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Mechanical Recycling of Bulk Molding Compound: A Technical and Environmental Assessment

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Mechanical Recycling of Bulk Molding Compound: A Technical and Environmental Assessment

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Abstract: This study evaluates the technical and environmental feasibility of mechanically recycling post-industrial bulk molding compound (BMC) waste from the manufacturing of low-voltage circuit breakers. Testing reveals that incorporating up to 10% recycled BMC as filler substitute maintains the required mechanical and electrical properties. A life cycle assessment shows that while replacing virgin fillers with recycled BMC has limited effects on the carbon footprint of the material, the overall product system benefits significantly by avoiding waste incineration. Moreover, optimized scenarios like maximizing recycled content and reducing transportations substantially reduce the environmental impacts. This study underscores the potential of circular production models to enhance sustainability in the thermoset composite industry.

Keywords: Bulk Molding Compound, Thermoset Composites, Mechanical Recycling, Life Cycle Assessment (LCA), Environmental Impact, Circular Economy

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Introduction

Bulk molding compound (BMC) and sheet molding compound (SMC) are widely produced materials in the thermoset glass fiber reinforced plastic (GFRP) industry. Their production reaches a volume of 268,000 tons per year (2022), reaching a market share of 23.5% within the composite thermoset industry [1]. Both materials are based on an unsaturated polyester (UP) matrix reinforced with varying contents of glass fibers and mineral fillers, like aluminum hydroxide (ATH) or calcium carbonate [2]. BMC is broadly exploited for a variety of applications, ranging from the automotive to the electrical industry [3], but its complex composition poses important challenges for waste management [4]. Specifically, thermal reprocessing is impossible due to the cross-linked nature of the polymeric matrix, and the considerable inorganic content (roughly 70%) reduces its GCV to about 10 MJ/kg [5,6], hindering its use in incineration plants.

In recent years, there has been growing interest in developing sustainable waste management practices for thermoset GFRP. Mechanical recycling, which involves reprocessing post-industrial BMC waste into reusable material, is one such practice [7]. This study evaluates the technical feasibility and environmental sustainability of mechanically recycling pre-consumer BMC waste used in the production of low-voltage circuit breakers.

By comparing the traditional linear production model with circular systems that incorporate mechanically recycled BMC, we aim to understand the potential environmental benefits of this practice. This comprehensive approach allows us to assess the benefits and challenges of transitioning from a linear to a circular production model, contributing to a more sustainable future for the industry.

Materials and Methods

Materials

The composition of the BMC used in this study, as provided by ABB through their suppliers, is reported in Table 1. Such formulation is optimized for use in structural components of low-voltage circuit breakers. The specific chemical composition of the resin, initiator, and other additives is not explicitly disclosed in this paper.

Additionally, the pre-consumer BMC waste sent to recycling is assumed to be sourced from the same supplier, therefore having approximately the same composition.

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Table 1. Composition of Bulk Molding Compound.

Material	Weight %
Aluminum hydroxide (ATH)	52%
Chopped glass fibers (GF)	20%
Unsaturated Polyester Resin (UPR)	18%
Styrene monomer	4%
Polyethylene (PE)	3%
Initiator and additives	3%

Mechanical Recycling and Testing

The mechanical recycling process adopted in this study involves the milling of post-industrial waste (i.e., manufacturing scraps). Such waste is generated during the molding of BMC parts and is typically sent to incineration. In our process, this scrap is collected and milled into a fine material. This milled material is then reused in the formulation of new BMC, substituting the alumina trihydrate (ATH) used as a filler and flame retardant in BMC production, resulting in parts containing up to 10% wt. of recycled material. Specifically, three types of samples were produced, with recycled contents of 0% (i.e., virgin), 5%, and 10%.

To assess the quality of the mechanically recycled BMC, some standardized tests were conducted on the samples. Tensile tests were performed using a INSTRON 5584 universal testing machine, to measure the tensile strength of the parts. Tests were directly conducted on the molded components to allow immediate comparison with the maximum load requirements set by ABB for the final application in circuit breakers. Up to 20 measurements per sample were taken to determine a statistical error. Additionally, Comparative Tracking Index (CTI) tests were conducted to evaluate electrical insulation properties following the IEC 1102 standard, and vertical burning tests (UL-94 standard) were executed to assess flame retardancy class.

The results of these tests provided valuable insights into the performance of the recycled BMC and its suitability for application in low-voltage circuit breakers.

Life Cycle Assessment: Goal and Scope

The LCA was conducted following ISO 14040 standards, which provide a robust framework for conducting a comprehensive environmental impact assessment.

The product system considered encompasses three distinct phases: (1) BMC production, (2) BMC parts molding, and (3) end-of-fife (EoL) treatment of production scrap.

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This LCA is cradle-to-gate, with system boundaries including raw material extraction, transportation, BMC production, manufacturing (molding), and end-of-life treatments (of manufacturing waste only). The use phase and product end-of-life are excluded from the system boundary. The declared unit is one kilogram of molded BMC parts.

In order to maintain a physically consistent mass balance among the defined scenarios, the following parameters were introduced:

- **P**: Reference flow of each system, always equal to 1 kg of molded parts, representing the output of phase 2 (molding).
- **W:** Amount of waste generated by the molding process.
- **F**: Amount of BMC fed to the molding process. Therefore, F represents the output to phase 1 (BMC production) and it is equal to P+W.
- **Y**: Ratio of W to F, representing the percentage of waste relative to the total BMC fed to the molding process. Since the values of both P and W are provided by the molder on an annual basis, the value of y is known and constant for all scenarios (y=0.1435).
- **R1**: Fraction of W which is fed to the recycling (milling) process
- **I1**: Fraction of W which is sent to incineration.
- **R2**: Amount of recycled material produced by the milling process, net of any losses.
- **I2**: Amount of waste generated by the milling process, sent to incineration.
- **L**: Ratio of I2 to R1, representing the percentage of material lost during milling.
- **x**: Recycled content in BMC, ranging from 0 to 12.5% (maximum recycled content achievable if all post-industrial waste from molding is recycled without loss).
- **V:** Amount of virgin material used in BMC production, the main input to phase 1 (BMC production), along with R2.

Consequently, three scenarios were defined for the LCA, namely:

- **Linear (L)**: Linear production system, where BMC is produced entirely from virgin resources and any waste generated during the molding phase is incinerated. Moreover, the current transportation distances are respected. Therefore, x=0 and D=1.
- **Circular (C)**: Currently implemented closed loop recycling chain, taking into account the technical constraints (maximum recycling content = 5%, material losses in recycling = 10%) and the actual transportation distances. In this case, the manufacturing waste is partially recycled and partially incinerated. Therefore, the variables for this scenario are x=0.05, L=0.1, and D=1.

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- **Optimized (O)**: Realistically achievable improvement with respect to scenario C. All the BMC waste is looped back into the production chain, achieving a recycled content of 12.5% (x=0.125), losses are minimized (L=0), and transportation distances are reduced by 75% (D=0.25).

A graphical visualization of scenarios L and O is reported in Figure 1. Scenario C is omitted from the figure for the sake of conciseness, as it can be seen as an intermediate situation between the two other cases.

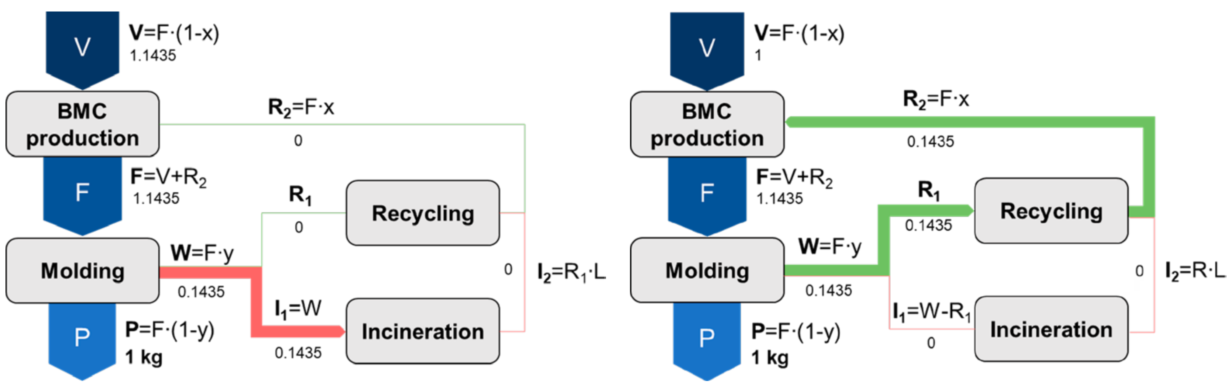

Figure 1. Flow diagram for two of the possible scenarios (L and O). The thickness of the arrows is proportional to the mass flow. Note that these two schemes represent two extremes: a number of intermediate situations are possible.

Life Cycle Assessment: Inventory

Primary data for this LCA study were sourced from two primary contributors. Data pertaining to BMC production (phase 1) and recycling (phase 3) were provided, through ABB, by the BMC supplier, located in northern Germany, while data concerning the molding (phase 2) and scrap incineration were provided by the molder, located in central Italy. Secondary data were either derived from literature or from the ecoinvent 3.9.1 database [8].

For phase 1 and 2, data concerning raw materials, utilities and energy consumption, transport distances and modes, direct emissions, packaging materials, and waste management were provided. Moreover, the specific energy-mix compositions were used in the modeling.

For phase 3, primary data were available only for the use of electrical energy and other utilities in the milling process, along with the efficiency of the process in terms of material losses. The incineration process was modeled using the ecoinvent dataset for the incineration of plastic from electrical waste, adapted to the composition of BMC in terms of carbon and inorganic content.

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Specific quantitative information on the full LCA inventory is not disclosed in this paper but may be available upon request to the authors.

Results and Discussion

In the following sections, the results of the mechanical testing and the LCA study are presented and discussed.

Mechanical Recycling and Testing

As shown in Figure 2, substituting alumina trihydrate (ATH) with recycled BMC has a noticeable detrimental effect on the load at break of parts, even at low recycled contents. Specifically, the sample with 5% recycled content showed a 7% reduction in load at break compared to the virgin sample. The mechanical performance further declined for the sample with 10% recycled BMC, with a total reduction of 13% compared to the virgin sample. Nonetheless, all samples met the minimum requirement set by ABB for low-voltage circuit breakers (2400 N), even when considering the standard deviation.

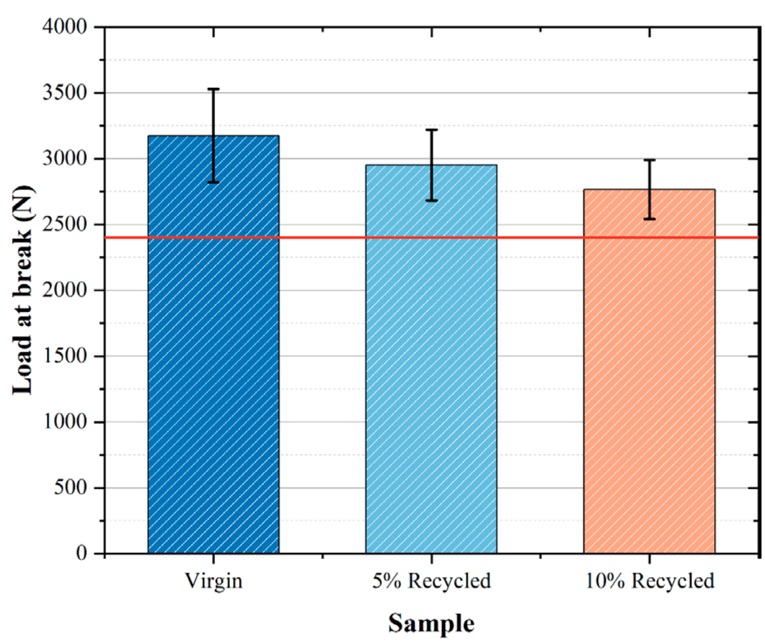

Figure 2. Load at break measurements for molded parts with a variable content of recycled material. The red line represents the minimum requirement set by ABB.

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Table 2. Results of tensile, vertical burning, and CTI tests for the three samples.

Recycled Content	Load at break	UL94 rating	CTI
	[N]	[-]	[V]
0%	3174.3	V-0	600
5%	2951.7	V-0	600
10%	2765.7	V-0	600

Other measured properties confirmed the suitability of all samples for use in circuit breakers. Specifically, as reported in Table 2, the CTI requirement of 600V and the UL94 V-0 classification were achieved, even for the sample with 10% recycled content.

Life Cycle Impact Assessment (LCIA)

All scenarios were analyzed using the Environmental Footprint 3.1 impact assessment method, encompassing all midpoint impact categories, with a primary focus on the climate change indicator. A cut-off approach (100:0) was adopted, choosing the "Allocation, cut-off by classification" system model in the LCA software SimaPro.

Focusing on phase 1 (BMC production), as shown in Figure 3, the main contributors to the climate change indicator are the polyester resin and glass fibers. In contrast, ATH accounts for only 18% of the total impact, despite constituting more than 50% by weight of the final material. This suggests that replacing ATH with another filler, such as milled BMC, might have a limited effect on the climate change impact category. This is further confirmed by Figure 4, which shows that the impacts of the two fillers (milled BMC and ATH) are quite similar.

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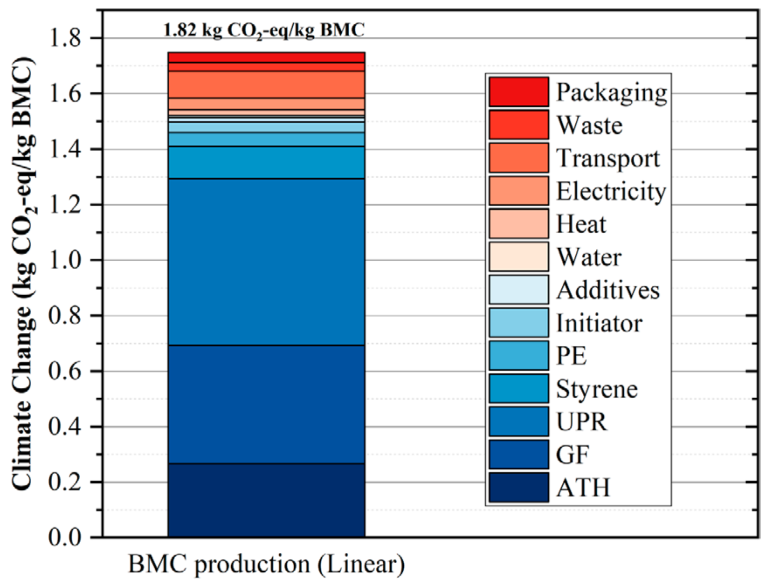

Figure 3. LCIA result and process contributions for BMC production (phase 1) in the Linear scenario; Climate Change.

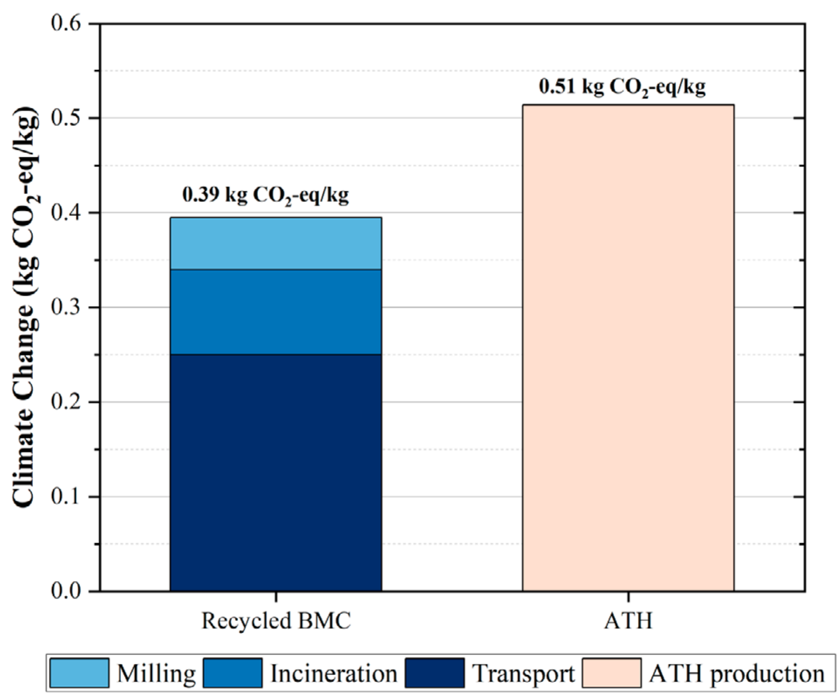

Figure 4. Impact comparison between the two possible fillers: milled BMC and virgin ATH (Aluminum Trihydrate), Climate Change.

When the entire product system is considered by including the molding phase and the end-of-life treatment of BMC scraps, the impact for the linear scenario increases to 2.96 kg of CO_2-eq/kg, with the main contributors being the production of virgin BMC, the electricity used for molding, and the transportation of BMC from Germany to Italy (Figure 5).

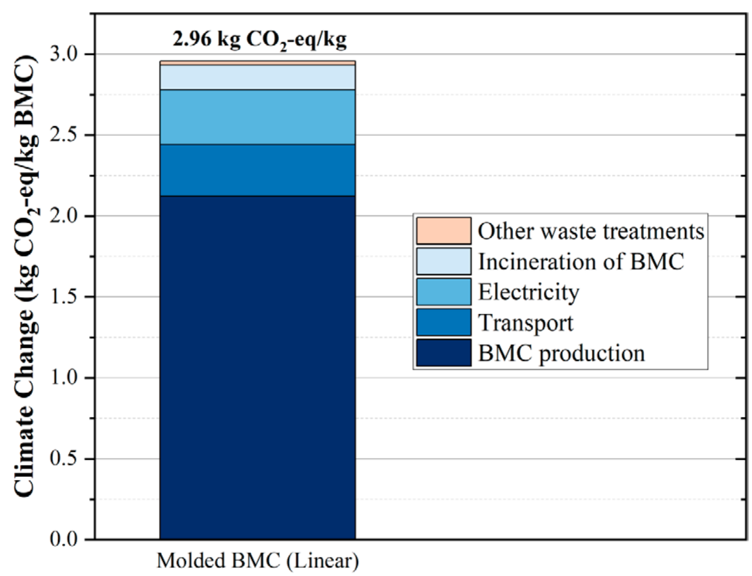

Figure 5. LCIA result and process contributions for 1 kg of BMC molded parts in the Linear scenario; Climate Change.

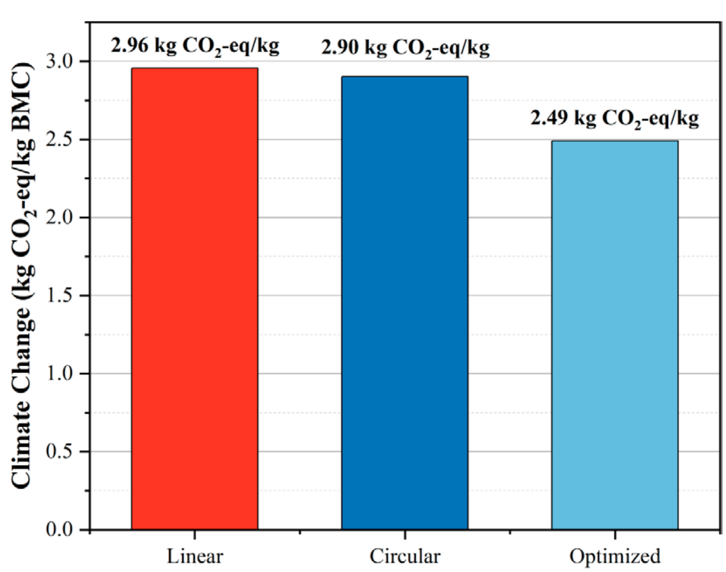

Figure 6. Impact comparison between the three scenarios: Linear, Circular, and Optimized for 1 kg of BMC molded parts; Climate Change.

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Comparing the linear system with the circular and the optimized scenario (Figure 6), the impact reduction in the circular scenario is almost negligible (-1.8%). On the other hand, in the case of an optimized system, where the recycled content is maximized and transportation distances are minimized, a much better result is obtained, with an impact reduction of 15.8%. The main reasons for such an improvement are the avoided incineration of BMC waste and the reduction of the transportation distances.

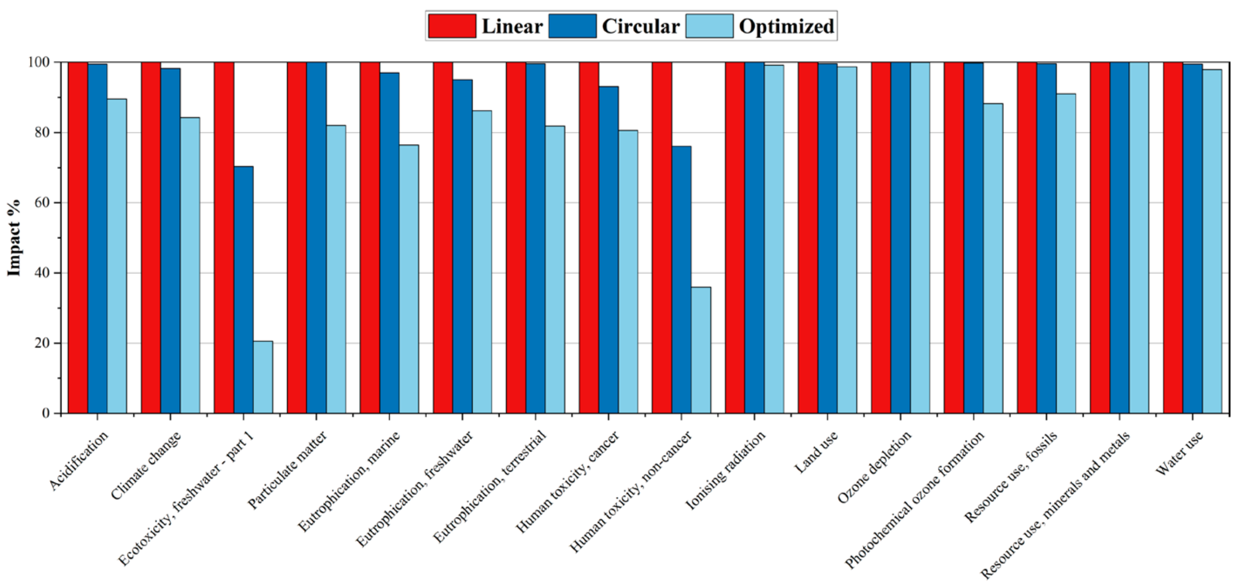

Figure 7. LCIA results comparison between the three scenarios: Linear, Circular, and Optimized for 1 kg of BMC molded parts. Method: Environmental Footprint 3.1.

Considering the full LCIA results (Figure 7), all the impact categories are improved or, at worst, unchanged by introducing the circular and optimized scenario. The avoided incineration of waste plays a major role in reducing the impacts, particularly for the two impact categories that are most affected by such process: ecotoxicity and human toxicity.

Finally, considering the optional LCA phases of normalization and weighting, the single score indicator provides a valuable indication of the overall environmental performance of the scenarios. Specifically, the linear scenario obtains a single score of 370 μPt/kg, while the circular and optimized scenarios achieve reductions of 4.3% (354 μPt/kg) and 17.5% (305 μPt/kg), respectively.

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Conclusion

This study evaluates the technical and environmental sustainability of mechanically recycling BMC used in low-voltage circuit breakers. The incorporation of recycled post-industrial waste as a filler replacement up to 10% by weight in BMC, maintains acceptable mechanical, electrical, and thermal properties, meeting the industry standards. The life cycle impact assessment reveals that replacing ATH with recycled BMC has a limited effect on the climate change impacts of the material production stage. However, considering the entire product system, a beneficial effect is obtained thanks to the avoided incineration of the waste. Moreover, an optimized system that maximizes recycled content and minimizes transportation distances can achieve a significant reduction in environmental impacts, particularly in the climate change, ecotoxicity, and human toxicity categories. The results underscore the potential benefits of transitioning from a linear to a circular production model, highlighting the importance of recycling and optimized logistics in reducing the environmental footprint of BMC production.

Acknowledgments

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