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DESIGN OF A COMPETITIVE WOOD-BASED INSULATION PRODUCT WITH INNOVIZATION

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Abstract:

Industrial processes from the textile industry and adapted to use wood fibers, have recently led to the development and marketing of products with high thermal insulation properties. These products based on wood, vegetable or animal fibers, currently represent 5% of the French market for house insulationmaterials. The main insulation materials are glass-wool, expanded polystyrene and mineral-wool. Among them, the wood-based products have a strong development potential, with 2.3% of the total market for insulating materials for the building envelope. This market share is expected to continue increasing by 2020. Drawing on this, the recently completed ECOMATFIB project focused on the optimization of the manufacture of existing wood-based insulation materials and on the eco-design of innovative multifunctional composites with optimized performances. This project was supported by ADEME and lead by FINSA Morcenx, a manufacturer of MDF. A consortium of scientific and industrial experts was drawn together so that all the knowledge domains needed to develop optimized insulation materials based on wood were covered. These domains embraced the whole production chain of materials, processes, structure, performance and end of life. The focus was primarily on materials of very low density for insulation and adapted to an existing partner industrial facility. The design process helped the decision makers choose the relevant parameters all along the manufacturing process and consequently has focused on answering the question: "How to support the eco-design of a bio-sourced insulation product using existing knowledge and interactive decision-making?" Results consist of several contributions: a methodology of material design; a causal map linking the optimization objectives (minimize thermal conductivity, economical cost and carbon cost) to the decision variables of the problem (density, fibre fineness etc); modelling of the objective functions; optimal solutions of the multi-objective optimization problem and exploration tools to interactively obtain the decision maker preferences; design rules; and an optimal solution meeting expectations of industrial goals and with thermal properties close to those of fiberglass insulation products.

Key words: *interactive optimization; insulation; wood fibr; eco-design methodology.*

INTRODUCTION

Wood composite material production is important in the French economy, with at least 5.3 million cubic meters of wood panels produced in 2016 (FCBA, Memento 2017). Nevertheless, wood-based insulation products represent a very small market share of insulation products in France, with less than 2.3% of the market, which is dominated by mineral-based wool and cellular plastic products. To change this situation, several issues linked to the technical, environmental and economical performances should be overcome. The price of wood-fibre insulation boards is also a key point, since their price is on average twice that of other common insulation materials. The optimization of the three main performance indicators previously mentioned could convince consumers to change and this was the starting point of this work done in the context of the ECOMATFIB project (50% funded by ADEME[*]). The main goal of this project was to improve or develop wood-fibre insulation products through a partnership between two companies (FINSA France, STEICO France), a French technical institute called the FCBA and 3 laboratories (I2M in Bordeaux, Institut P' in Poitiers and LIMBHA ESB in Nantes). This consortium of scientists and industrials was drawn together so that all the knowledge domains needed to develop optimized insulation materials based on wood were theoretically covered. These domains embraced the whole production chain of materials, processes, structure, performance and end of life. The focus was primarily on materials of very low density for insulation and adapted to a current partner industrial facility. The design process used facilitated the interaction between the decision makers about optimization parameters all along the manufacturing process and consequently focused on somehow answering the question: "*How to support the eco-design of a bio-sourced insulation product using existing knowledge and interactive decision-support making*?" This paper focuses on a specific approach that can be applied to a wide range of different engineering problems. At each step, knowledge collected and generated for this particular application, wood-fibre insulation boards, will be shown.

MATERIALS AND METHODS

Material

In order to understand the results of the whole approach, a short description of the experimental work will be presented. It is voluntarily not complete, because information can be found in other publications such as (Hobballah 2018, Vignon et al 2016, Délisée et al. 2017). For this study, the manufacture of wood-fiber insulation board was divided into the following six process steps (Fig. 1): (1) chip defibration; (2) fibre drying; (3) fibre mat forming; (4) hot-low-pressing of the fibre mat in oven; (5) sizing and packaging and (6) transport to the client. Four wood species, chosen according to their availability in the southwest of France, were tested: maritime pine (*Pinus pinaster)*, loblolly pine (*Pinus taeda*), poplar (*Populus spp)* and eucalyptus (*Eucalyptus spp).* Control of the defibring process at the laboratory scale permitted the production of several fibre sizes and to measure energy consumption. Six different energy levels, ranging from 36 to 215kWh/t, were used to generate fibre. The lowest energy resulted in sizes with an average diameter of 350µm whereas the highest energy loadings generated fine fibre with an average diameter less than 80µm). Mat-forming (Fig. 2) was done with an opening-napping machine (Laroche Cadette) in order to obtain a good mix of wood fibre and bicomponent plastic fibre that has a core of polypropylene and a sheath of polyethylene. The latter is used to thermally bind the fibre mix creating a fibre network. A hot air oven provided heat and applied a slight compression in order to calibrate the board thickness. The fibres are randomly orientated in the plane of the board and generally horizontal to the faces.

The performance was evaluated by measuring thermal conductivity (λ in $W.m^{-1}.K^{-1}$) and residual strain of the mat after pressing (ε_r in mm) (Vignon et al 2016, Délisée et al. 2017). The latter test is done because the thickness of these products tends to be reduced during storage and transport and the ability to recover thickness once installed is an important evaluation criteria.

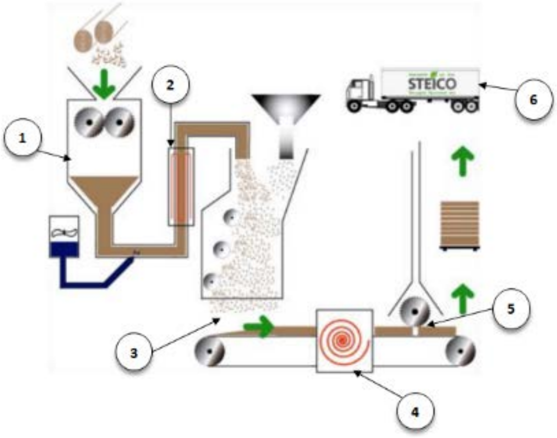

Fig. 1.
Fibre insulation mat production process (adapted from STEICO, Hobballah 2018).

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[*] French Environment & Energy Management Agency

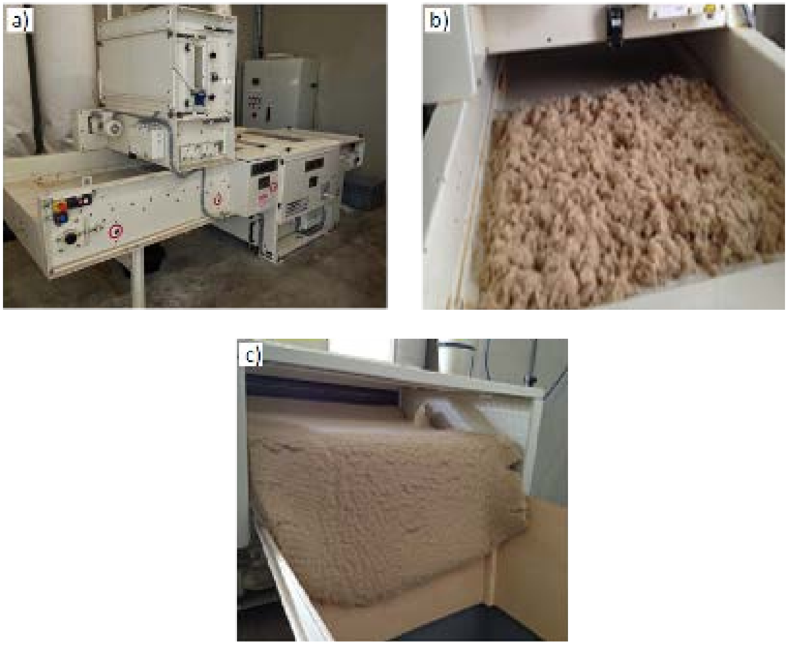

Fig. 2.
Experimental device for fibrous mat production (images provided by Pierre VIGNON of I2M, Bordeaux): (a) opening-napping machine overview, (b) feeding of raw materials and (c) output of the device.

Method

The optimization methodology used is based on the Vercellis pyramid (Vercellis 2011) and spiral model of NASA (1995). This interactive design approach (Hobballah 2018) integrates several methods at different steps of the process and the main goal is to help decision makers to participate and use the results of new material design. Fig. 3 shows the global approach for material design optimization. Different methods and literature review are associated at each step and this paper presents and discusses how knowledge on insulation wood-fibre boards from different sources can be combined to improve a product. The five-step methodology can be described as follows: collection of knowledge, mathematical modelling of elicited knowledge, implementation of a multi-objective optimization algorithm, mining and analysis of optimal solutions, aiding decision maker. The collection of available knowledge (based on elicitation techniques and sorting tools) is a necessary starting point for all designs in order to obtain a state of the art on the subject through knowledge models (scoping matrix, causal maps etc.). The knowledge models allow, among others, to facilitate the communication between the cognitician and the expert and to be able to perform an easy cross-validation by the experts of the knowledge collected during interviews, identify the variables and explain the relationships between the variables in view to facilitate the development of underlying mathematical models (equations, rules or algorithm). The mathematical modelling of collected knowledge exists mainly to express the design optimization problem as a multi-objective optimization problem that allows to optimize several conflicting objectives at the same time. The implementation of a multi-objective optimization algorithm can be done by choosing a relevant existing algorithm, if not by proposing an adapted new one. Metaheuristic algorithms are generally adapted to real-world multi-objective optimization problems and deliver a large number of optimal solutions. The mining and analysis of optimal solutions is for generating new relevant knowledge and providing a better understanding of the design problem. In the end, for aiding the decision maker to choose an optimal solution to achieve, decision technics (interactive optimization algorithm, decision algorithm) have to be used to help finding the decision maker's preferred solution. It is worth noting that this methodology is characterized by its general character; the choice of methods in each part of this methodology depends on the context of the design problem (Fig. 3).

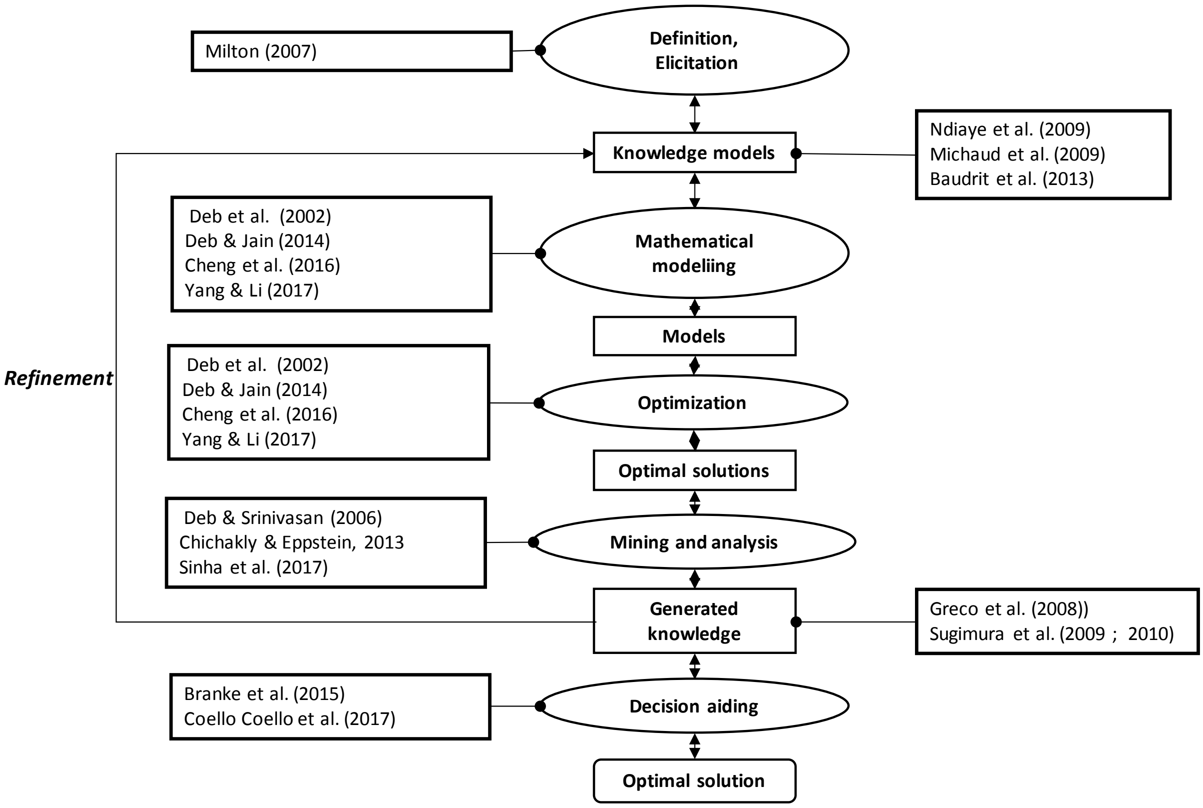

Fig. 3.
Methodology of multi-objective optimization design process (adapted from Hobballah 2018).

GLOBAL APPROACH: RESULTS AND DISCUSSION AT DIFFERENT STEPS

In this part, the main results obtained are highlighted and discussed.

Relationship between design and performance variables

The first step of knowledge modelling for this project is presented by the scoping matrix and the global causal map (Table 1 and Fig. 4). This kind of scoping allowed the group project to identify and define a consensus on how to manage the work regarding data collection and the orientation of specific experimental work in order to avoid critical lack of knowledge. For example, some production variables were identified as hard to obtain but very important in this case. Industrialists were involved in this project-from the beginning and advised on the production process, which was done at the laboratory scale, using more or less industrial parameters.

Elicitation techniques, mainly semi-structured interviews, were conducted with the experts following a knowledge collection methodology (Hobballah et al. 2018); the result is a causal map that encompasses the knowledge collected from all the project experts. This causal map contains manufacturing and raw material variables that influence the optimization objectives. An example of existing knowledge in this causal map is the value of the insulation capacity of the product via its thermal conductivity, which is influenced by the fineness of the fibers. The expert on the thermal performance of materials asserted that this variable has a major influence on the insulation performance of the product. As it is a light material, the influence of the thermal properties of the raw material on the thermal conductivity of the material is negligible. However, even though the fine fibers are better in terms of insulation capabilities, the use of fine fibers can create different problems. According to the expert in mechanical behavior of fibrous materials, the fine fiber is more sensitive to compression and, therefore, a material made with fine fibers may not regain its original thickness when compressed. In this example, it is clear that the use of fine fibres has conflicting effects on the performance of the product and such conflicts are easily seen when using mapping tools, which facilitate the communication of complex design problems (Fig. 4). Then optimization can be defined as simultaneously optimising: thermal conductivity, thickness recovery, production costs and environmental impact.

Table 1

Scoping matrix of this project for wood-fibre insulation board optimization (Hobballah et al. 2018)

		Difficulty		
		Easy	Medium	Hard
Importance	Very important	Mechanical properties	Raw materials	Production Variables
	Medium importance	Wood fiber production	Hygroscopicity of wood	Environmental impact
	Less important	Thermal properties	Image processing	Glue Wood panel production

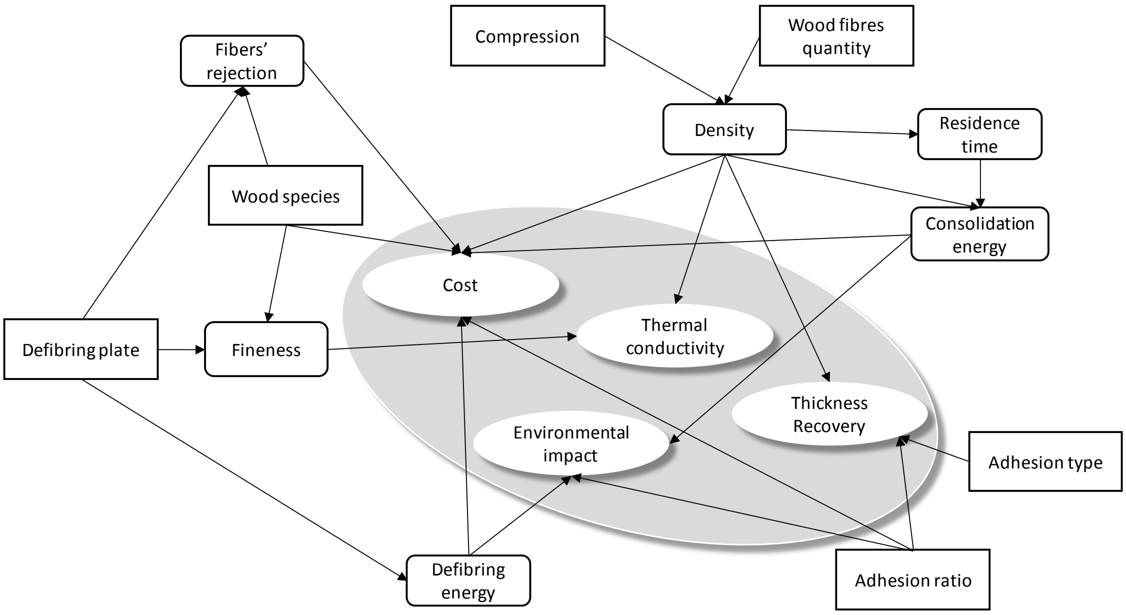

Fig. 4.
Global causal map wood-fibre insulation board (adapted from Hobballah 2018).

Modelling objective functions

Based on the previous step's work, each expert has been able to find or develop a model of the objective function that can be reliable with knowledge acquisition. This formulation in mathematical models is a key point for further mathematical optimization. Equations directly established from the causal map are:

$$\begin{aligned}
&\text{Min } \lambda = F\left(d(C_{\%}, q_w), f_w(T_w, P_d)\right)\\
&\text{Min } \varepsilon_r = F\left(T_a, q_a, f_w(T_w, P_d), d(C_{\%}, q_w)\right)\\
&\text{Min } C = F\left(f_r(P_d, T_w), q_a, T_w, E_d(d_p), E_c\left(t_r\left(f_w(T_w, P_d), d(C_{\%}, q_w)\right)\right)\right)\\
&\text{Min } \omega = F\left(q_a, E_d(d_p), E_c\left(t_r\left(f_w(T_w, P_d), d(C_{\%}, q_w)\right)\right)\right)\\
&\text{Subject to}\\
&\quad d(C_{\%}, q_w) \le 60\ kg/m^2\\
&\quad f_r(P_d, T_w) \le 15\%
\end{aligned} \qquad (1)$$

where:

	Symbol	***Definition***
Optimization objectives	C	Production costs
	ε_r	Compressibility
	λ	Thermal Conductivity
	ω	Environmental impact (IE)
Decision variables	$C_{\%}$	Compression ratio
	ρ	Density
	E_c	Consolidation energy
	E_d	Defibering energy
	f_w	Fibre fineness
	f_r	Fiber's rejection ratio
	P_d	Defibering disk diameter
	q_a	Synthetic fiber's quantity
	q_w	Wood fiber's quantity
	T_a	Synthetic fiber type
	t_r	Time in oven
	T_w	Wood fiber's type

Using experimental results, mathematical models of the objective function were established. One might note that due to insufficient knowledge being obtained on the compressibility and recovery of the insulation products, this objective was omitted from further exploration and thus was not put in the optimization algorithm. The mathematical objective functions are the following (Eq 2):

$$\begin{aligned}
&\mathrm{Min}\,\lambda\ \ with\ \ \lambda = 0{,}2572T^{-9{,}97} + 0{,}17\rho^{0{,}24}(1 + 0.1883T) + \frac{4\sigma T^3}{1.25 + \beta\rho} \\
&\mathrm{Min}\,C\ with\ \ C = E_d \cdot C_{elec} + E_{\mathrm{c}} \cdot C_{gaz} + q_w \cdot C_w + q_a \cdot C_a + D_{tran} \cdot \frac{C_{tran}}{N_{matelas}} \\
&\mathrm{Min}\,IE\ with\ \ IE = E_d \cdot Ca_{elec} + E_{\mathrm{c}} \cdot Ca_{gaz} + q_w \cdot C_w + q_a \cdot C_a + D_{tran} \cdot \frac{Ca_{tran}}{N_{matelas}} \\
&\text{subject to}\ R = 7
\end{aligned} \tag{2}$$

where $= 1.8 \cdot f_w^{-1.5} + 3.086$ *;* T=293.15°K; C_i and Ca_i economical and carbon costs, respectively; D to take transport into account and $N_{matelas}$ is the number of products inside a 70m^3 lorry (Délisée et al. 2017).

Optimal solution and interactive exploration

It is important to specify that all comparisons have been made on one single unit corresponding to 1m^2 of insulation board with a thickness, *e,* giving a thermal resistance of 7m²K/W (according to French standard RT2020) and delivered by trucks of 70m^3. STEICO's insulation material made from *Pinus pinaster* fibre has been taken as reference product.

An evolutionary multi-objective optimization algorithm was developed (called RNSEA, Hobballah 2018) to calculate the optimal solutions of the problem. The optimization results contained by the so-called Pareto Front, a front in the objective space that contains the non-dominated solutions i.e. solutions such that there are no other solutions in the objective space better than them, with regard to all objectives together. In order to obtain a better understanding of the effect of the wood fiber fineness, different values of fiber fineness, f_w, were fixed in the mathematical models (PM2 to PM5 in the Fig. 5). Again, one can see that due to preliminary results a focus on *Pinus pinaster* (PM) with different morphology has been done. Refiner energy progressively increases and, therefore, fibre finess also increases from PM2 to PM5.

Fig. 5 clearly depicts a strong trend confirming that morphology (and by the way tortuosity) of fibre is a key parameter for wood-fibre insulation product optimization. Although the "classic" representation of the optimal solutions may give some insights on the nature of the optimal solutions, it is still not very readable by a decision maker. Data mining and visualization methods may be used to provide a more human-readable and more intuitive form of visualization.

The first form is a design rule, consisting of a mathematical equation (Eq 3) that provides the decision maker with a method for calculating the value of the objective function with the other objective in a simple way, allowing the decision maker to test different preferences and see the cost induced on all of the objectives chosen to fix one of them.

$$C - 26.61 * \lambda - 0.6466 * IE + 0.472 = 0 \tag{3}$$

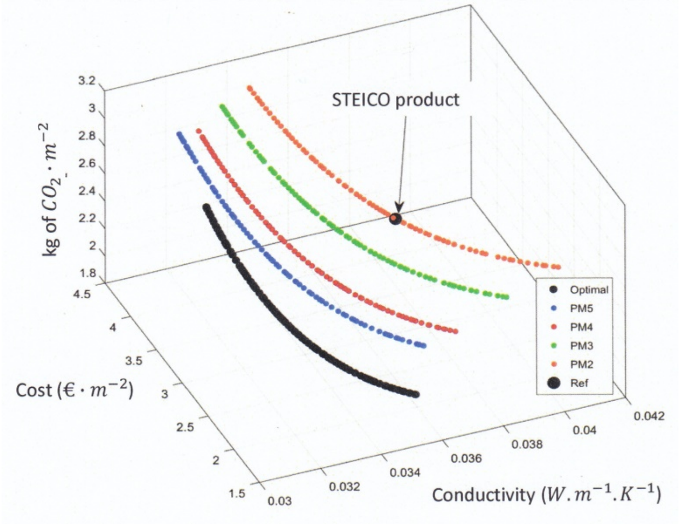

Fig. 5.
Optimal solutions for minimizing three objectives (Pareto front in black, and others optimum front for fixed fibre finess).

The other proposed form is a decision tree (Fig. 6). The decision tree provides an intuitive visualization that allows to view explicitly how optimal solutions can be obtained. In this case, wood fineness had major influence on optimal solutions as it is shown in the decision tree: any other value than the maximal fineness value will induce a sub-optimal solution.

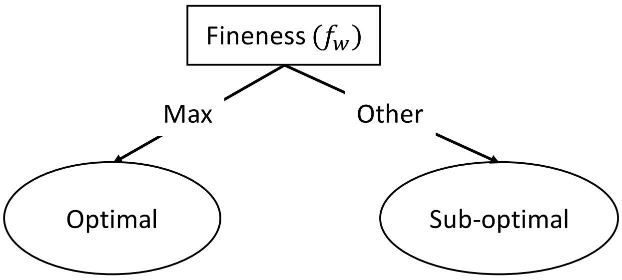

Fig. 6.
Decision tree for the insulation wood-fibre board designing process.

Finally, after a sampling process (clustering method) to define representative optimal solutions of the Pareto front, only six solutions can be observed. A direct comparison can then be done with the reference materials currently produced. Solutions 1, 4 and 5 are clearly better than the reference on all objectives, with a good balance for solution 4. More insights on data mining and analysis are provided in Hobballah (2018). For example, it is interesting to note that solution 1 is a 40kg·m^{-3} and 0.0321W·m^{-1}·K^{-1} compared to 50kg·m^{-3} and 0.0374W·m^{-1}·K^{-1} for the reference materials.

Table 2

Ratio of improvements expected for representative optimal solution regarding reference solution (adapted from Hobballah 2018)

Solution	***Conductivity***	***Economical Cost***	***Carbon Cost***
1	6%	21%	21%
2	15%	-17%	-5%
3	14%	-7%	1%
4	10%	12%	15%
5	13%	2%	8%
6	16%	-26%	-13%

CONCLUSION

This paper shows industrialists and researchers how to develop understanding in a specified field, namely wood-fibre insulation products. A global methodology of design and optimization has been developed with some examples of relevant calculation or optimization techniques and methods. Application of this methodology to the specific problem has permitted:

- The definition of design and state variables of the product material;
- The founding of relationships between performances and variables;
- The design of specific experiments to enlarge knowledge about the studied subject;
- The creation of model objective functions representative of thermal conductivity, economical cost and environmental impact of a wood-fibre insulation board;
- The identification of optimal solutions through a Pareto front, a simple visualization;
- The designation of relevant design rules that the decision-maker can further use in design reasoning.
- The design and test at laboratory scale of a wood-fibre insulation material with more than 15% improvement in thermal conductivity without deterioration of economical and environmental performances of a reference product.

Additional work has to be conducted to test the optimization of the production at the industrial-scale. From the point of view of innovation, this approach can be maximized with more freedom in problem formulation. In fact, including more options or parameters with fewer constraints leads to the exploration of an enlarged domain of solutions and allows breakthroughs due to this innovization process.

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