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ORIGINAL ARTICLE

Parametric LCA for optimizing rotational moulding of composite products to support eco-design

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Abstract

Rotational moulding (RM) is a versatile technique for producing plastic products, but its environmental sustainability needs deeper analysis. Existing life cycle assessment (LCA) studies are often limited, focusing on single materials and ignoring variations in process parameters. This study introduces a parametric LCA model designed to minimize the environmental impact of RM composite products by optimizing material composition, specifically blends of polyethylene and natural fibre (e.g., abaca). The model allows users to set control parameters, including product dimensions, mould material and thickness, energy consumption, from gas furnace and motor, number of moulds, geographical location, and the impact category to assess. Applied to case studies with abaca fibre composites, the model demonstrated that optimizing the fibre-to-polymer ratio can significantly reduce environmental impacts. These reductions vary depending on the input parameters, confirming that a one-size-fits-all approach is inadequate. The model's ability to process multiple heterogeneous factors makes it a robust tool for eco-assessment. It supports systematic sensitivity analysis and offers practical, flexible guidance for eco-design in RM, particularly for multi-material products. Its strengths, flexibility, low cost, and ease of integration make it especially valuable for small and medium-sized enterprises with diverse product lines, enabling more sustainable decision-making without requiring extensive resources.

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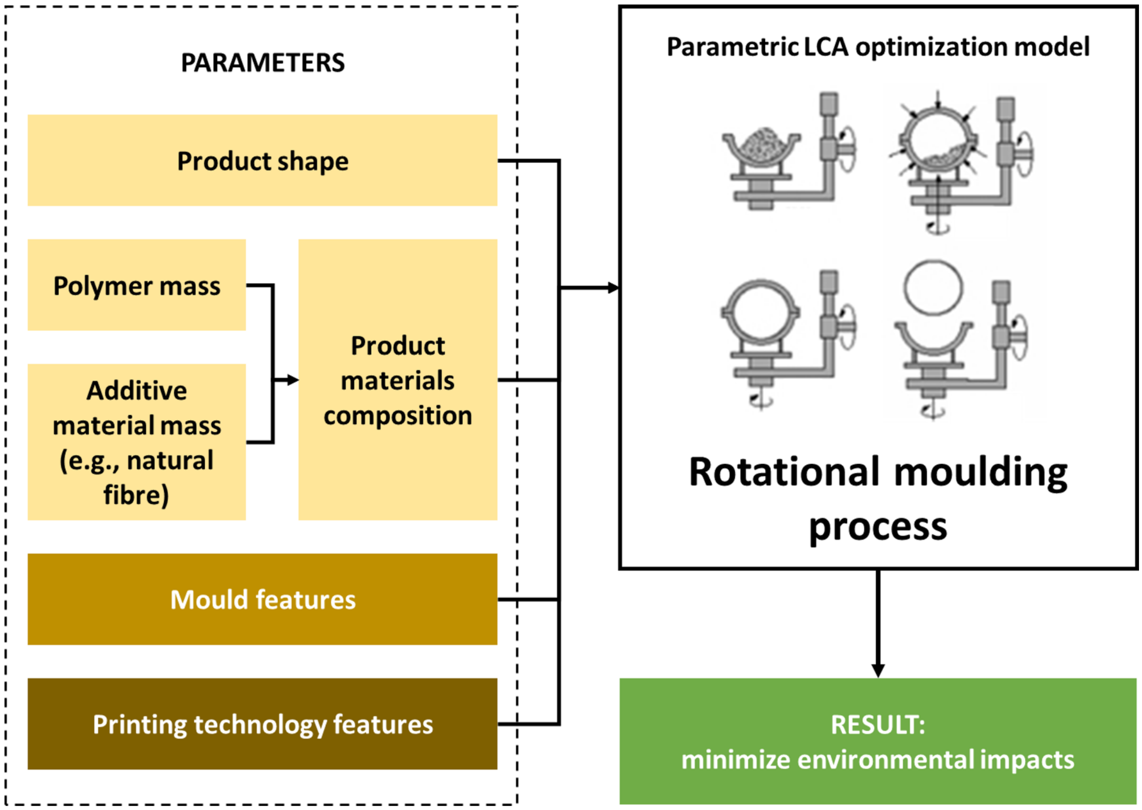
Graphical abstract



Keywords Parametric LCA · Rotational moulding · Natural fibre · Eco-design · Abaca · Bio composite

1 Introduction

Rotational moulding (RM) is an extremely versatile process as it allows the creation of products, typically plastic and hollow, of very different sizes and shapes, such as garden lamps, tanks, chairs and tables, portable toilets, or road dividers for construction sites. Furthermore, the RM process allows the simultaneous production of multiple products within the same batch, provided that appropriate operating parameters are identified. This enables high machine utilization and supports on-demand production across a varied product catalogue [21].

To increase the environmental sustainability of RM, some experimental solutions have been proposed in recent years. Defects and therefore waste have been reduced through greater process control with the introduction of dedicated sensors and predictive models based on mathematical models and machine learning [30, 39].

Production planning models have been developed to enable more strategic machine utilization so as to assimilate production efficiency, reducing energy consumption (Baxendale et al. 2021). More sustainable materials, e.g., recycled polyethylene, natural fibres, and biopolymers like PLA, have been used in RM products with the attempt to improve the mechanical properties and reduce the impact of synthetic polymer production [4, 6, 33, 35, 41]. In parallel with natural-fibre and recycled-content solutions, recent research on polyethylene-based composites has also focused on micro- and nano-scale reinforcements to tailor mechanical performance and functional properties. For instance, Chaurasia et al. [5] combined experimental testing and computational analysis to evaluate how h-BN nanosheets affect the mechanical behaviour of polyethylene nanocomposites, highlighting the potential of advanced fillers to modify stiffness and strength. Although such nano-reinforced PE systems are not the focus of the present case studies, these contributions further confirm the breadth of current polyethylene-composite research and support the relevance of systematic assessment tools capable of linking material choices to performance and sustainability indicators. Process energy consumption and cycle times were reduced by introducing new technologies like robotic mould heating and microwave-assisted heating [25, 27]. These proposals result in lower energy consumption associated with shorter cycle times. In this sense, some other authors have proposed using mould pressurization with this same objective, while also improving shrinkage [26, 31].

In the context of energy consumption, it is crucial to analyse how processing parameters such as rotational speed and material selection affect the overall energy usage in RM. Studies have demonstrated that the processing conditions greatly influence the mechanical properties and energy efficiency of RM products. For example, Greco et al. [16] highlighted that low oven temperatures with long processing times enhance the sintering of linear low-density polyethylene and can lead to better energy utilization due to reduced thermal gradients across moulded products. Similarly, the rotational speed of the mould significantly influences the quality of the moulded product, particularly concerning wall thickness uniformity, energy consumption, and overall process efficiency. This relationship is critical as it affects not only the final properties of the moulded items but also the environmental impact during manufacturing. The study by Adams et al. [1] has demonstrated that an increase in rotational speed can enhance the flowability of molten materials, allowing for more uniform wall thickness and better distribution of the material within the mould. In a different study, Jachowicz and Sikora [19] highlighted that an increase in mould rotational speed directly affects the cast wall thickness. Finally, the study conducted by Głogowska et al. [13] presents a crucial analysis of electricity consumption in RM, specifically focusing on how varying rotational speeds affect energy usage. Their findings indicate that the relationship between rotational speed and energy consumption is significant, implying that optimization of this parameter can lead to reduced electricity costs during the moulding process. In summary, increasing rotational speed enhances material distribution throughout the mould, improving uniformity and mechanical properties. However, this benefit is counteracted by higher energy consumption. Therefore, a balanced approach in speed adjustments to optimize both product quality and energy efficiency in moulding processes is needed, and each part design should be analysed to determine optimal rotating conditions, making it complicated to provide a general indication on processing parameters.

To continue proposing solutions to improve RM sustainability as well as to develop those already proposed by implementing them on a large scale, material-based research and process modifications would benefit from life cycle assessment (LCA). This would enable a clearer consideration of the potential for progress towards sustainability and the current limitations [22]. However, LCA studies that can be collected from the literature (see Sect. 2) are few and very specific regarding the materials and process parameters that are explored. More in detail:

- Only two LCA studies have been published in international peer-review journals. The others are a poster, a Master of Science thesis and two Environmental Product Declarations (EPD) drawn up by industries.
- The items produced were always tubular tanks or similar items that have different dimensions.
- The materials explored are almost always virgin polyethylene PE, and only in two cases a part of recycled PE and a small quantity of additives.
- The effects related to the variability of the process parameters during the RM have not been explored.

Building upon these identified gaps, this study introduces a parametric LCA model designed to minimize the environmental impact of RM products by optimizing the material composition. Unlike previous LCA studies that primarily focused on single materials and fixed process parameters, this research explores composites of low-density polyethylene (LDPE) and natural fibre.

The main contribution of this study lies in the development of a parametric LCA-based optimization framework that enables the systematic exploration of how material composition and process-related parameters jointly influence environmental impacts in RM. Unlike existing LCA studies, which are predominantly static and product-specific, the proposed approach allows scenario-based optimization and sensitivity analysis across multiple impact categories. By establishing the environmental impact as a function of material masses, the model identifies the most sustainable material distribution, demonstrated through case studies involving abaca fibre composites, thus offering a more adaptable and comprehensive sustainability assessment for RM processes.

2 Literature review

LCA studies of RM are extremely limited. Only five documents have been collected from Google Scholar, Scopus, and on the web by launching the query "LCA AND (ROTOMOULDING OR ROTOMOLDING OR "ROTATIONAL MOULDING" OR "ROTATIONAL MOLDING")" in title, abstract and keywords.

Table 1 summarizes the details of the considered LCA studies about RM. Among the retrieved LCA works, De Feo et al., [9] and De Feo and Ferrara [8] published their studies in international peer-review journals that use LCA to evaluate the impacts related to the production, through RM. De Feo et al., [9] provided a comparative LCA analysis specifically evaluating the environmental impacts of the RM process used to produce components for small-scale activated sludge total oxidation wastewater treatment systems. Two system materials, linear low-density polyethylene (LDPE) produced via RM and vibrated reinforced concrete, were assessed. The analysis included multiple treatment capacities

Table 1 LCA studies from literature about RM

Document	Type	Product	Material	Process parameters
De Feo et al., [9]	Article published in international peer-review journal	Three sludge collection tanks of different size	LDPE	Fixed temperature, time and speed ratio
De Feo and Ferrara [8]	Article published in international peer-review journal	Sludge collection tank	LDPE	Fixed temperature, time and speed ratio
Axén Stålberg [3]	Master of Science thesis	Waste collection bin	LDPE	Fixed temperature, time and speed ratio
Mehta et al. [28]	Poster for a conference	Showcase object	Virgin PE vs 75% virgin PE and 25% recycled PE	Fixed temperature, time and speed ratio
Pipelife Finland Oy [36]	EPD	Tubular object	PE and small amount of not better specified additives	Fixed temperature, time and speed ratio
Hydraloop [18]	EPD	Tank for greywater	HDPE	Fixed temperature, time and speed ratio

and investigated environmental impacts from the construction, operational, and disposal phases. Results of the LCA analysis showed the operational phase as the most significant contributor to environmental impacts, primarily due to energy consumption and sludge disposal. The RM process for LDPE components, including methane gas and electricity consumption during production, was identified as a sensitive parameter influencing the overall impacts. Despite this, the rotationally moulded LDPE systems exhibited lower environmental impacts than the concrete-based systems across all LCA methods applied, highlighting RM of LDPE as a comparatively sustainable manufacturing method for wastewater treatment plant components [9]. In another study, De Feo and Ferrara [8] discussed the LCA of RM process in terms of the environmental impacts arising primarily from the gas consumption required during the production of LDPE components. RM was identified as one of the sensitive parameters since it significantly contributed to the environmental impacts during the production phase of evaluated wastewater treatment systems. The scholars performed a sensitivity analysis using three values (2, 3, and 4 MJ/kg LDPE) for gas consumption in RM, indicating variations in this parameter notably affect the environmental performance. These authors reported that this difference in gas consumption impacted the constructed wetland system more since it required a larger surface area and, consequently, more plastic materials. This study highlighted the importance of accurately assessing the gas consumption parameters in small-scale wastewater treatment systems produced via RM [8].

A Master of Science thesis by Axén Stålberg [3] discussed at Chalmers University proposed LCA to evaluate the environmental impacts of a garbage collection bin made by LDPE. The thesis compared the environmental impacts of street sandboxes made from PE using RM and glass fibre-reinforced plastic (GFRP) using vacuum infusion. Four impact categories were evaluated in the LCA across different waste management scenarios, including climate change, stratospheric ozone depletion, acidification, and human toxicity. Results indicated that the PE sandboxes produced via RM had significantly lower impacts than GFRP sandboxes across all categories. The thesis concluded that RM-ed PE sandboxes were found to be environmentally preferable to those made from GFRP from a lifecycle perspective.

A poster for a conference was produced by Mehta et al. [28] in which LCA is used to compare the impact of the production of two showcase objects produced via RM, one made entirely from virgin PE and the other from a mixture of 75% virgin and 25% of recycled PE. The authors compared the energy consumption and CO_2 emissions between the virgin and recycled PE. The results showed that the incorporation of 25% recycled PE reduce the energy consumption by 41% per kg of showcase object produced, concluding that producing showcase objects from recycled plastics provides an environmentally beneficial end-market, and thus encouraging a greater use of recycled materials.

Pipelife Finland Oy [36] and Hydraloop [18] are EPDs drawn up by two companies in the sector. The LCAs implemented in the two documents analyse a tubular object made of polyethylene and additives and a greywater collection tank made of high-density polyethylene (HDPE). Pipelife Finland Oy [36] provided the details of a product made of PE by RM. The product's environmental impacts were assessed from raw material extraction to product dispatch and recycling at end-of-life. The EPD emphasised the significant recycling potential of the tank and provided extensive data on its global warming potential, energy use, and water consumption, clearly illustrating the environmental implications associated with the RM process. In Hydraloop [18] environmental impacts were analysed by comparing the Hydraloop system to traditional linear water supply systems, demonstrating significant potential eco-cost savings. The assessment identified HDPE, formed through RM, stainless steel, and printed circuit boards as major contributors to the product's environmental impact, suggesting potential improvements by optimising these materials and incorporating renewable energy sources.

Several research gaps emerged from the reviewed literature. Only two reviewed LCA studies were published in international peer-reviewed journals, while the remaining studies included a poster, a Master of Science thesis, and two industry-generated EPDs. The products evaluated were consistently tubular tanks or similarly shaped items, differing mainly in dimensions. Virgin PE was predominantly chosen as material, with only two examples examining recycled PE blends and minor additives. Moreover, existing studies have not investigated the impact of variations in RM process parameters.

Hence, the proposed parametric LCA approach introduces some novelties compared to the contributions reported in Table 1. The novelties of this LCA study are listed below:

- This study performs LCA using composites of different materials including PE, abaca fibres and Maleated PE (PEMA) as additive, while previous studies focused on performing an LCA using single material.
- This study uses the parametric LCA methodology to minimize the impact of RM by optimizing process parameters such as rotational speed, temperature, cooking and cooling times, composite material ratios, and thickness while existing studies focussed on fixed parameters.

3 Problem definition and modelling

3.1 Model assumptions

The proposed parametric model minimizes the environmental impact (objective function) within a specific impact category of RM in the production of composite product made of different materials. This optimization considers the cumulative effects of material extraction, cooking and rotating. The control parameters, provided by the user, are the thickness of the product entirely made by LDPE, the product external surface that is equal to the mould internal surface, the number of moulds, the furnace power, the mould material, the mould thickness, the rotating motor power, the impact category and the geographical scenario. Whereas the independent variable optimized to minimize environmental impact is the fibre mass ratio.

The material impact is determined by the mass of LDPE, fibres, and PEMA used in the composite product, as well as by the specific impact coefficients of the materials, which vary based on the impact category and the geographical scenario. The mass of PEMA is proportional to the mass of fibre according to a specific ratio, and consequently, the mass of LDPE in the composite is obtained by subtracting the combined mass of fibres and PEMA from the total composite mass. The total composite mass is influenced by its mechanical resistance and is calculated based on the required thickness that ensures the composite can withstand the same mechanical stress as a part made entirely of LDPE. In the model, the mass is determined in relation to the composite density and the volume of the composite part, that is derived from the thickness of the LDPE piece, accounting for the different mechanical resistance of the composite compared to LDPE, and the external surface of the product.

The impact of the cooking depends on the energy consumption of the gas furnace and the specific impact of natural gas. The energy consumed by the gas furnace is determined by its power and the cooking time, which in turn depend on the composition of the materials in the product, the overall mass of the product, and the material of the mould.

The rotation impact depends on the electricity consumed for rotation and the electricity specific impact. The energy required for rotation is influenced by the mass of the composite part, the mass of the mould, the rotating radius at which the mould is positioned, which affects rotational inertia, the rotational speed and the cooking and cooling time when rotation takes place. The cooling time depends on the mass distribution of the materials in the composite. As an assumption, in the model the rotational speed is considered constant.

The parametric LCA model is graphically represented in Fig. 1, highlighting in different colours the control parameters, the independent variables, the dependent variable, comprising the impacts and the constants.

3.2 Parameters

The control parameters, the independent and dependent variables and constants related to the parametric LCA of RM process are presented in Table 2.

3.3 Objective function

The parametric LCA model deals with the minimization of the overall environmental impact of RM process which is defined as the sum of the impacts of the material and the manufacturing impact as presented in Eq. 1.

$$I_{tot} = I_{mat} + I_{cooking} + I_{rotating} \quad (1)$$

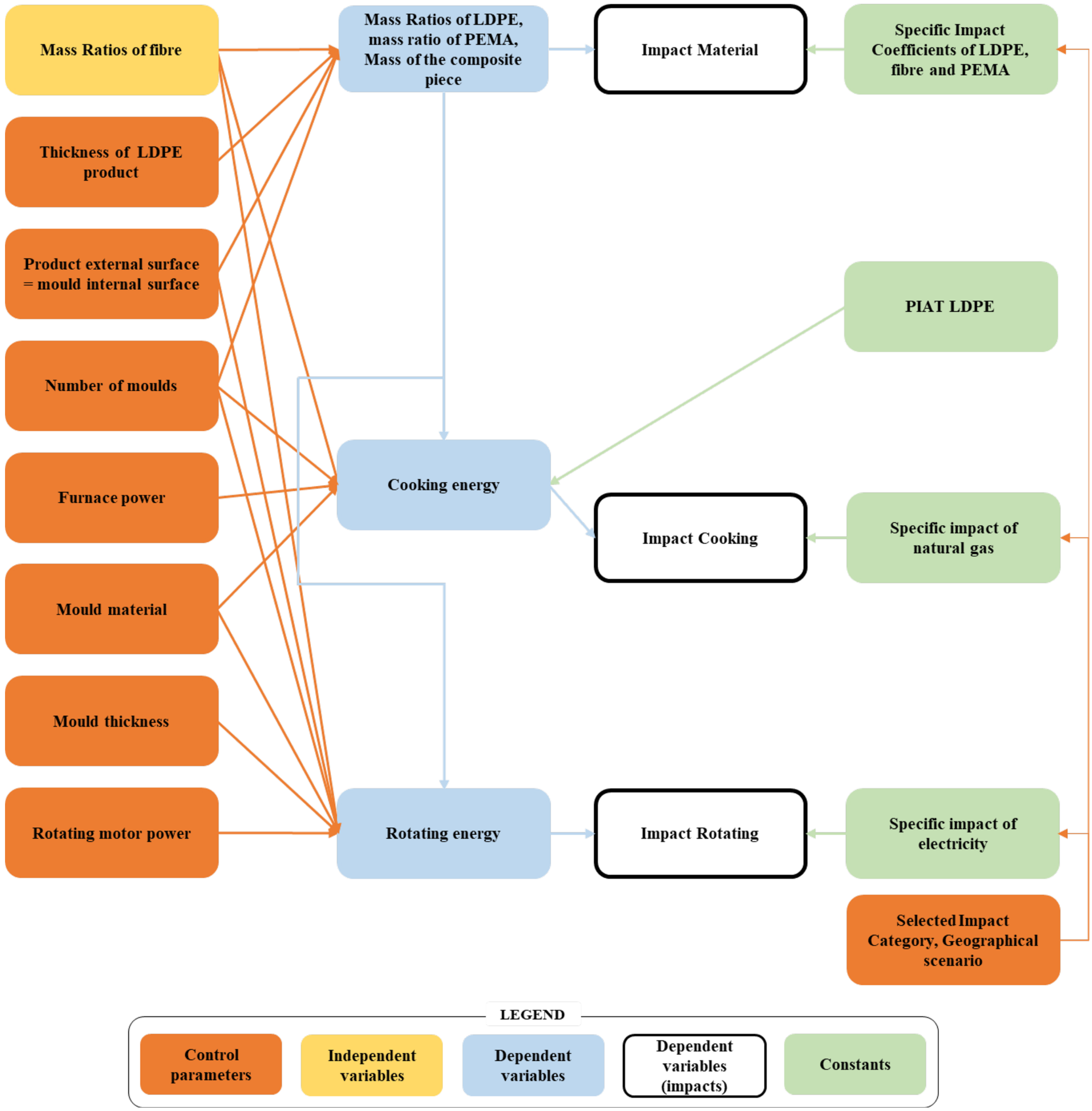


Fig. 1 Graphical representation of the parametric LCA model for RM

Impacts of the materials that constitute the composite depend on the number of moulds, mass of each constituting element in the composite, and the selected impact category. The impacts associated with materials can be calculated using Eq. 2, where the masses of the constituent materials are represented as fractions of the total mass of the composite product, using appropriate coefficients (Eqs. 3–5). In particular the mass of the fibre (if natural) can be related to that of the PEMA as in Ortega et al., [32] using Eq. 5.

$$I_{mat} = n_{moulds} \bullet (m_{LDPE} \bullet Ic_{LPDE} + m_{fibre} \bullet Ic_{fibre} + m_{PEMA} \bullet Ic_{PEMA}) \quad (2)$$

$$\alpha_{LDPE} = \frac{m_{LDPE}}{m_{productComposite}} \quad (3)$$

$$\alpha_{fibre} = \frac{m_{fibre}}{m_{productComposite}} \quad (4)$$

Table 2 Independent, dependent, and constant variables used in the parametric LCA

Control parameters		
A	External surface of the product and internal surface of the mould	m^2
$mouldMaterial$	Material of the mould	
n_{moulds}	Number of moulds	
$tk_{productLDPE}$	Thickness of product if completely made of LDPE	m
$fibreType$	Fibre used as reinforcement	
T_{amb}	Ambient temperature	°C
$En_{m,cookingLDPE}$	Specific energy of the furnace for cooking 1 kg of LDPE	MJ/kg
$Ps_{rotatingMotor}$	Power of the rotating motor per kg of rotating object (product and mould)	kWh/kg
$selectedRegion$	Geographical region where the assessment is to be set	
$impactCategory$	Selected category of impact to be minimized	
Independent Variables		
α_{fibre}	Fibre content: mass ratio of fibre in the product	
Dependent Variables		
$I_{material}$	Material impact	
α_{LDPE}	LDPE content: mass ratio of LDPE in the product	
α_{PEMA}	PEMA content: mass ratio of PEMA in the product	
m_{LDPE}	Mass of LDPE in the product	kg
m_{PEMA}	Mass of PEMA in the product	kg
m_{fibre}	Mass of fibre in the product	kg
$m_{productComposite}$	Total mass of the product	kg
$\rho_{productComposite}$	Density of the product	kg/m^3
$tk_{productComposite}$	Thickness of the product	m
$I_{cooking}$	Cooking impact	
$En_{cooking}$	Cooking energy	MJ
$t_{cooking}$	Cooking time of the product	s
$PIAT_{productComposite}$	Peak internal ambient temperature of the product	°C
$Slope_{mould}$	Heating temperature of the mould depending on the material and the mass of the mould	°C/s
$I_{rotating}$	Rotating impact	
$En_{rotatingmotor}$	Electricity consumption of rotating motor	kWh
$t_{cooling}$	Cooling time of the product	s
Constants		
β_{PEMA}	Ratio between mass of PEMA and mass of fibre	
ρ_{LDPE}	Density of LDPE	kg/m^3
ρ_{PEMA}	Density of PEMA	kg/m^3
ρ_{fibre}	Density of fibre	kg/m^3
σ_{LDPE}	Mechanical strength of LDPE	MPa
σ_{PEMA}	Mechanical strength of PEMA	MPa
σ_{fibre}	Mechanical strength of fibre	MPa
Ic_{LDPE}	Impact coefficient of 1 kg of LDPE	
Ic_{PEMA}	Impact coefficient of 1 kg of PEMA	
Ic_{fibre}	Impact coefficient of 1 kg of fibre	
$PIAT_{LDPE}$	Peak internal ambient temperature of LDPE	°C
ΔT_{fibre}	Temperature reduction coefficient between PIAT of the product and PIAT of LDPE, function of α_{fibre}	°C

Table 2 (continued)

Control parameters		
Ic_{ng}	Impact coefficient of 1 MJ of natural gas	
$t_{coolingLDPE}$	Cooling time of the product if made by LDPE	s
Ic_{el}	Impact coefficient of 1 kWh of electricity	
$\alpha_{fibreMin}$	Minimum fibre content in the product	
$\alpha_{fibreMax}$	Maximum fibre content in the product	

$$\alpha_{PEMA} = \frac{m_{PEMA}}{m_{productComposite}} = \beta_{PEMA} \bullet \alpha_{fibre} \quad (5)$$

The mass of the product composite (Eq. 6) is calculated as function of the average density of the composite depending on the material distribution (Eq. 7), the overall external surface of the product and its thickness. In turn, the latter can be derived from that of the product made of LDPE by using the ratio of their respective tensile strengths (Eq. 8), where typically the strength decreases in the composite, and therefore the thickness increases to compensate for this. In particular, the composite tensile strength can be calculated in relation to the amount of fibre in the composite and the tensile strength of the LDPE through the approximated linear relationship [17] (Eq. 9).

$$m_{productComposite} = \rho_{productComposite} \bullet A \bullet tk_{productComposite} \quad (6)$$

$$\rho_{productComposite} = \alpha_{fiber} \bullet \rho_{fibre} + \alpha_{LDPE} \bullet \rho_{LDPE} + \alpha_{PEMA} \bullet \rho_{PEMA} \quad (7)$$

$$tk_{productComposite} = \frac{\sigma_{LDPE}}{\sigma_{composite}} \bullet tk_{productLDPE} \quad (8)$$

$$\sigma_{composite} = \delta_{fibre} \bullet \alpha_{fibre} + \sigma_{LDPE} \quad (9)$$

The cooking impact is calculated considering the number of moulds, the energy consumption of the furnace per one mould and the impact coefficient of the natural gas feeding the furnace (Eq. 10). The cooking energy is determined by the furnace power used for cooking the product and the cooking time of the composite (11). In turn the power depends, by the specific energy for cooking 1 kg of LDPE divided by the cooking time of the product entirely made by LDPE and the mass of the product composite (12).

$$I_{cooking} = n_{moulds} \bullet En_{cooking} \bullet Ic_{ng} \quad (10)$$

$$En_{cooking} = P_{furnace} \bullet t_{cooking,\, productComposite} \quad (11)$$

$$P_{furnace} = \frac{En_{m,\, cookingLDPE}}{t_{cooking,\, productLDPE}} \bullet m_{productComposite} \quad (12)$$

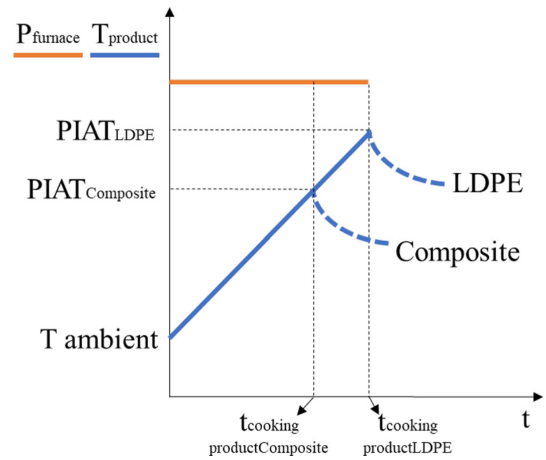


Fig. 2 Approximated furnace power and temperature vs cooking time

The cooking times for the LDPE product and the composite product are determined based on the achievement of the PIAT temperature in the products, using the heating characteristic curve shown in Fig. 2. The slope of the curve depends on the mould material and the mass of the composite product, while the PIAT temperature is influenced by the final composition of the product.

Consequently, using the graph in Fig. 2, the cooking time for the LDPE product (Eq. 13) and the cooking time for the composite product (Eq. 14) can be calculated.

$$t_{cooking,\, productLDPE} = \frac{PIAT_{LDPE} - T_{amb}}{Slope_{mouldMaterial}} \quad (13)$$

$$t_{cooking,\, productComposite} = \frac{PIAT_{composite} - T_{amb}}{Slope_{mouldMaterial}} \quad (14)$$

The equations for calculating the slope depending by the mould material and the mass of the LDPE product were retrieved by using empirical data from the literature for aluminium mould [7, 15] (Eq. 15) and for steel mould [7, 23, 29, 37] (Eq. 16).

$$Slope_{aluminium} = 0.1957 \bullet m_{productLDPE} + 0.0304 \quad (15)$$

$$Slope_{steel} = 0.1755 \bullet m_{productLDPE} + 0.0258 \quad (16)$$

In turn, PIAT of the composite material depends on the PIAT of the LDPE, the content of fibre and an empirical coefficient related to the temperature, as in Fletes et al. [12] (Eq. 17).

$$PIAT_{composite} = PIAT_{LDPE} - \alpha_{fibre} \bullet \Delta T_{fibre} \quad (17)$$

The rotation impact depends on the energy consumed by the rotation motor and impact coefficient of electricity (Eq. 18). The energy consumed by the rotation motor is calculated by taking the full-load power of the motor, multiplying it by the rotated mass, dividing by the total rotatable mass, and then multiplying by the cycle time, which corresponds to the sum of the cooking and cooling times (Eq. 19). The cooling time of the composite product is calculated using the empirical formula which relates it to the cooling time of the LDPE product and the amount of fibre in the composite product, through a multiplicative coefficient [38] (Eq. 20).

$$I_{rotating} = En_{rotatingMotor} \bullet Ic_{el} \quad (18)$$

$$En_{rotatingMotor} = Ps_{rotatingMotor} \bullet \left(\frac{n_{moulds} \bullet (m_{productComposite} + m_{mould})}{maxLoad} \right) \bullet (t_{cooking,\, productComposite} + t_{cooling,\, productComposite}) \quad (19)$$

$$t_{cooling,\, productComposite} = \tau_{fibre} \bullet \alpha_{fiber} + t_{cooling,\, productLDPE} \quad (20)$$

3.4 Constraints

The unique constraint considered in the model deals with the mass ratio of the fibre in the product (Eq. 21) to consider the limits of aggregation and structural resistance.

$$\alpha_{fibre} \leq \alpha_{fibre,\, Max} \quad (21)$$

4 Numerical investigation

This section presents the numerical implementation and solution of the optimization problem defined in Sect. 3. The aim of the optimization is to determine the fibre mass ratio that minimizes the overall RM process environmental impact, under a given set of control parameters and constraints. For clarity, the optimization problem formulation and solution procedure are briefly recalled and discussed before presenting the case study results.

4.1 Optimization problem formulation and solution procedure

The optimization problem addressed in this study consists of minimizing the total environmental impact of the RM process, expressed as the sum of material, cooking, and rotating impacts (Eq. 22). The decision variable is the fibre mass ratio in the composite product, while all other parameters, such as product geometry, mould material, energy characteristics, geographical scenario, and selected impact category, are treated as fixed control parameters defined by the user.

The optimization problem can therefore be formulated as: Minimize:

$$I_{\text{tot}}(\alpha_{\text{fibre}}) = I_{\text{material}} + I_{\text{cooking}} + I_{\text{rotating}} \quad (22)$$

Subject to:

$$0 \leq \alpha_{\text{fibre}} \leq \alpha_{\text{fibre, Max}} \quad (23)$$

For each environmental impact category, the optimization is performed independently, allowing the identification of the material composition that minimizes the selected indicator. The resulting optimal fibre content varies across impact categories, reflecting the multi-dimensional and non-univocal nature of environmental performance in RM.

The problem is solved numerically using a constrained non-linear optimization approach implemented in MATLAB. Multiple initial values are used to reduce sensitivity to local minima, and the solution yielding the lowest impact value is retained. The optimization outputs include the optimal fibre, polymer, and additive fractions, the corresponding product mass and thickness, and the breakdown of environmental impacts across materials and process phases.

4.2 Case studies and discussion

Figures 3 and 4 report the results of the optimization process, showing respectively the optimal material composition and the corresponding impact breakdown obtained by solving the optimization problem for each impact category and case study.

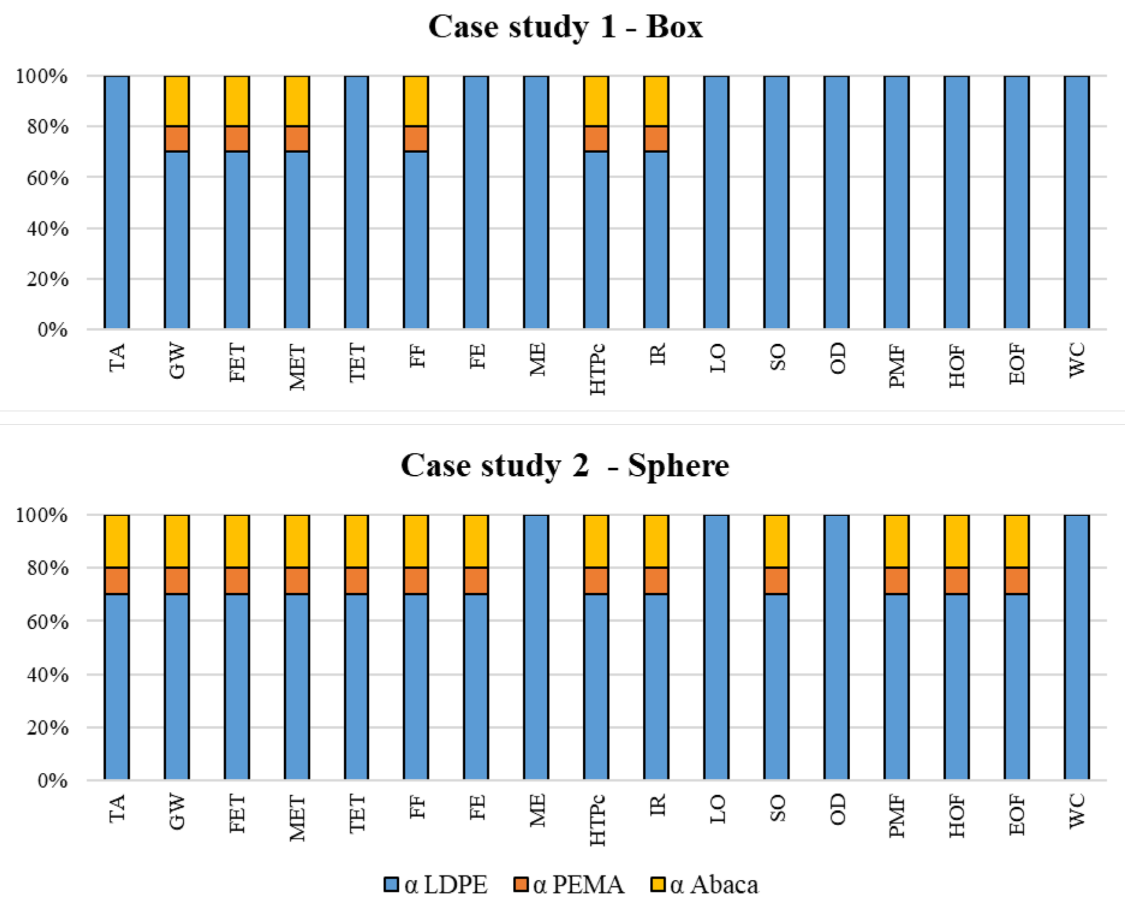


Fig. 3 Optimal material composition in the product to minimize the impacts across different categories in the two case studies considered

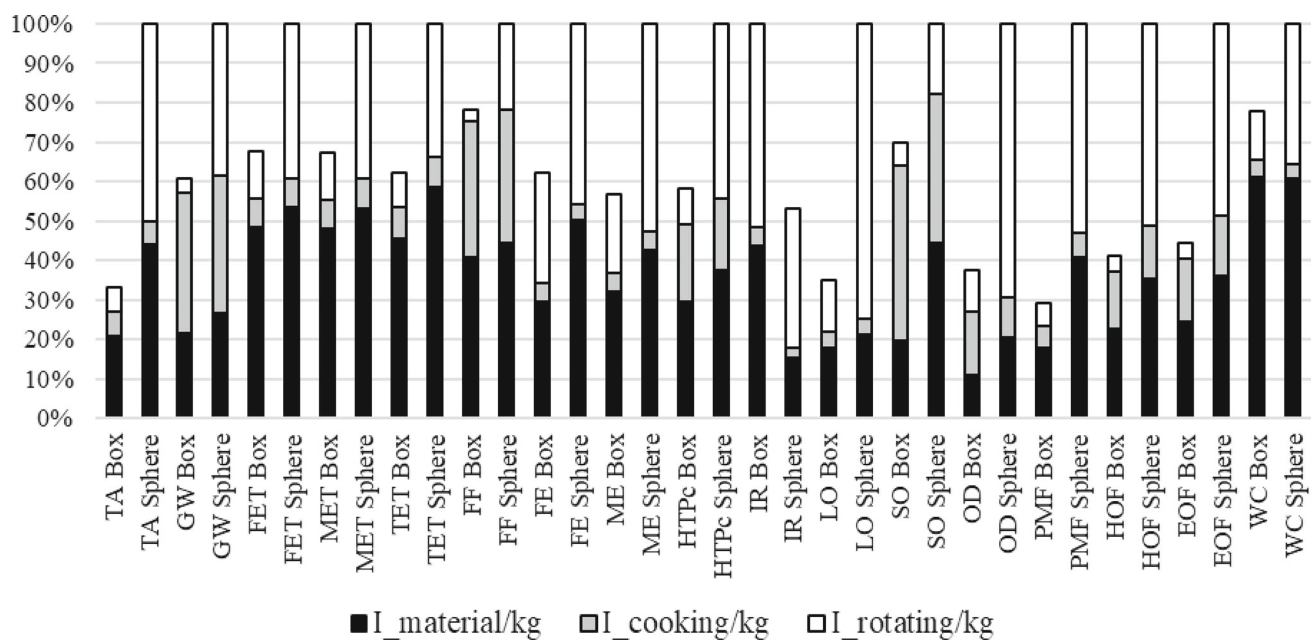
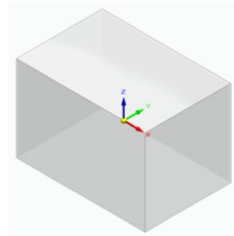
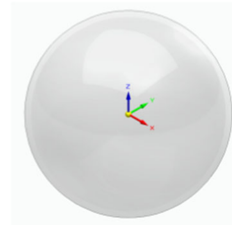


Fig. 4 Comparison of the impacts of the two case studies across each category, broken down by the constituent phases

Table 3 Control parameters in the considered case studies

Features	Case study 1—Box	Case study 2—Sphere
		
Product dimensions	Length: 1.5 m, width: 1 m, height: 1 m	Diameter: 0.1 m
External product surface and internal mould area	8 m^2	0.0314 m^2
Product thickness	0.01 m	0.003 m
Mould material	Aluminium	Steel
Mould thickness	0.01 m	0.005 m
Number of moulds	2	1
Furnace power	44 MJ/kg [27]	
Rotating motor power	7.5 kW (*Ferry RotoSpeed, RS–1600 Turret Style model)*	
Geographical region	European Union (EU)	China (CN)
Impact categories	ReCiPe Midpoint (H) method categories: terrestrial acidification (TA), global warming (GW), freshwater ecotoxicity (FET), marine ecotoxicity (MET), terrestrial ecotoxicity (TET), fossil fuel (FF), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity cancerogenic (HTPc), ionising radiation (IR), land occupation (LO), surplus ore (SO), ozone depletion (OD), particulate matter formation (PMF), humans photochemical oxidant formation (HOF), ecosystems photochemical oxidant formation (EOF), water consumption (WC)	

The two case studies refer to the production, through RM, of a box and a sphere made from composite material, with abaca fibre used in both cases. To demonstrate the applicability of the proposed parametric model, two case studies were selected that differ significantly, allowing for an exploration of the model's response to variations in the control parameters. In both cases, the characteristics of the products considered reflect those commonly manufactured using RM, ensuring the relevance of the investigation. In particular, the products differ significantly in terms of shape, size, and thickness, in order to account for the variability of environmental impacts, especially in relation to the mass of the material. The mould materials are also different, to capture variations in impacts associated with heating and rotation energy requirements. The geographical scenarios are varied to reflect differences in contextual factors (e.g., electricity mix) and upstream material flows (e.g., characteristics of the production site and logistics). Different environmental impact categories are considered to explore how the model responds to various environmental effects to be minimized, and how these impacts are distributed across the different materials and energy sources modelled.

Table 4 Values associated with parametric model constants in numerical investigation

Property	Value	References
$PIAT_{LDPE}$	200 °C	Ortega et al. [34]
$\alpha_{fibre,Max}$	0.2	Ortega et al. [32]
ΔT_{fibre}	50.67	Fletes et al. [12]
β_{PEMA}	0.5	Ortega et al. [32]
ρ_{fibre}	1500 kg/m^3	Ahmad et al. [2]
ρ_{LDPE}	924.2 kg/m^3	Jordan et al. [20]
ρ_{PEMA}	930 kg/m^3	Ortega et al. [34]
δ_{fibre}	− 34	Ortega et al. [32]
τ_{fibre}	50	Ortega et al. [34]

Table 3 reports the control parameters related to the two considered case studies.

The values associated with the constants of the parametric model are reported in Table 4 with the relative sources.

The specific impact coefficients of all the considered impact categories in the two considered scenarios were defined by selecting datasets from Ecoinvent v3.9.1 database with reference to the most compatible geographical region.

If datasets relating to flows, and referred to production and supply, are already available in the database, those were used. Otherwise, impact coefficients were constructed by combining data from different datasets according to specific criteria. Specifically, the impact coefficient of abaca for the given impact category was derived by summing the impact coefficient associated with the production of kenaf, an equivalent natural fibre, and the impact coefficient related to the transport of 1 kg of material under two different geographical scenarios. The transport assumptions include 650 km by truck and 10,964 km by ship for the EU scenario, and 380 km by truck and 16,938 km by ship for the CN scenario. These assumptions are consistent with the typical production of abaca in Ecuador, which is then transported to more industrialized regions of the EU and CN, respectively by sea and subsequently by land via truck. Transport data were sourced from the Ecoinvent database. While the impact coefficient of PEMA was calculated by summing the impact of 90% by weight HDPE and 10% by weight maleic anhydride. For both materials, datasets from Ecoinvent were used.

Table 5 presents the Ecoinvent datasets used to model the impact coefficients across different impact categories in the considered scenarios.

The model was implemented and executed in MATLAB,[1] using the Optimization Toolbox to minimize the total environmental impact of RM. User-defined objective and constraint functions encoded the process model and ensured physical and performance-based limitations were satisfied. Table 6 presents the structure of the pseudocode of the parametric LCA model.

As a result, the parametric model identified the optimal abaca fibre content in the product that minimizes the overall environmental impact, depending on the scenario considered. Figure 3 compares the optimal abaca content and, consequently, the corresponding proportions of PEMA and LDPE in the product, required to minimize each environmental impact category in the two considered case studies.

Furthermore, the model was used to extract and compare the impacts referred to the considered case study minimizing each category. The comparison is carried out both at the level of total impacts of RM and those of the constitutive phases (materials production, cooking and rotating). The dimensionless comparison per kg of product is reported in Fig. 4.

Although based solely on the differences in control parameters between the two case studies tested, the results shown in Figs. 3 and 4 allow for a discussion of the usefulness and versatility of the proposed model.

Figure 3 shows completely contrasting results across different impact categories, i.e., TA, TET, FE, SO, PMF, HOF, and EOF, demonstrating the highly variable nature of environmental performance in RM products. These variations underscore the complexity of selecting an optimal material composition to minimize environmental impact, as such decisions are influenced by a range of factors included within the control parameters: the type of natural fibre, product dimensions, mould material, geographical context, and the specific environmental impact category considered. Notably, even in the two case studies examined, both of which employ the same natural fibre (abaca), the analysis does not lead to a univocal eco-design guideline. This finding highlights the

[1] GitHub repository.

Table 5 Used Ecoinvent datasets in the considered scenarios

Specific Impact Coefficient	EU	CN
Ic_{LDPE}	Polyethylene production, low density, granulate (RER)	Polyethylene production, low density, granulate (RoW)
Ic_{fiber}(Abaca)	Fibre production, kenaf, retting (RoW) and transport through freight and truck from Ecuador to EU	Fibre production, kenaf, retting (RoW) and transport through freight and truck from Ecuador to CN
$Ic_{freight}$	Transport, freight, sea, container ship (GLO)	Transport, freight, sea, container ship (GLO)
Ic_{truck}	Transport, freight, lorry, all sizes, EURO6 to generic market for transport, freight, lorry, unspecified (RER)	Transport, freight, lorry, all sizes, EURO6 to generic market for transport, freight, lorry, unspecified (RoW)
Ic_{PEMA}	Calculated weight 90% HDPE, 10% maleic anhydride	Calculated weight 90% HDPE, 10% maleic anhydride
$Ic_{maleicAnhydride}$	Maleic anhydride production by catalytic oxidation of benzene (RER)	Maleic anhydride production by catalytic oxidation of benzene (RoW)
IC_{HDPE}	Polyethylene production, high density, granulate (RER)	Polyethylene production, high density, granulate (RoW)
IC_{ng}	Heat production, natural gas, at industrial furnace > 100 kW (Europe without Switzerland)	Heat production, natural gas, at industrial furnace > 100 kW (RoW)
Ic_{el}	Market group for electricity, medium voltage (RER)	Market group for electricity, medium voltage (CN)

Table 6 Pseudocode of the parametric LCA model

A	Optimize function
1	Initialize constants and load impact categories
2	Define lower and upper bounds for fibre content (0 to 0.2)
3	FOR each impact category:
	Set this category as the optimization target
	Initialize best impact value as infinite
	REPEAT 10 trials:
	Generate random initial fibre ratio (× 0)
	Run constrained optimization (fmincon) to minimize objective_fibre
	IF current result is better:
	Save current fibre ratio as best solution
	Compute:
	- LDPE and PEMA fractions from best fibre value
	- Composite PIAT temperature
	- Required cooking time
	Calculate impacts and mass using compute_all_impacts()
	Save results into a table row
4	Write all results to Excel
5	Display optimization summary
B	Objective Function
1	Compute:
	- alpha_PEMA = 0.5 * alpha_Fibre
	- alpha_LDPE = 1—alpha_Fibre—alpha_PEMA
2	IF any alpha < 0:
	Return a high penalty (infeasible)
3	Compute:
	- Composite PIAT temperature (decreases with fibre)
	- Cooking time required
4	Use compute_all_impacts() to calculate impact values
5	Return the normalized impact of the current target category
6	Log values for analysis
C	Compute all Impacts Function
1	Extract inputs:
	- Cooking time
	- Fibre and PEMA content
	- Compute LDPE content = 1—(fibre + PEMA)
2	IF any alpha < 0:
	Return infinite impacts and NaN mass
3	Compute:
	- Composite tensile strength (as function of fibre)
	- Thickness required to maintain strength
	- Total mass of composite (density * volume)
4	Calculate:
	- Energy for cooking: proportional to mass and time
	- Cooling time: longer with more fibre
	- Energy for rotation: depends on mould and part mass
5	FOR each impact category:
	- Compute material impact from LDPE, PEMA, and Fibre (includes transport)
	- Compute cooking impact (via natural gas EF)
	- Compute rotation impact (via electricity EF)
	- Normalize impact by composite mass
6	Return:
	- Normalized impacts
	- Cooking, rotation, and material impacts (absolute)
	- Composite mass
D	Constants Function
1	Ask user for:
	- Ambient temperature
	- Mould material (aluminium or steel)
	- Number of moulds
	- Mould rotation radius
	- Furnace energy (MJ/kg)
	- Mould thickness and surface area
	- LDPE product thickness
	- Region (EU or CN)
2	Set default values for:
	- LDPE PIAT, cooling time, strength, densities
	- Rotational power
	- Temperature reduction due to fibre
3	Calculate:
	- Slope for heat transfer based on mould material
	- Mould density
4	Set transport distances based on region
5	Define list of impact categories
6	Read environmental factors from Excel
	- Match materials to impact values for selected region
7	Return constants

inherently parametric nature of the problem, wherein minor variations in input parameters can substantially shift the environmental profile of the final product. This observation is consistent with the conclusions of Kelly-Walley et al. [22], who, in their review on the sustainability of RM, pointed out the fragmented and non-systematic nature of eco-design strategies in the field. However, their review was limited to static or general environmental assessments, often accompanied by non-integrated sensitivity analyses, and did not consider parametric LCA models capable of capturing the multi-variable interactions inherent in RM processes.

Figure 4 further reinforces this perspective by directly comparing the impacts of the two case studies and illustrating how variations in control parameter combinations can significantly alter the environmental burden per kilogram, both in total and at different stages of the process, across multiple impact categories. The parametric model proves particularly effective in this context, functioning as a decision-support tool that allows for targeted sensitivity analyses by adjusting individual or grouped parameters and observing their influence on selected environmental indicators. This dynamic capability addresses a critical gap in current LCA applications for RM, where conventional models tend to be static and product-specific, thus limiting their scalability and practical utility in real-world industrial contexts. From a broader perspective, the proposed parametric LCA framework aligns with recent research advocating for prospective and design-oriented LCA approaches, capable of supporting early-stage eco-design under uncertainty [40].

In addition, the model developed in this study, through the systematic parameterization and explicit formulation of impact coefficients, enables a high degree of customization in environmental impact assessment. This flexibility allows users to tailor the model to a wide variety of scenarios by selecting alternative impact categories, incorporating updated or localized datasets, and applying different life cycle impact assessment (LCIA) methods, such as the CML-IA baseline method in place of ReCiPe Midpoint (H), depending on the specific goals and constraints of the analysis. This approach may further facilitate the harmonization of Life Cycle Assessment (LCA) methodologies, enabling a more standardized and interoperable framework for evaluating environmental, economic, and societal impacts. By integrating these dimensions into a cohesive system, it can serve as a robust foundation for developing a digital green passport in RM that not only ensures transparency and comparability but also supports informed decision-making by policymakers, industries, and consumers. Such harmonization could address existing challenges in data interoperability, methodological inconsistencies, and the integration of social sustainability metrics, ultimately advancing global efforts toward holistic sustainability assessments [24].

This approach is particularly relevant to the operational context of RM companies, which are typically small to medium-sized enterprises (SMEs) characterized by limited technical and financial resources and highly heterogeneous product portfolios. For such companies, conducting a full LCA for each unique product would be prohibitively costly and time-consuming [42]. The proposed parametric model provides a cost-effective and scalable solution that aligns with the production realities of RM SMEs. By parameterizing key variables such as product weight, material type, energy consumption, and cycle duration, the model allows for the rapid generation of reliable environmental performance estimates across a diverse array of products. The resulting data can serve multiple strategic functions: informing eco-design decisions, guiding internal process optimization, supporting external sustainability communication, and contributing to the development of company-specific environmental databases for long-term scenario analysis and continuous improvement. Moreover, this approach lays the groundwork for the integration of LCA into digital design, production tools and digital green passport, facilitating the transition toward more sustainable manufacturing practices in resource-constrained industrial settings.

From a broader perspective, the results presented in Figs. 3 and 4 directly address the research gaps identified in the literature review (Sect. 2). Previous LCA studies on RM were largely limited to static assessments of single products, fixed process parameters, and predominantly virgin polyethylene materials, which prevented the exploration of interactions between material composition, process conditions, and contextual factors.

The proposed parametric LCA framework overcomes these limitations by explicitly linking material selection and process-related parameters to environmental impacts within a unified optimization approach. The results demonstrate that the optimal fibre–polymer composition varies significantly across impact categories, product geometries, mould materials, and geographical scenarios, confirming that no single eco-design solution can be considered universally optimal for RM products.

Moreover, the comparative analysis across impact categories highlights the presence of environmental trade-offs when different sustainability objectives are prioritized. This capability is largely absent in existing RM LCA studies and represents a key methodological contribution of this work. By enabling systematic sensitivity analysis and scenario-based optimization, the proposed model bridges the gap between conventional, product-specific LCA studies and the practical needs of eco-design decision-making, particularly for small and medium-sized enterprises operating in highly heterogeneous production contexts.

5 Assumptions and limitations of the study

The proposed parametric LCA model is based on a number of assumptions that are necessary to ensure model transparency, usability, and computational efficiency, particularly in early-stage eco-design applications. The proposed study is based on numerical modelling and literature-derived data; no experimental fabrication or laboratory testing of composite products was conducted within the scope of this work.

From a process modelling perspective, the RM process is represented through a simplified and functional formulation aimed at estimating energy consumption and material-related impacts rather than accurately reproducing detailed thermo-mechanical process dynamics. In particular, rotational speed is assumed to be constant, heat transfer is approximated through empirical linear relationships derived from literature data, and cooling behaviour is modelled using simplified correlations as a function of fibre content. These assumptions allow the integration of process parameters into the LCA framework but do not capture transient effects, machine-specific behaviour, or operational variability typical of industrial RM processes.

Regarding material modelling, the mechanical behaviour of composite products is simplified through linear relationships between fibre content and tensile strength, based on literature sources. This approach neglects potential nonlinear effects, fibre dispersion issues, interfacial phenomena, and anisotropies that may arise in real composites. Consequently, the calculated thickness adjustments required to match LDPE mechanical performance should be interpreted as indicative rather than predictive.

From an LCA perspective, the model follows a streamlined and parametric approach rather than a fully detailed, standard-compliant life cycle assessment. Broad cut-offs are applied, and the system boundaries are limited to material production, cooking, and rotation phases, excluding downstream stages such as use phase and end-of-life scenarios. The environmental impact coefficients are derived from the Ecoinvent v3.9.1 database; however, for some materials, such as abaca fibre, proxy datasets, e.g., kenaf fibre, and assumed transport distances are used. While these choices are consistent with best practices in comparative and early-stage LCA, they introduce uncertainty and limit the absolute accuracy of the results.

Furthermore, the model is not intended for regulatory, certification, or EPD purposes. Its level of aggregation and the use of simplified assumptions make it unsuitable for compliance with ISO standards or official reporting frameworks. Instead, the primary objective of the model is to support conceptual eco-design, sensitivity analysis, and comparative decision-making, especially in contexts where complete data availability is limited.

Finally, the numerical investigation presented in this study is limited to two case studies and a specific natural fibre, i.e., abaca. Although these cases were selected to demonstrate the flexibility and robustness of the parametric framework, the results should not be generalized without caution to other geometries, fibres, polymers, or processing conditions.

Despite these limitations, the model provides a transparent, flexible, and low-cost tool for exploring sustainability trade-offs in RM. Its value lies in enabling informed decision-making at early design stages, where relative trends and parametric sensitivities are often more relevant than absolute impact values.

6 Conclusions

This study developed and validated a parametric LCA model to optimize material composition in RM processes, minimizing environmental impacts based on user-defined control parameters. The model introduces three significant contributions to the field:

- Overcomes the limitations of traditional, and static, LCA of RM, allowing to link process parameters to environmental impacts.
- Provides a validated methodology for defining sustainable materials mixture in RM composite products.
- Establishes quantitative relationships between material composition, mechanical performance, and environmental indicators in RM.

These conclusions must be read in light of the limitations of this study. The proposed model is simplified both in the modelling of the RM process and in the application of the LCA methodology. This simplification reflects the primary objective of the model, which is not to provide an exhaustive or regulatory-compliant tool, but rather to offer a practical and conceptual support framework, particularly in the early stages of eco-design. The process modelling is purely functional to the environmental assessment, rather than aimed at investigating its actual functioning or optimizing its operational performance. At the same time, the model is intentionally not geared toward conducting rigorous environmental assessments for certification purposes. The extent of the approximations, such as broad cut-offs and streamlined data modelling, makes it unsuitable for compliance with current standards and official guidelines. Instead, its value lies in fostering awareness of environmental considerations during the ideation phase, where greater flexibility exists, and design choices can still be influenced. By prioritizing conceptual clarity over technical precision, the model enables designers and stakeholders to engage with sustainability principles without the burden of complete data or exhaustive analysis, thus supporting informed decision-making in contexts where regulatory rigor is not the immediate goal.

Due to its fully parametric structure and limited number of required user inputs, the proposed model is inherently suitable for integration into a GUI-based toolbox. Such an implementation would significantly improve usability for designers and practitioners, particularly in small and medium-sized enterprises, and represents a natural extension of this work for future research.

Beyond the specific results discussed in this study, the broader motivation of this work lies in addressing the lack of flexible, scalable, and decision-oriented environmental assessment tools for RM processes. Existing LCA studies in this field are often product-specific, static, and difficult to generalize across different materials, geometries, and production contexts. The proposed parametric LCA framework aims to bridge this gap by enabling systematic exploration of sustainability trade-offs at early design stages, where material and process choices can still be effectively influenced.

Future research should focus on extending and strengthening the proposed framework in several directions. Experimental validation in collaboration with industrial partners would improve the robustness of the model assumptions and parameterization. Further refinement of process modelling, including uncertainty and variability in material properties and energy consumption, would enhance predictive capabilities. In addition, the integration of the model into user-oriented tools, such as GUI-based toolboxes, and its coupling with techno-economic analysis represent promising avenues to support holistic sustainability-driven decision-making in RM.

Author contributions Baris Ördek: Software, Investigation, Writing—original draft. Zaida Ortega: Data curation, Validation, Writing—review & editing. Jake Kelly-Walley: Data curation, Validation. Mark McCourt: Data curation, Validation. Christian Spreafico: Supervision, Conceptualization, Methodology, Formal analysis, Investigation, Writing—original draft, Writing—review & editing,

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Data availability The code is freely available to readers and can be accessed through the following link: https://github.com/brsordk/Optimization_RM.

Declarations

Conflict of interest The authors declare no conflict of interest.

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