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Article

Material Design-for-Excellence (M-DFX) – A New Holistic Analysis for Glass and Basalt Composite Materials

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Abstract: Advanced composite materials have drawn significant interest in the last years as an alternative to traditional materials due to their higher performance. However, industry struggle to provide low-cost, higher occupational safety, lower footprint with composites, making them suitable for holistic analyses. Therefore, the material design becomes an essential element that can impact the competitiveness, particularly in terms of productivity, circularity, safety, sustainability, and quality of the value chain. The Material Design-for-eXcellence is a state-of-art methodology for material performance multi-dimensional assessment along its life cycle phases, either useful to support material selection for new products or also to new material design support optimizing resource efficiency. In this methodology, the material behaviour and its multiple characteristics assessment, and the manufacturing processes efficiency are evaluated. The framework considers the analogy of product design holistic approaches, as Lean Design-for-X, to organize and assess the multi-dimensional performance for each "X" Material Property. In this work, it was possible to observe that the bio-based composites solutions could be a good sustainable alternative for several sectors. Every day researchers are creating more new materials, having a diversity of properties at different scales, Material Design-for-eXcellence must also in the near future consider other factors. Hence, additional studies are thus foreseen to explore and develop this new tool.

Keywords: material design-for-eXcellence; material design-for-X; M-DfX; advanced materials; material performance assessment; eco-efficiency; sustainability; material life cycle

1. Introduction

Rapid growth in population has led to high demand for buildings, being the construction sector one with the highest environmental impact. Nevertheless, each year new and more complex challenges appear to the industry. For example, recently there is a shortage of raw materials because of pandemics, wars, etc., making several sectors seek for holistic solutions. These guarantee the reduction of the footprint, leads to less material consumptions, reduce time in the product development process, has higher product quality, reduce overall costs and fulfilling customers' requirements. Modular construction made with composites sandwich panels seems to be a solution that can respond to this demand, since it is an easy construction method, time-effective and also more sustainable, because it does not need as many resources as traditional construction [1-4].

Normally, composite sandwich panels are made with an insulation foam combined with exterior layers made with fibre-reinforced polymer (FRP) laminates, giving them multifunctional properties. It allows them to meet various requirements, such as structural, thermal and acoustic performance. However, this solution is commonly made with artificial materials and also from fossil resources, being the fire behaviour one of their main drawbacks [2, 5, 6].

So, advanced composite materials have drawn significant interest in the last years as an alternative to traditional materials due to their higher performance. Consequently, they have been used in many applications in several sectors. However, industry struggle to provide low-cost, higher occupational safety, lower footprint with composites, making them suitable for holistic analyses [3, 7-10].

Due to these issues, natural or bio-based raw materials to produce composite sandwich panels have received considerable attention lately, since they are from sustainable sources. However, usually, they have lower performance than the ones made with non-renewable resources. A possible solution to overcome this is through a compromise strategy or produce hybrid composite sandwich panels with natural or bio-based combined with artificial raw materials, allowing to achieve a superior properties and sustainability [4, 11-13].

Bio-based fibres can be from different origins, namely vegetal (i.e., plants), mineral (i.e., ceramic/rock and metal) or animal (i.e., hair). One of the most promising bio-based materials are the basalt fibres and are currently known as “green industrial material”. They are made from natural material (basalt volcanic rock) and during its production no chemical or other hazardous materials are added. Besides, these fibres have higher performance and easier to be recycled when compared with the typical glass fibres and with other bio-based fibres [4, 13].

The combination of distinct materials can offer balanced solutions to the broaden applications of multifunctional composite sandwiches (MCS) by developing synergetic effects [12, 14]. Therefore, the material design becomes an essential element that can impact the competitiveness, particularly in terms of productivity, circularity, safety, sustainability, and quality of the value chain [3, 7-9].

Even though extensive research work has been carried out on sandwich panels, only a limited number of studies have been published with basalt fibres [11, 12, 15, 16]. Moreover, besides the need to provide a multi-criteria comparison of these materials with other conventional ones, a comprehensive life cycle performance assessment is of nowadays great importance, regarding the need to use more environmentally sustainable materials. Therefore, this work aims to produce and test sandwich panels with diverse raw materials (bio-based and artificial) and analyse them through the novel Material Design-for-X (M-DFX) approach. This considers several requirements through different material properties “X”, to improve the product design, as well as, to support the process design enhancement. Moreover, the results provided complement the public material performance library of M-DfX framework.

2. Materials and Methods

2.1. Material Design-for-eXcellence description

The so called “Material Design-for-eXcellence" or “Material Design-for-X" (adopting the similar name designation made popular in product development research science, between “Design-for-eXcellence" and “Design-for-X"), M-DfX for short, is a state-of-art methodology developed by INEGI, to support decision in novel complex material design. It allows a multi-dimensional performance assessment of materials, both in technical properties and resource efficiency along the material life cycle. In this methodology, the material behaviour and its multiple characteristics assessment is assessed via an original approach to analyse the effectiveness of a material characteristic or parameter regarding a given reference value (relative comparison in a close set of material alternatives, or an absolute comparison to the best material available). In addition to the technical performance assessment, for multi-dimensional “X” Material Property analysis, the methodology cross-assesses the material life cycle efficiency for life cycle macro-phases and a set of key parameters indicators, namely Energy, Material Yield, Water consumption, CO_2 emissions, recyclability. The methodology is structed in four main pillars [3]:

- **Pillar 1** - Material break down decomposition
- **Pillar 2** - Selection of the relevant variables for each “X” material property dimensions and material KPI (characteristics or parameters)
- **Pillar 3** - Simple Visual Management elements

- **Pillar 4 –** Calculation of aggregated effectiveness assessment of technical material performance and material process production efficiency along the life cycle macro-phases.

In Figure 1 it is presented the Material Design-for-X multi-dimensional diagram, with an overview for the material life cycle key macro-phases and material properties "X" examples [3, 10, 17, 18].

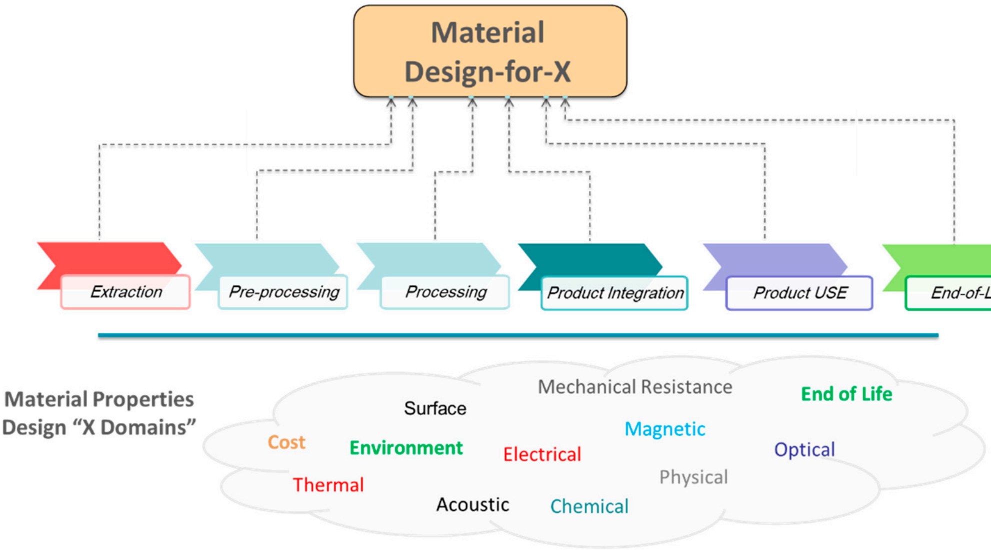

Figure 1. Material Design-for-X multi-dimensional diagram overview regarding material life cycle key macro-phases and material properties "X" examples.

2.2. Materials Use Case Characterization

To produce the standard, hybrid and bio-based composite sandwich panels, it was used commercially available two-component epoxy (Biresin CR83/CH 83-6, SIKA) resin, glass (+45°/-45°, 450 g/m^2, Castro Composites) and basalt (+45°/-45°, 450 g/m^2, Castro Composites) fabrics and 20 mm thick extruded polystyrene (XPS - ifoam®, IMPERALUM) core. The main properties of the raw-materials, as supplied by the manufacturer, are displayed in Table 1 (the indicated properties are based on the supplier's data sheets and information and on the Granta database) [19].

Table 1. Main properties of the raw-materials.

Properties		Matrix	Fibre		Core
		Epoxy	Glass	Basalt	XPS
Tensile strength (MPa)		91,0	1 990,0	3 165,0	0,3
Tensile E-Modulus (GPa)		3,2	78,5	90,5	5,2
Elongation at break (%)		8,4	5,3	3,2	4,0
Density (g/cm^3)		1,2	2,5	2,7	0,03
Glass transition temperature (°C)		80,0	-	-	-
Thermal conductivity (W/m·°C)		0,2	1,3	0,04	0,03
Max. service temperature (ºC)		130,0	355,0	675,0	80,0
Cost		19,1 €/kg	6,5 $€/m^2$	13,0 $€/m^2$	4,0 $€/m^2$
Primary production	Energy (MJ/kg)	128,5	51,8	0,9	87,8*
	CO_2 (kg/kg)	6,6	3,0	0,1	2,4*
	Water (l/kg)	28,0	296,0	13,7	456,0*
Recycle fraction Currently (%)		0,7	0,1	-	1,0*
Production in Europe (Yes/No)		Yes	Yes	Yes	Yes

* Based on data relating to Expanded Polystyrene (as it is a similar material), as the Granta database does not have information on XPS.

2.3. Experimental Procedure

The composite laminates, were produced by vacuum infusion using several layers of glass or basalt fabric, to achieve a thickness of around 2 mm. The epoxy resin system was mixed at room temperature and degassed for 10 minutes prior to use, to minimize the presence of air bubbles and, therefore, potential voids and defects in the final composite. After the application of the release agent, positioning of the peel ply, infusion mesh, spiral, tubes, vacuum bag and sealant tape, a vacuum pressure of 500 mbar was set, and a leak test was performed. Subsequently, the inlet valve was opened and the resin started to flow through the layers of fibre fabrics. The composites were cured at room temperature for ~16h and post cured at 70 °C for 10h, keeping the vacuum pressure till the end of the procedure. The MCS were prepared using the same conditions, with 4 layers of fibre fabric both on top and at the bottom of the core material (Figure 2). After the produced laminates and sandwich panels were machined into different specimens for further characterization.

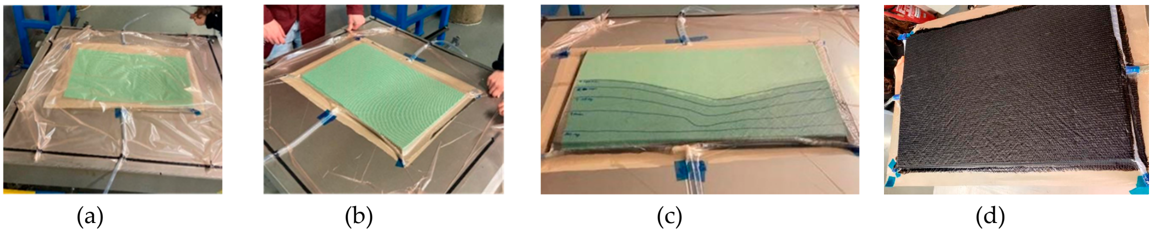
(a) (b) (c) (d)

Figure 2. Vacuum infusion process: (a) preparation before applying the vacuum; (b) leak test; (c) resin flow through the layers of fibre fabrics; (d) final panel.

2.4. Test procedures

The composites (laminates and MCS) physical, thermal, and mechanical properties were assessed by several characterization techniques. The sustainability of developed solutions was also characterized by using CES EduPack eco audit tool.

2.4.1. Laminates Characterization Methods

The standard ASTM D 792 (Method A) with an analytical scale (Radwag AS 220.R2) was used to determinate the laminates density.

The fibre volume fraction was measured by burning the matrix at 625 °C in a muffle furnace (SNOL 3/1100) over 90 minutes, in accordance with ASTM D 3171- G.

The DSC tests were performed to determine the thermal behaviour of the laminates and it were carried out following ISO 11357, using a TA Instruments (model Q20) with cooling system coupling RCS90. All experiments were conducted under an inert atmosphere (nitrogen at flow rate of 50 mL/min), to prevent oxidative degradation. The samples were heated from 50 to 150 °C, cooled down to 50 °C and heated again to 150 °C at 10 °C/min.

To determine the in-plane shear stress, the specimens were characterized based on ISO 14129. Before mechanical testing, the specimens were painted to measure the full-field strain over their surface using digital image correlation (DIC). A universal testing machine (Instron 5900R) with a 100 kN load cell were used. The samples were tested under tensile mode at a speed of 2 mm/min, and a distance between grips of 136 mm. DIC was used to record all experiments, allowing the visualization of cracks formation and propagation during mechanical solicitation.

2.4.2. Sandwich Panels Characterization Methods

Three-point flexural test was performed in a Instron 5900R Universal Testing Machine, according to ASTM C 393/ C3939 M, with 100 kN load cell and at a constant loading rate of 6 mm/min. The dimensions of the specimens for the three-point flexural test were 200 mm × 75 mm.

Edgewise compression test was performed in a Instron 5900R Universal Testing Machine, according to ASTM C 364/C 364-M, with a 100 kN load cell and at a speed of 0.5 mm/min. The specimens with 160 mm × 40 mm were subjected to a compression force parallel to the plane of the laminates.

The composite sandwich panels' density was calculated based on the ASTM C271, by using a digital calliper (150 mm ProK) and a Radwag Scale AS 220.R2.

The thermal properties of the sandwich panels, specifically the heat transfer coefficient was calculated through the thermal conductivity divided by the thickness of each layer of material making up the sandwich panel [20].

To analyse the sustainability of the developed composite solutions, it was used the CES EduPack eco audit tool (at material level, since the process to manufacture the composites is the same). This software allows the analysis of the energy consumption and carbon footprint of each sandwich panel for the whole life cycle, without exploring every parameter [21].

3. Results

3.1. Laminates properties

Data test results performed to the laminates are summarized in Table 2. The presented values represent the average results and correspondent standard deviations.

Table 2. Data test results of the developed laminates.

Test	Properties	Epoxy + Glass Fibre	Epoxy + Basalt Fibre
Density	**Composite density (g/cm^3)**	1,7 ± 0,0	1,8 ± 0,1
Constituent Content	**Fibre volume (%)**	47,4 ± 3,2	46,0 ± 2,0
	Void volume (%)	5,4 ± 0,4	5,5 ± 1,8
DSC	**Glass transition temperature (°C)**	82,4 ± 0,4	84,2 ± 5,0
In-plane shear	**In-plane shear strength (MPa)**	47,9 ± 2,3	342,3 ± 2,4
	Shear modulus (GPa)	1,7 ± 0,1	3,2 ± 0,1
Cost	**Price (€/m^2)**	19,1	34,6
Sustainability (Material level)	**Energy (MJ)**	80,2	41,6
	CO_2 Footprint (kg)	4,3	2,14

3.2. Sandwich panels properties

Data test results performed to the sandwich panels are summarized in Table 3. The presented values represent the average results and correspondent standard deviations.

Table 3. Data test results of the sandwich panels.

Test	Properties	Epoxy + Glass Fibre + XPS Core	Epoxy + Basalt Fibre + XPS Core
Flexural Test	**Core shear ultimate strength (MPa)**	0,2 ± 0,0	0,2 ± 0,0
	Facing stress (MPa)	29,7 ± 2,0	28,6 ± 1,0
	Modulus of elasticity in bending (MPa)	307,5 ± 25,3	331,0 ± 5,1
Compression Test	**Ultimate edgewise compressive strength (MPa)**	32,2 ± 10,6	30,1 ± 5,3
Density	**Composite sandwich panel density (g/cm^3)**	0,2 ± 0,0	0,2 ± 0,0
Thermal isolation	**Heat transfer coefficient (W/m^2 ºC)**	0,1	0,1
Cost	**Price (€/m^2)**	42,1	69,2
Sustainability	**Energy (MJ)**	153,0	120,0

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(Material level)	**CO₂ Footprint (kg)**	7,2	5,3

3.3. Material-Design-for-X results assessment of the developed composites

The different effectiveness scorecards with different KPIs and results, for each property X of the Material-Design-for-X methodology, are presented from Figure 3 to Figure 5.

M-DfX Scorecard X1: Mechanical Properties	Glass Fibre	Basalt Fibre
Overall Effectiveness	83%	87%
KPI1 Young's Modulus (GPA)	87%	100%
KPI2 Tensile Strength (MPa)	63%	100%
KPI3 Elongation (% strain)	100%	60%

M-DfX scorecard X2: Thermal Properties	Glass Fibre	Basalt Fibre
Overall Effectiveness	28%	100%
KPI1 Maximum service t (ºC)	53%	100%
KPI2 Thermal conductivi (W/mºC)	3%	100%

M-DfX scorecard X3: Physical Properties	Glass Fibre	Basalt Fibre
Overall Effectiveness	100%	93%
KPI1 Density (g/cm³)	100%	93%

M-DfX scorecard X4: Cost	Glass Fibre	Basalt Fibre
Overall Effectiveness	100%	50%
KPI1 Price (€/kg)	100%	50%

🟩 Efectiveness [100 - 90%]
🟧 Efectiveness [69 - 40%]
🟨 Efectiveness [89 - 70%]
🟥 Efectiveness [0 < 40%]

Figure 3. M-DfX Scorecards Effectiveness for the glass and basalt fibres.

M-DfX Scorecard X1: Mechanical Properties	Glass Fibre Laminate	Basalt Fibre Laminate
Overall Effectiveness	34%	100%
KPI1 In-plane shear strength (MPa)	14%	100%
KPI2 Shear modulus (GPa)	53%	100%

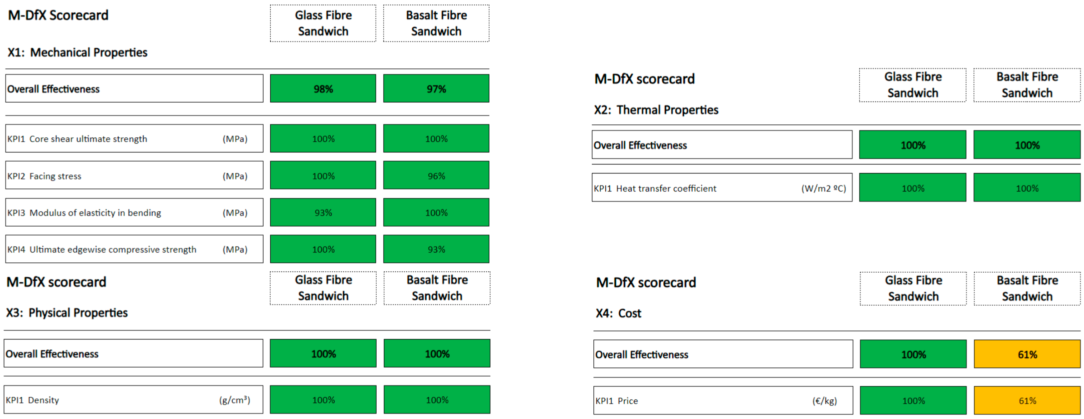
M-DfX Scorecard X2: Thermal Properties	Glass Fibre Laminate	Basalt Fibre Laminate
Overall Effectiveness	98%	100%
KPI1 Glass transition temperature (ºC)	98%	100%

M-DfX scorecard X3: Physical Properties	Glass Fibre Laminate	Basalt Fibre Laminate
Overall Effectiveness	99%	98%
KPI1 Density (g/cm³)	100%	94%
KPI2 Fibre volume (%)	98%	100%
KPI3 Void volume (%)	100%	98%

M-DfX Scorecard X4: Cost	Glass Fibre Laminate	Basalt Fibre Laminate
Overall Effectiveness	100%	55%
KPI1 Price (€/m2)	100%	55%

🟩 Efectiveness [100 - 90%]
🟧 Efectiveness [69 - 40%]
🟨 Efectiveness [89 - 70%]
🟥 Efectiveness [0 < 40%]

Figure 4. M-DfX Scorecards Effectiveness for the glass and basalt laminates.



M-DfX Scorecard X1: Mechanical Properties	Glass Fibre Sandwich	Basalt Fibre Sandwich
Overall Effectiveness	98%	97%
KPI1 Core shear ultimate strength (MPa)	100%	100%
KPI2 Facing stress (MPa)	100%	96%
KPI3 Modulus of elasticity in bending (MPa)	93%	100%
KPI4 Ultimate edgewise compressive strength (MPa)	100%	93%

M-DfX scorecard X2: Thermal Properties	Glass Fibre Sandwich	Basalt Fibre Sandwich
Overall Effectiveness	100%	100%
KPI1 Heat transfer coefficient (W/m2 ºC)	100%	100%

M-DfX scorecard X3: Physical Properties	Glass Fibre Sandwich	Basalt Fibre Sandwich
Overall Effectiveness	100%	100%
KPI1 Density (g/cm³)	100%	100%

M-DfX scorecard X4: Cost	Glass Fibre Sandwich	Basalt Fibre Sandwich
Overall Effectiveness	100%	61%
KPI1 Price (€/kg)	100%	61%

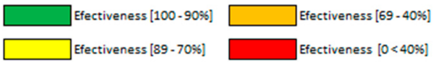
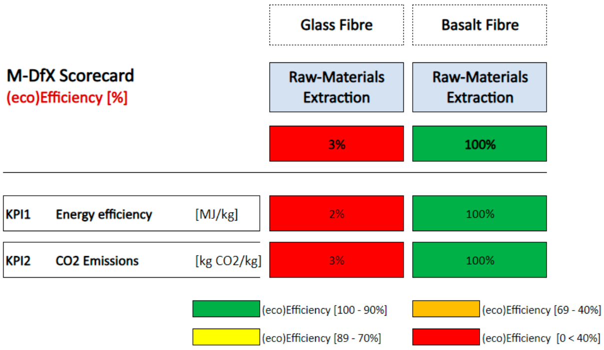

🟩 Efectiveness [100 - 90%] 🟧 Efectiveness [69 - 40%]
🟨 Efectiveness [89 - 70%] 🟥 Efectiveness [0 < 40%]

Figure 5. M-DfX Scorecards Effectiveness for the glass and basalt sandwich panels.

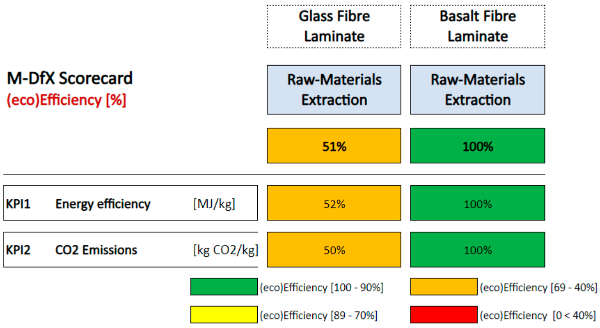
The different scorecards of (Eco)Efficiency with different KPIs, and results, for each property X of the Material-Design-for-X methodology are presented from Figure 6to Figure 8.



M-DfX Scorecard (eco)Efficiency [%]			Glass Fibre Raw-Materials Extraction	Basalt Fibre Raw-Materials Extraction
			3%	100%
KPI1	Energy efficiency	[MJ/kg]	2%	100%
KPI2	CO2 Emissions	[kg CO2/kg]	3%	100%

🟩 (eco)Efficiency [100 - 90%] 🟧 (eco)Efficiency [69 - 40%]
🟨 (eco)Efficiency [89 - 70%] 🟥 (eco)Efficiency [0 < 40%]

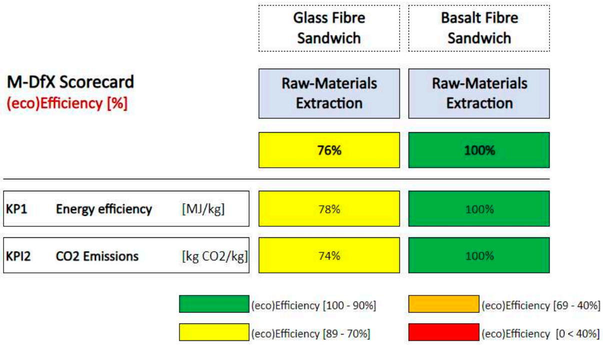
Figure 6. M-DfX Scorecards (Eco)Efficiency for the glass and basalt fibres.



M-DfX Scorecard (eco)Efficiency [%]			Glass Fibre Laminate Raw-Materials Extraction	Basalt Fibre Laminate Raw-Materials Extraction
			51%	100%
KPI1	Energy efficiency	[MJ/kg]	52%	100%
KPI2	CO2 Emissions	[kg CO2/kg]	50%	100%

🟩 (eco)Efficiency [100 - 90%] 🟧 (eco)Efficiency [69 - 40%]
🟨 (eco)Efficiency [89 - 70%] 🟥 (eco)Efficiency [0 < 40%]

Figure 7. M-DfX Scorecards (Eco)Efficiency for the glass and basalt laminates.



M-DfX Scorecard (eco)Efficiency [%]			Glass Fibre Sandwich Raw-Materials Extraction	Basalt Fibre Sandwich Raw-Materials Extraction
			76%	100%
KP1	Energy efficiency	[MJ/kg]	78%	100%
KPI2	CO2 Emissions	[kg CO2/kg]	74%	100%

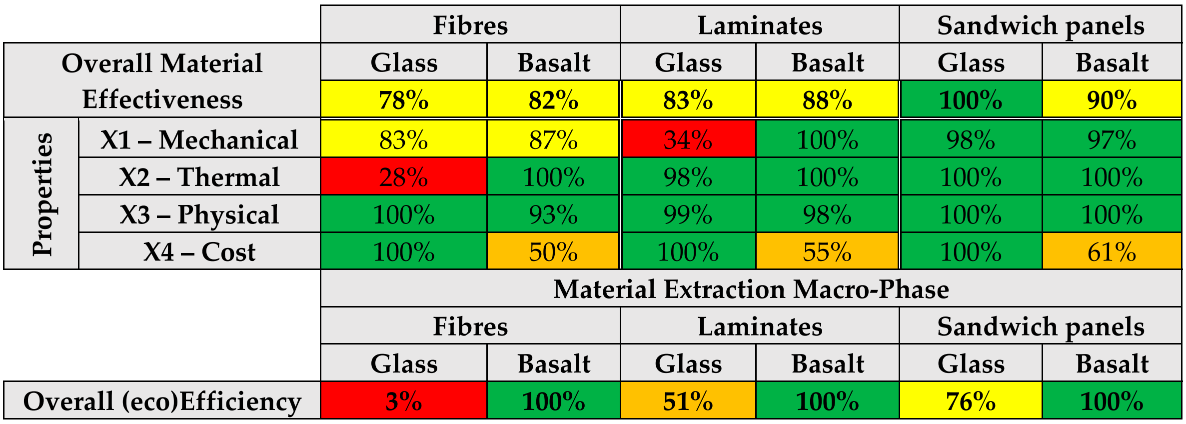
🟩 (eco)Efficiency [100 - 90%] 🟧 (eco)Efficiency [69 - 40%]
🟨 (eco)Efficiency [89 - 70%] 🟥 (eco)Efficiency [0 < 40%]

Figure 8. M-DfX Scorecards (Eco)Efficiency for the glass and basalt sandwich panels.

Material-Design-for-X results of the raw-materials (fibres, since the other materials are the same), laminates and sandwich panels are summarized in Table 4. As the life cycle of the material production macro-phases is similar between materials and composites, the focus of this work was only on the raw materials extraction phase, since this phase is very different between glass and basalt fibres and composites. Furthermore, the information availability to map with detail more eco-efficiency oriented KPIs is still scarce to the basalt fibres.

Table 4. M-DfX results.

Material Comparison M-DfX Scorecard – Extraction Phase



		Fibres		Laminates		Sandwich panels	
Overall Material Effectiveness		**Glass**	**Basalt**	**Glass**	**Basalt**	**Glass**	**Basalt**
		78%	**82%**	**83%**	**88%**	**100%**	**90%**
Properties	**X1 – Mechanical**	83%	87%	34%	100%	98%	97%
	X2 – Thermal	28%	100%	98%	100%	100%	100%
	X3 – Physical	100%	93%	99%	98%	100%	100%
	X4 – Cost	100%	50%	100%	55%	100%	61%
		Material Extraction Macro-Phase					
		Fibres		**Laminates**		**Sandwich panels**	
		Glass	**Basalt**	**Glass**	**Basalt**	**Glass**	**Basalt**
Overall (eco)Efficiency		**3%**	**100%**	**51%**	**100%**	**76%**	**100%**

To better understand the relation between the Material Effectiveness vs. (Eco)Efficiency of the results obtained, this relationship is presented in quadrants through the Figure 9 to Figure 11.

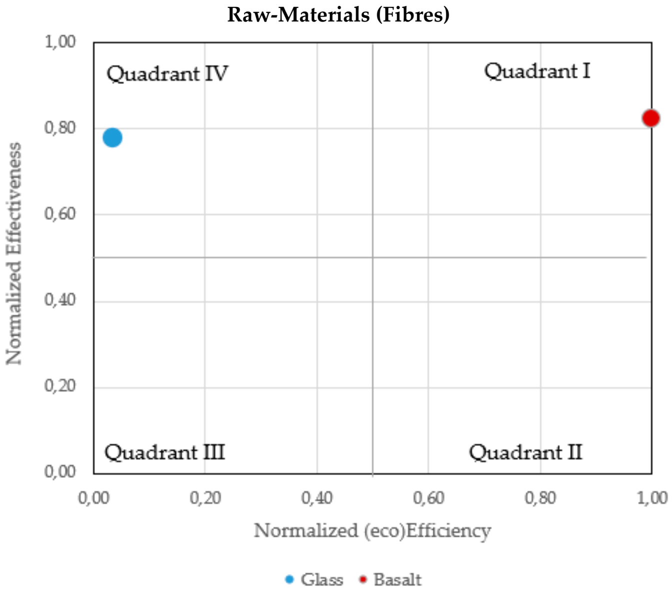


Figure 9. Quadrants Diagram - Material Effectiveness vs. (Eco)Efficiency of the fibres.

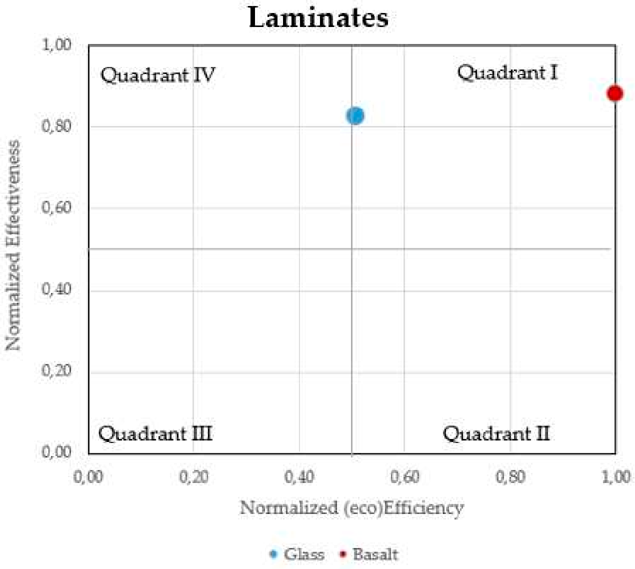


Figure 10. Quadrants Diagram - Material Effectiveness vs. (Eco)Efficiency of the laminates.

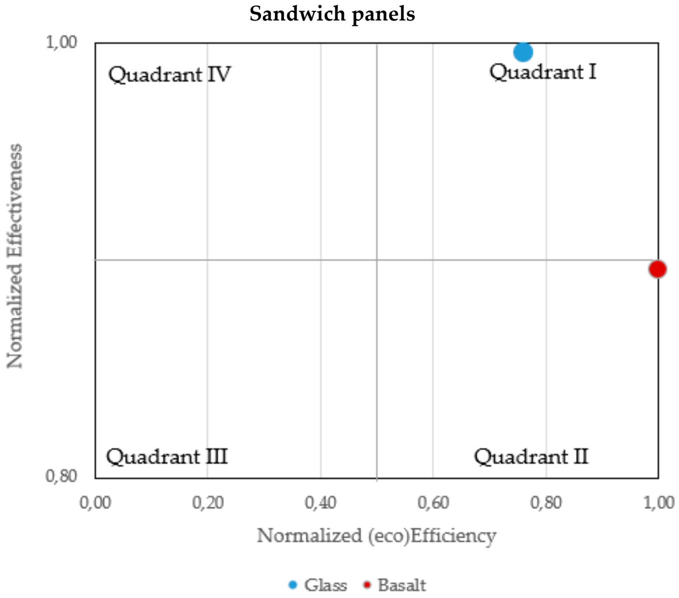


Figure 11. Quadrants Diagram - Material Effectiveness vs. (Eco)Efficiency of the sandwich panels.

4. Discussion

When analysing the properties of the fibres only, it is observed that, in terms of all properties and sustainability, basalt fibres represent the best compromise solution. However, in terms of costs they are around 50% more expensive than glass fibres. By simply comparing the relative results of the laminates, it is possible to verify that the density of the glass laminate is slightly lower than the counterparts containing glass fibres (-6%) as expected. Considering that the basalt fibres are denser, the fibre volume fraction of the produced glass composites are also a little higher (+3%) and the void content is more a less the same in both laminates. Moreover, the DSC experiments revealed that the basalt laminate, contrary to the glass counterparts, achieve higher glass transition temperature than the one presented in the resin datasheet (80 °C), what can lead to better properties. The most significant differences between the two laminates are in mechanical properties (the basalt laminate has an in-plane shear strength 86% and a shear modulus 47% higher than the glass laminate). Regarding cost, the basalt laminate is 45% more expensive comparatively to the glass laminate. With respect to sustainability, the glass laminate has an environmental footprint around 50% higher when compared with the basalt laminate.

The differences in the properties of sandwich panels are not so noticeable between panels, since the material that most influences their final properties is the core. However, when we analyse costs and environmental sustainability, it is clearly observed that the basalt fibre sandwich panel is more expensive (+39%) and has a smaller environmental footprint (-32%). It must be stand out that regarding the sustainability study, since GRANTA Edupack 2021 software does not consider XPS, a similar material, expanded polystyrene (EPS) was used.

In the M-DfX analysis it was adopted the "relative best" approach to the normalization of the effectiveness ratios, and for the (eco)efficiency along the macro-phases selected [3]. For the fibres, laminates and sandwich panels diverse number of characteristics were selected for each proprietary, being the ones that were considered the most relevant for the project design. The aggregated results for all "X properties" and the studied materials was made. The overall result is different in the three kinds of materials studied, being possible to observe that the basalt fibres, basalt laminates and glass sandwich panels have a higher overall material effectiveness. The basalt fibres have general better properties that lead to better characteristics of the basalt laminates. However, the same does not happen in the sandwich panel, since the core has a higher contribution to the final properties, leading to the sandwich panel with glass fibres having overall higher properties, due to the impact of the cost. For the (eco)efficiency analysis four KPI were selected: Energy Efficiency, CO_2 Emissions and H_2O consumption (only for the fibres). It was only possible to map these KPI for the Raw Material

Macro Phase, due to the absence of data available, especially for the basalt composites. Besides, since both laminates and sandwich panels are processed by vacuum infusion, the production phase was not considered. The basalt fibres and composites perform much better than the glass fibres and composites, with significant better results for the material production raw material macro-phase life-cycle.

5. Conclusions

With the goal of finding a sustainable product for the construction sector, it was proposed the use of composite sandwich panels. In this research, several properties of the developed solutions, by vacuum infusion, were evaluated as well as their sustainability. It was also applied an innovative holistic analysis, Material Design-for-eXcellence Framework, to evaluate the materials performance with a multi-dimensional assessment for the material properties, relating to the inner structure of the material in a multi-scale proposition, and supported by a life-cycle engineering mind-set for different macro-phases assessment of eco-efficiency oriented KPIs. It was possible to compare, for the first time with M-DfX methodology the glass fibres-based materials with the basalt fibres-based materials, for three different materialization macro composite materials (original fibres, laminate material and sandwich), exploring more definitions on M-DfX composition for material comparisons and the quadrant diagram results complementary analysis.

In this work, it was possible to observe via the M-DfX methodology that the basalt-based composites are a bio-based solution that could be a good sustainable alternative for construction sector and for others. Every day researchers are creating more new materials, having a diversity of properties at different scales. Material Design-for-eXcellence must also in the near future consider other factors such the properties technical assessment along scale integration (for instance, from micro to meso, and from meso to macro-scale). Hence, additional studies are thus foreseen to explore and develop more this new methodology, compiling more material individual characterization (more X-Properties and detailed life-cycle eco-efficiency macro-phases assessment), and also comparisons and cross-assessment for different material families.

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