Perspective

Materializing Our Future Society: Introducing the Feedstock-Material-Product Framework for a Circular Bioeconomy

Marita Sauerwein[1,2] and Peter R. Mooij[1,2,*]

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Abstract

The circular bioeconomy, merging circular economy principles with biobased resources, represents a critical pathway towards a sustainable future. However, effectively designing and developing truly valuable biobased products within this system requires a holistic approach. We introduce the Feedstock-Material-Product (FMP) framework to address this need. This framework emphasizes the crucial interdependencies between feedstock sourcing, material properties, and product design. We argue that a holistic framework on these three levels is essential for maximizing value retention and sustainability throughout the entire lifecycle. By adopting the FMP framework, a pathway is offered to accelerate the transition towards a circular bioeconomy in which our sustainable future can be effectively materialized.

Keywords: Circular Economy · Biobased Economy · Circular Bioeconomy · Biobased Feedstock · Biobased Materials · Product Design

The circular economy and biobased economy are both systemic pathways to move towards a sustainable future. There are strong thematic links between circular and bioeconomy policies and therefore it is suggested to better integrate these systems (European Environment Agency, 2018). Furthermore, such a 'circular bioeconomy' is in line with recent legislation (e.g. the European Green deal (European Commission, 2020)) and ESPR requirements (European Parliament & Council of the European Union, 2024).
A circular bioeconomy is especially interesting as it can account for shortcomings in both economic systems:

- The circular economy aims to eliminate waste. However, in reality waste is unavoidable, due to for example wear and quality loss (Corvellec et al., 2022; Korhonen et al., 2018). Therefore, shifting from non-renewable resources to biobased feedstocks is a valuable innovation in the circular economy (European Environment Agency, 2018), which provides opportunities for biodegradable end-of-life options.
- The materials used in a biobased economy store atmospheric carbon during photosynthesis. However, these materials are not inherently sustainable, as production of biobased feedstocks, materials and products consumes additional energy, and has an impact on e.g. land-, fertilizer-, and pesticide-use (Corrado & Sala, 2018; Weiss et al., 2012). Therefore, maximal value retention, which is a key principle of the circular economy, also benefits the biobased economy.

With this in mind, it would be logical to apply circular economy principles to biobased materials and products to extend their lifetime. However, the butterfly diagram (MacArthur, 2013) makes a visual separation between the bio- and techno cycle by representing them in opposite wings. Recently, several scholars have called for a better

[1] AMS institute, Kattenburgerstraat 5, 1018 JA Amsterdam The Netherlands
[2] Delft University of Technology, Mekelweg 5, 2628 CD Delft, The Netherlandds
[*] Corresponding author: peter.mooij@ams-institute.org

integration of those wings to include biobased materials and products in the technical cycle (Bakker & Balkenende, 2021; Keith R. Skene & Andreea Oarga-Mulec, 2024; Vural Gursel et al., 2022).

Hence, it requires a holistic approach to effectively design and develop valuable biobased products within a circular bioeconomy. To address this need, we introduce the Feedstock-Material-Product (FMP) framework. This framework supports theoretical thinking and practical execution by emphasizing the crucial interdependencies between feedstock sourcing, material properties, and product design (figure 1). In this context feedstock is defined as resources that serve as input for the material (e.g. crop-residues, algae, and organic waste streams), materials as processed resources that are suitable for manufacturing (e.g. cross laminated timber, bioplastics, biocomposites), and products as manufactured artefacts that fulfil a function (e.g. façade panels, consumer products).

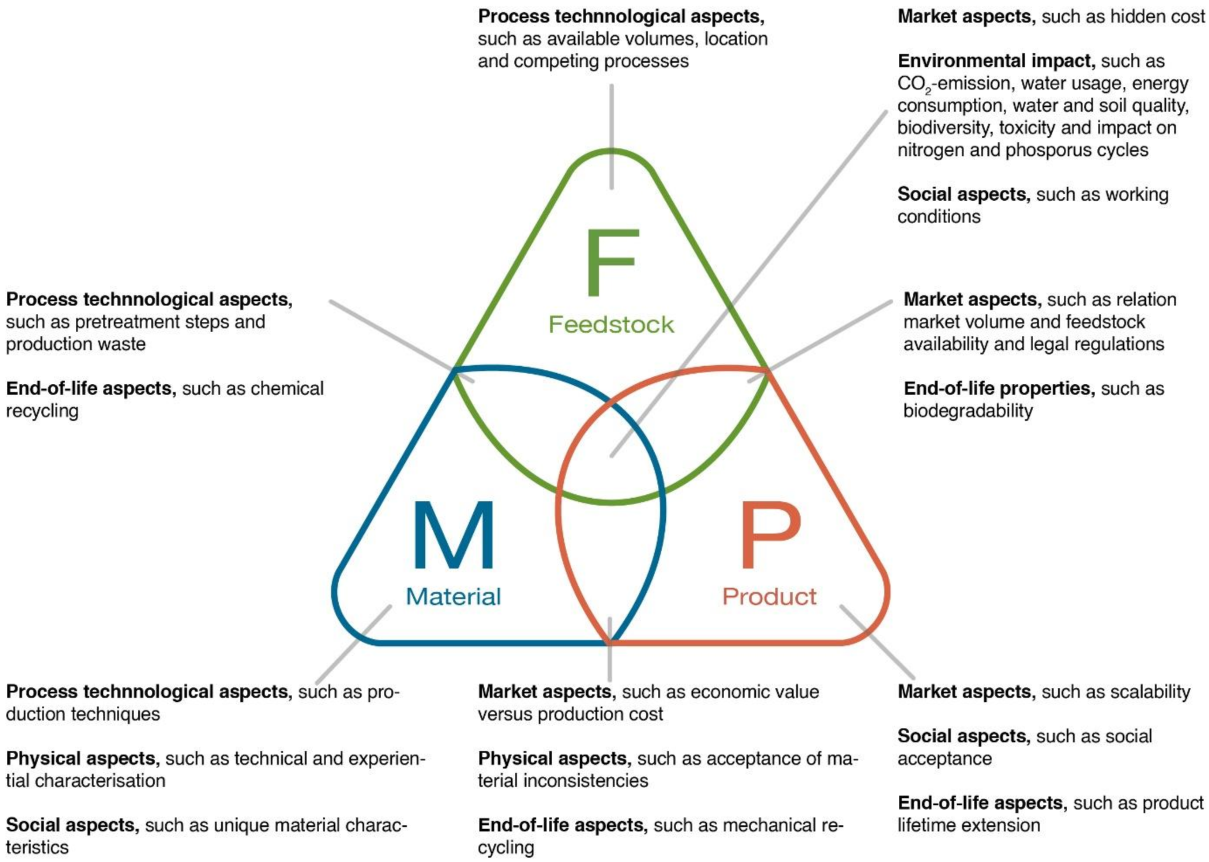

Figure 1. Feedstock-Material-Product Framework With Examples of Aspects Related to (Interfaces Of) the Feedstock, Material and Product Level

The feedstock, material and product level are interdependent, because multiple essential criteria that decide whether a product has true value in a circular bioeconomy relate to the interfaces of these levels. An example concerns the end-of-life possibilities. In a linear design process the product is the end goal, whereas in a circular bioeconomy the final product solution includes the start of a new cycle with the highest value retention possible. Consequently, the end-of-life scenarios relates to multiple levels:

- Product life extension strategies (including repair, reuse, remanufacturing, etc.) operate on the product and material level as both material- and product-properties influence the possibilities for product life extension. For example, only properly designed products, that can be taken apart, made from durable materials, that do not easily break or wear down, can be repaired;
- Recycling couples the product level to the material- and feedstock-level by recycling. For example, materials can only be recycled when they can be separated and harvested from a product;

- Biodegradation links the product level to the feedstock level as products degrade to biobased monomers from which new feedstock can be generated.

However, the value and sustainability of a biobased product depends on more than its end-of-life scenarios. To be viable alternatives to fossil-based products, biobased products should outcompete fossil alternatives on process technological, environmental, market, physical, and social aspects. A selection of these aspects is presented in Figure 1. Many of these aspects relates to the interfaces between the feedstock, material and product level. Focussing on the interdependency of these levels throughout the entire design process, rather than a subsequent focus by different experts, will optimize product solutions retaining value in a circular bioeconomy. Consequently, applying the Feedstock-Material-Product framework will maximize value retention and sustainability throughout the entire lifecycle with environmental, social and economic impact.

To reach this aim and assess the practical value of the FMP-framework, we currently develop a guiding canvas. This canvas should act as a tracking tool throughout a research and design process by addressing questions, such as ‘What is the overall CO_2-emission’ and ‘Are there hidden costs in the current economic system?’. Initially, the canvas can be used as a quick scan to identify strength and weaknesses. During the development process, it can steer research and design efforts to improve the current combination, or opt for a different feedstock, material and/or product. Furthermore, the canvas will refer to more in-depth support tools, such as life cycle assessment (Guinée et al., 2012), Safe by Design (Van de Poel & Robaey, 2017), and circular design tools (Rexfelt & Selvefors, 2024). Throughout the entire design process, the canvas will act as communication tool to facilitate the discussion between feedstock suppliers, material experts and product designers. This will strengthen systems thinking and break down silos in decision-making at different parts of the value chain

To conclude, our future society should integrate key aspects from the circular and biobased economy to maximize value retention of biobased feedstocks, materials and products. To do so, we suggest placing the interdependency of feedstock, material and product central in the design process, as essential aspects determining the value and sustainability of biobased products relates to multiple levels. By adopting the FMP framework, facilitated by tools like the guiding canvas, the collaboration and systems thinking needed for the development of truly sustainable, high-value biobased solutions can be fostered. A pathway is offered by this framework to accelerate the transition towards a circular bioeconomy in which our sustainable future can be effectively materialized.

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AUTHOR CONTRIBUTIONS

Marita Sauerwein: Conceptualization, methodology, writing- original draft, writing- review & editing, visualization
Peter R. Mooij: Conceptualization, methodology, writing- original draft, writing- review & editing, visualization

DECLARATIONS

Competing interests The authors declare no competing interests.

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