sustainable solutions and the more likely it is to apply circular materials. This logic considers that most of the circularity rests inside the sustainability field, while sustainability remains a broader concept.

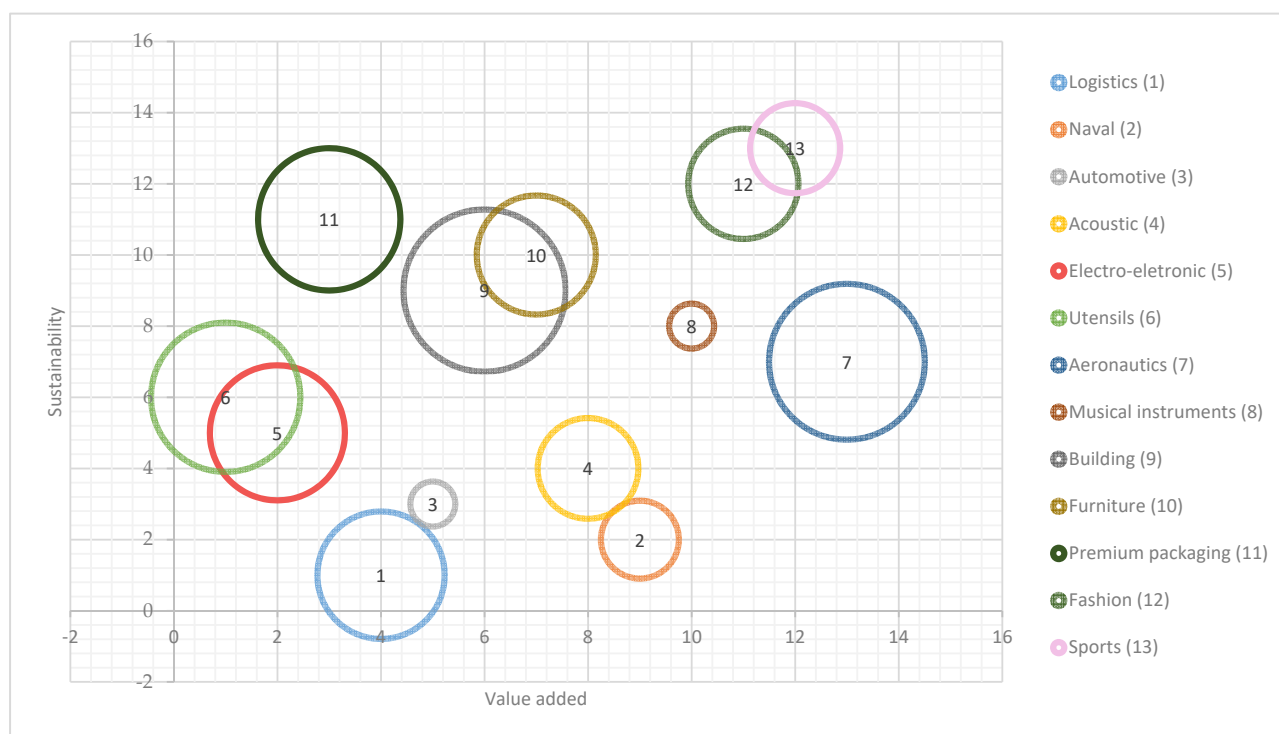


Figure 3. Bubble chart representing the market ranking: market size denoted by bubble size; value added on the *x* axis; sustainability appeal on the *y* axis. Each criterion shows scores obtained from the group activity.

Regarding metrics of sustainability appeal, value added, and market size, the bubble chart in Figure 3 shows the Sports (5) and Fashion (6) markets as the top-ranked alternatives. Although the Furniture (7) and Building (1) markets did not score as highly in the “value added” criterion in comparison to Aeronautics (11) and Musical Instruments (10), they were selected and combined into a single market segment called Civil, which scored relatively high in sustainability appeal. Additionally, the “value added” score increased in markets that included products with premium design, which also improves the metric “market size” as it decreases the number of products. Accordingly, the market segments selected for the subsequent workshop were: the Fashion, Sports, Civil, and Miscellaneous goods segments. The participants proposed this last segment for avoiding limiting creativity in the product workshop, and opening possibilities for small-sized products for personal use.

Furthermore, the “Product” workshop aims to identify product families within the selected markets and classify the options according to the third set of general and circular metrics. After brainstorming and evaluating the products in the selected markets, the facilitators guided the group in ranking them and choosing the best to assemble the final Circular TRM.

In the pilot application, the participants reviewed the four market segments selected in the second workshop, and proposed 29 product families. Lastly, these product families were classified and ranked based on two criteria: “servitisation” and “interest in starting a business”. When giving servitisation scores, participants expressed whether or not they believed a product family had the potential to integrate product–service systems, which, in a Circular Economy perspective, could mean fewer products and less waste at their end of life. Following a different procedure, the “degree of interest” measured the willingness to

invest in a particular product family, which allowed participants to assign limited positive and negative scores to the alternatives. Table 5 shows the final product families selection. Non-serviceable options with low scores in the “degree of interest” metric were excluded.

Table 5. Selected product families from the ranking by interest in starting a business, value added and servitisation.

Product Family	Degree of Interest		Servitisation
	Positive Scores	Negative Scores	
Street furniture	4	0	1
Bike accessories	4	0	−1
Toys	3	0	1
Bags (premium design)	3	0	1
Domestic utensils and premium design packaging	4	1	1
Glasses frames	3	1	−1
Roof racks for cars	2	1	1
Skateboards	2	1	1
Gardening and plant vases	2	1	−1
Wristwatches	2	1	−1
Wall cladding	1	1	1

3.3. Assembly

“Assembly” is the last step of the circular TRM method. It is conducted by the facilitators and consists of building the final circular TRM through the pondering of the results of the three workshops. A central goal of this step is the identification of alternatives that better represent the projects’ circular strategy symbolized by the metrics used for ranking the alternatives at each workshop. After that, it is possible to distinguish circular feedback loops and use this knowledge to formulate operational plans.

Figure 4 shows the circular TRM resultant from the pilot application and outcomes of each workshop. In addition to assisting strategies formulation, similarly to a classic TRM, the Circular TRM provides feedback loops that are designed when preparing the roadmap’s graphic output. Part of the materials’ circular classification comes from the Pugh matrix in Figure 3. For this reason, materials M5, M7, and M8, which have the lowest “recyclability” scores, received the “low circularity” tag. The classification of products as circular also considered the servitization criterion. Arrows 1 and 2 indicate product servitization potential, with products coming back from the market. Similarly, arrows 3, 4, and 5 indicate the recyclability potential of the alternatives, represented by products turning back into material inputs and vice versa.

All three circular metrics also impacted the timeline of the strategies. Recyclability was reflected in short-term strategies that privileged less complex (more recyclable) materials. Regarding medium-term ones, materials become more complex (less recyclable), but products become more serviceable, showing a shift from recycling to servitization strategies. In the long-term, we find that the technologies with the lowest potential for circularity compensate for this aspect by being used in high-value products produced in a small volume. Moreover, products from long-term strategies were the ones with the slightest degree of interest in starting a business, and depend on further material development and changes in the current market to become technically and economically viable.

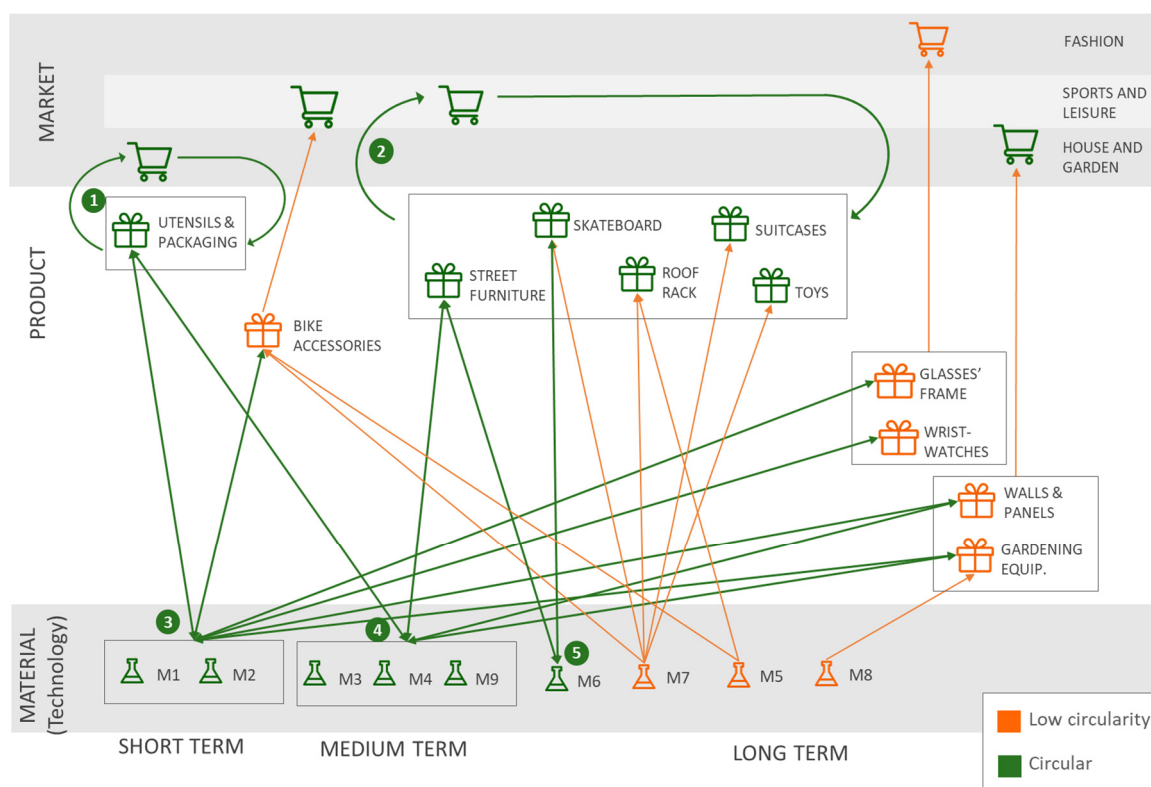


Figure 4. Circular TRM from the fiber-polymer material development.

4. Discussion

The Preparation step was indispensable in establishing a research base through developing and characterizing the initial material technologies and customizing the TRM. Such customization involves bold propositions such as circular metrics and order the workshops, i.e., first technology, second market, and third product. Although several other metrics could have been considered, the intention was to initiate a journey, rather than exhaust the possibilities. A restricted array of circular targets chosen collectively was more beneficial for putting the strategy in motion; moreover, the initial group of metrics must not restrict a future addition of other circular indicators and goals. The workshop order obeyed a crescent number of details building from the initial technologies.

In the technology workshop, the participants suggested new material compositions with distinct mechanical properties, recyclability, and durability, which would connect with existing waste supply chains. The specialists suggested the addition of ABS for enhancing impact resistance. ABS is a low-cost material easily found as industrial waste, which reinforces its circular characteristic and favours business symbiosis. Polyamide (PA), also available as industrial waste, was another recommendation that attends the same circular demand. Despite its high cost, carbon fiber, widely used in the aeronautical industry due to its excellent strength-to-weight ratio, is a desirable component in high-performance applications. While polylactic acid (PLA) remains relatively expensive, it could also have unpredicted consequences as it is considered biodegradable with a degradation time of approximately one year. After analyzing all nine technologies and based on the seven metrics addressed, the participants considered M1 the most balanced technology. This technology results in a material that is the least complex, the cheapest, and the most recyclable.

The sustainability appeal in the market workshop represented the perception of consumer willingness to acquire circular solutions. In this choice, we see circularity also contributing to achieving sustainability goals even if there are disputes on how the

constructs interact. Besides seeking a receptive market for sustainable/circular solutions, the target was to prioritize smaller markets with high-value products. Even though it could appear to be a green and premium strategy, the idea was to test the materials in niche markets and not compete directly with commodity materials.

Assessing the interest in investing in a particular product family helped simulate the business interest in using new materials as inputs. Additionally, servitization offered an alternative to the constant flow of materials for the manufacture new products, and motivated participants, highlighting the possible establishment of product–service systems even with restricted sources of materials.

Lastly, all specialists approved the first trial application of the circular TRM method and were interested in replicating it in their companies. When all layers of the method came together, the recycling and servitization possibilities surfaced, indicating how to operationalize the feedback loops for recovering functioning products or materials.

5. Conclusions

After the successful development of new waste-based polymer composite materials, the application of the Circular TRM suggested the integration of TRM and the CE. Circular TRM enabled the tracing of circular paths for the new materials, promote collaboration between participants from different areas who felt motivated, and demonstrated interest in replicating the method. First, the circular paths gathered the options with the best scores according to circular metrics, and required the development of alternatives for maintaining the materials inside the cycle; in other words, ensuring the flow of material from the market/user back to the users or to the recycling paths. Such workshop-based procedure is significantly responsible for the collaborative character of the Circular TRM and development of sustainable strategies out of the scope of sustainability teams and at the core of the multisectoral strategy. The appropriations of the CE strategies by different professionals are fundamental for achieving systemic change.

This study attempts to contribute to both theories involved in the method proposal, the CE and TRM. The method successfully stimulated critical thinking towards materials circularity and environmental impacts in the technology planning phase. The Circular TRM introduced new elements into the standard workshop-based TRM, which proved helpful in narrowing the options and supporting decision making. Even though this proposal originates from the specific case of waste-based material technology, it could serve as an example of the use of TRM for the Circular Economy and stimulate their association in different contexts. When adopting the Circular Economy perspective, it becomes mandatory to plan the flows of circular materials. Responding to this need, the Circular TRM effectively integrated management and operational personnel while guiding circular strategy design.

The application used for testing the proposed Circular TRM has empirical contributions to itself as it shows the case of a company concerned with the waste of materials that still have value and provide new business opportunities. In addition, this case described the pioneer Circular TRM with sufficient details to inspire other business and research initiatives. Society may enjoy additional benefits from this work as it represents the development of sustainable technologies by a university–business partnership. The Brazilian case addressed highlights the importance of building “networks” or “ecosystems” that foster circular solutions.

The pilot case study showed the Circular TRM relies on the support of some hypothesis for market and product decisions. Such a gap could be filled by improvement cycles that would collect operations data and confirming or refuting hypotheses. Future work aims at investigating how TRM can support a circular ecosystems strategies. Another possibility can be the use data mining and technology forecasting methods in a market and product workshops. Moreover, quantitative tools that measure material’s properties, costs, and environmental impacts can deepen understanding of the Circular TRM process.

Notwithstanding the Circular TRM application to create strategies, companies are not exempt from thorough operational circularity initiatives.

Author Contributions: Conceptualization, M.B.; data curation, P.S.; formal analysis, R.C. and J.M.; investigation, R.C. and P.S.; methodology, R.C., P.S. and M.B.; project administration, M.B. and J.M.; resources, M.B.; supervision, M.B. and J.M.; validation, M.B.; writing—original draft, R.C. and P.S.; writing—review and editing, R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, grant number 88882.379087/2019-01.

Institutional Review Board Statement: Ethical review and approval were waived for this study, due to the fact that this falls into the category of research which aims at the theoretical deepening of situations that arise spontaneously and contingently in professional practice and do not reveal data that can identify or expose participants.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data available on request due to privacy and corporation restrictions.

Acknowledgments: The authors acknowledge Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Brazil—finance code 001—for the financial support, A. Francisco (São Carlos Carpet Company), C. A. Beatrice (UFSCar), H. Finocchio (Afinko), S. Machado Filho (Tecnomotor), S. Aleixo (USP), C. N. Zabotto (USP), K. Egg (USP), G. Medeiros (USP), G. Nascimento (USP), M. Rosa (USP), and V. Uemura (USP), for participating in the workshops.

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

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