SB&WRC Project

Economic assessment of prototype 3 – Optimized wheat straw bale

June 2019

Abstract of the project

The SB&WRC *(Sustainable Bio&Waste Resources for Construction)* project, an undertaking of more than two years, aims to conceive, produce and test three innovative, low-carbon, thermal insulation materials from agricultural co-products and recycled waste. The project is supported by the development program Interreg France (Channel) England and is co-financed by the ERDF (European Regional Development Fund) for 69% of its total budget which is estimated to be 1.8M€ (including a 1.26M€ contribution from ERDF).

This project, led by Nomadéis, is carried out by a cross-channel partnership which gathers academic research laboratories, private research and consulting companies, manufacturers and professional non-profit organisation of the building sector:

- Nomadéis;
- Veolia Propreté Nord Normandie;
- University of Bath;
- Ecole Supérieure d’Ingénieurs des Travaux de la Construction de Caen (ESITC Caen);
- Construction 21;
- UniLaSalle;
- University of Brighton;
- Alliance for Sustainable Building Products.

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List of acronyms and abbreviations

Acronyms

- LCA: Life-cycle assessment
- SB&WRC: Sustainable bio and waste resources for construction
- SME: Small and medium enterprises

Abbreviations

- H: hour
- K: Kelvin
- kg: kilogram(s)
- m: metre(s)
- W: Watt
- t: ton(s)
- λ: thermal conductivity
- R: thermal performance

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1. Introduction

As part of the SB&WRC project, the technical, environmental and economic characteristics of the three low-carbon insulation materials prototypes for construction are assessed in order to gain a comprehensive and multi-dimensional understanding of their strengths and weaknesses. Many innovative products that are developed in research centres never reach the market because they are simply not price-competitive compared to existing products. The economic assessment aims to determine whether the three bio and waste-based insulation materials that were developed would be competitive relative to conventional, mineral-based insulation materials by estimating the selling price of the prototypes. It is also an opportunity to identify the factors that have a large impact on production costs and thus to devise cost-optimisation strategies. These results will be useful in the perspective of mass production and dissemination of insulation products on the market.

This report focuses on the prototype that consists in a straw-based insulation material for construction, developed by a team of researchers at the University of Bath in England. University of Bath devised a novel technique that orientates the straw stems of standard agricultural straw bales in a way that lowers thermal conductivity. These optimised straw bales are manufactured specifically as a non-load bearing insulation material for construction applications, used in conjunction with timber frames.

2. Methodology and data

The economic assessment of the insulation materials for construction is essentially a simulation exercise because these materials are not yet produced on a large scale given that they are still at the prototype stage. For the purposes of this study, we have conceived a representative and fictitious company that would manufacture the straw bale insulation material in France. Our aim is to explore how the company would produce the prototype, how much this would cost, and at what price the final good could be feasibly sold to consumers on the market, all from the perspective of this company.

Two different production scenarios have been identified for the prototype:

- A **small-scale scenario** that consists in re-baling standard straw bales to optimise the orientation of straw stems and hence thermal performance using a hydraulic press. The manufacturing process of this scenario is closely based on laboratory conditions.
- A **large-scale scenario** that involves adapting existing balers (agricultural machinery that compresses cut and raked crop into compact bales) so that they may directly produce bales with the required characteristics (stem orientation, size, density etc.).

It should be noted that the present analysis is a simulation exercise that relies on certain hypotheses and on available data. As an example, production scenarios may be further optimised. Thus, selling prices should not be taken at face value. However, these results give a good idea of the magnitude and distribution of production costs, and hence of the selling price under certain conditions.

The modelling methodology that was developed follows a bottom-up approach. First, unit costs of production were estimated based on a hypothetical production scenario. A realistic profit margin based on official INSEE data[1] (industry averages) was then added to the unit cost of production to provide the selling price of the prototype. Unit costs of production are computed in four stages:

1. The production process of the straw bale insulation material is broken down into its main steps: i) sourcing of raw materials ii) transformation of raw materials into the insulation material, iii) administrative, management and distribution costs. The amount of inputs required at each step is estimated (e.g. machinery, consumables, labour).

[1] INSEE (2016) Caractéristiques comptables, financières et d'emploi des entreprises - Ratios comptables au niveau groupe, *ESANE*. Accessed on 04/06/19

2. All variable and fixed[2] costs associated with each step of the production process are identified and measured in a detailed and comprehensive way. Total annual production costs can thus be derived.
3. Total feasible output over a year for a given production unit is estimated.
4. Unit cost of production is computed as total annual costs divided by total annual output.

This modelling exercise is particularly data-intensive, since the quantity and unit cost of all inputs (including labour, rent, advertising etc.) must be known, and total output must also be estimated. Data sources mainly include:

- Scientific papers: a paper by Platt et al. (2019)[3] explaining the technical characteristics of the prototype, and an LCA of the prototype by Yao (2018)[4];
- Discussions with the researchers from the University of Bath that were involved in the project;
- Additional research. For instance, most price data come from the internet or from discussions with suppliers.

3. Prototype description: the "optimised" straw bale

Current balers produce straw bales with sub-optimal insulation properties, because straw stems are oriented parallelly to the heat flow, and hence a large amount of insulation material is needed to attain a desirable level of thermal resistance. Therefore, straw-bale based constructions require a large volume of insulation material and are thus characterised by excessively thick walls. Samples of optimised straw bales are presented in Figure 1.

The fundamental innovation proposed by the University of Bath is to improve the thermal performance of straw bales while maintaining their structural integrity by using a process that orientates straw stems perpendicularly to the heat flow. The optimised straw bales produced following this method benefit from a lower thermal conductivity (so a better thermal resistance R for a given level of thickness) compared to standard bales.

Table 1 compares the characteristics of the prototype (optimised straw bale) with those of a standard straw bale used for construction and insulation purposes. Standard bale characteristics are based on an LCA of agricultural straw bales used in construction as insulation materials by CEREMA (2010)[5]. This "standard" bale is representative of the various types of bales that are used in construction.

[2] Variable costs refer to costs that vary closely with output, while fixed costs do not.
[3] Platt S., Walker P., Maskell D., Laborel-Préneron A. (2019) Re-baling straw for better insulation, *3rd International Conference on Bio-based building material*, June 26th – 28th 2019 Belfast (UK)
[4] Y. Yao (2018) *Life-cycle analysis on bio-based construction materials*, Msc. Thesis submitted to the University of Bath for the Msc in Innovative Structural Materials in the Faculty of Architecture & Civil Engineering
[5] CEREMA (2015) *Rapport d'étude ACV / FDES conforme aux exigences de la norme NF EN 15804 – Remplissage isolant en bottes de pailles (issues de l'agriculture conventionnelle) conformément aux règles professionnelles de construction en paille CP 2012*

Figure 1: Optimised straw bales in an OSB frame (left); optimised straw bale (right)

It must be stressed that the reported dimensions and characteristics are not definitive. As the manufacturing process is relatively simple and flexible, optimised straw bales could be produced with different dimensions. For example, the standard bales used as raw material could be cut in larger chunks, while the hydraulic press and the wooden case could be modified to produce larger or more compact bales. However, Platt et al. (2019)[6] point that there is a constraint on the dimensions of the optimised bale: the width to height (i.e. thickness) ratio must remain smaller than 2.

Given that the width to thickness ratio (0.47/0.37) of a standard agricultural bale is lower than 2, the optimised bale could be produced with the same dimensions as a standard bale. The optimised bale would benefit from a lower thermal conductivity however, owing to its optimised straw stem orientation. Since insulation materials are generally characterised by different dimensions (including thickness) and thermal conductivities, and that both factors affect thermal performance at the same time, it is common to compare them based on an equivalent level of thermal resistance R. Thermal resistance R is the ratio of thickness over thermal conductivity. Thus, thermal resistance of the optimised bale is equal to: $R = \frac{t}{\lambda} = 8.41\ \frac{m^2K}{W}$. To reach a thermal resistance of 5 $\frac{m^2K}{W}$, the optimised bale would have to be 22 cm thick, while a standard bale would require a thickness of 26 cm.

The optimised straw bale is ready to use as a non-load bearing insulation material which can be encased in a timber frame for example, like standard straw bales.

In laboratory conditions, the thermal conductivity optimising process was applied to existing, standard straw bales that were cut into smaller portions to then be re-baled into more compact, optimised bales. This production process is analysed in the **small-scale scenario**.

However, ideally this re-baling process could be integrated into balers so that a farmer may produce optimised straw bales directly from his field, while collecting cut and raked crop. In short, balers could manufacture optimised straw bales directly, instead of producing standard bales with sub-optimal thermal properties and dimensions. This would imply modifying the way that existing balers compress straw stems into agricultural bales. This is the production process that is assessed in the **large-scale scenario**.

[6] Platt S., Walker P., Maskell D., Laborel-Préneron A. (2019) Re-baling straw for better insulation, *3rd International Conference on Bio-based building material*, June 26th – 28th 2019 Belfast (UK)

Characteristics			
	optimised bale	**standard bale**	**unit**
length	1	1	m
width	0.47	0.47	m
thickness	0.37	0.37	m
area	0.47	0.47	m^2
volume	0.1739	0.1739	m^3
density	100	100	kg/m^3
mass	17.39	17.39	kg
thermal conductivity	0.044	0.052	W/mK
thermal performance	8.41	7.12	$m^2.K/W$
thickness for R = 5 $m^2.K/W$	0.22	0.26	m
cost of straw	0.15		€/kg

Table 1: Characteristics of standard and optimised bales

Nota: The simulations performed in this study are based on a thermal conductivity of 0.044 $W.m^{-1}.K^{-1}$, a value that was obtained in the laboratory by the University of Bath team on a small, handmade sample. However, it should be noted that tests carried out on larger prototypes produced using a hydraulic press revealed thermal conductivities closer to those commonly observed for standard bales.

4. Large-scale scenario: "modified" balers dedicated to the production of optimised straw bales

4.1 Introduction

As explained in the previous section, by changing the way that bales are compressed by agricultural balers, *modified balers* could produce optimised straw bales directly in the field, instead of standard straw bales that are characterised by sub-optimal thermal properties. This modified baler would be bought by a farmer who produces straw bales for construction purposes. Optimised straw bales would then be sold directly to construction professionals or indirectly *via* straw merchants. It is indeed standard practice for construction professionals to source straw bales directly from farmers or straw merchants in a 50km radius around the building site to minimise costs (Nomadéis 2017[7]). As such, the market for straw bale insulation is rather decentralised, since any cereal cultivator could potentially produce optimised straw bales for construction if there is sufficiently high demand for straw-based construction materials.

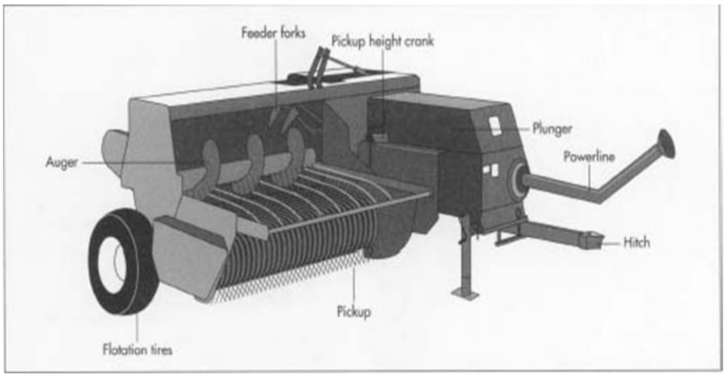
4.2 Functionning of the balers

Various types of agricultural balers exist: round balers and rectangular balers (which produce the types of bales used for construction purposes), tractor-propelled or self-propelled balers, field or stationary balers, automatic or manual, etc. Generally speaking, standard, modern, rectangular, mobile balers transform collected straw into bales in the following way[8]:

- a tractor in the field pulls and powers a baler;
- the pickup on the baler collects straw from the ground;
- the auger feeds the collected straw to a precompression chamber, where feeder forks then move straw to the bale chamber;
- in the compression chamber, a plunger drives in and out (80 – 100 strokes per minute), each time compressing and packing the straw into small layers across the bale of around 100mm width. Once stacked into the desired bale length (a metering device controls this), these layers form a square, compact bale;
- A knotter unit ties up the bales with twine;
- Square bales are ejected back to the ground or onto a wheeled cart or rack attached to the baler.

[7] Ministère de la Transition Ecologique et Solidaire, Ministère de la Cohésion des Territoires, Nomadéis (2017). Etude sur le secteur et les filières de production des matériaux et produits biosourcés utilisés dans la construction – Etat des lieux économique du secteur et des filières, Mise à jour 2017

[8] Sources: How products are made website (2019) Hay baler, accessed on 27/05/19: http://www.madehow.com/Volume-2/Hay-Baler.html ;



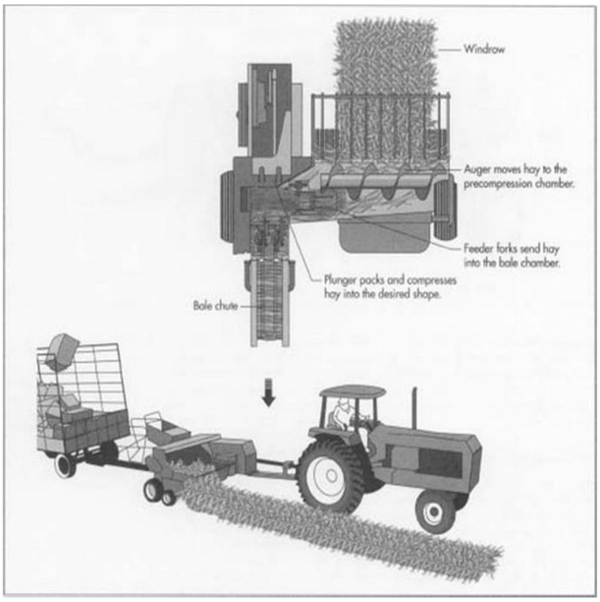


Figure 2: Main components of agricultural balers. Source: How Products are made? (2019)[9]

4.2.1 Possible modification of balers

Balers are relatively simple machines that come in various models, and as such they should be easily modifiable. The manufacturing process is not particularly complex, while the components used are standard:

- Sheet metal is cut into various parts that will constitute the outer skin of the baler;
- Heavier structural steel parts such as the frames and shafts are cut, and the different fabricated parts are welded by robotic machines;
- All the parts are then cleaned and painted by being submerged into an electrostatic paint tank;
- The various components (e.g. hydraulics, wheels, tires, pickup components, bale tensioners, knotters etc.) are progressively assembled onto the frame – which is placed on a wheeled cart - at multiple workstations, like cars in a factory;
- Finally, the baler is comprehensively inspected and tested, prior to be being packaged and shipped.

[9] Platt S., Walker P., Maskell D., Laborel-Préneron A. (2019) Re-baling straw for better insulation, 3rd International Conference on Bio-based building material, June 26th – 28th 2019 Belfast (UK) ;
Central Institute of Agricultural Engineering (2008) Success stories on: Tractor operated straw baler, Extension Bulletin No.CIAE/FIM/2008/80, accessed on 27/05/19: https://aicrp.icar.gov.in/fim/wp-content/uploads/2016/12/42.TRACTOR-OPERATED-STRAW-BALER.pdf

To produce "optimised" bales with the right dimensions, density and straw orientation, the dimensions of the compression chamber, the plunger (and perhaps the compressive pressure it applies and its size), the knotter unit and the metering device may have to be modified.

4.2.2 The price of an optimised straw bale: an estimate

Within the frame of the current study, it was not possible to model the cost of modifying existing balers in the way described above. Indeed, in order to do so, one would have to model the organisation of an entire factory dedicated to manufacturing "improved" agricultural balers. However, it is reasonable to assume that in the long run, an agricultural machinery manufacturer that has adapted the design and manufacturing process of balers would produce a *modified baler* at a similar cost, once all additional fixed costs linked to the production of this new baler have been sufficiently absorbed. In this scenario, a modified rectangular baler would therefore be sold at about the same price as current balers. This implies that **optimised bales would be produced at the same cost as standard ones used in construction**, if the following assumptions hold:

- Modified balers and standard balers can operate under the same conditions (e.g. weather, output, maintenance etc.). For example, modified balers should have the same output per hour or per hectare as standard balers, meaning that the same volume of optimised bales is produced for every hour (or hectare) during which the baler operates. If for some reason modified balers yield a lower output per hour, unit production costs for optimised bales will be higher than those of standard bales, all other things equal.
- The costs associated with handling, packaging, storing and checking the quality of optimised bales are equivalent to those of standard bales used in construction.

If unit production costs of optimised bales are equivalent to those of standard bales, then they should be sold at the same unit price. Thermal conductivity for a **standard bale** is equal to 7.12 m².K/W, while its density is assumed to be 100 kg/m^3. Given that the price of such straw bales is around 0.15€ per kg when it leaves the farm, this yields a sale price of 2.63€ per *standard bale* for a thermal performance R = 7.12 m².K/W, thus corresponding to a mural cover of 0.47 m^2. The equivalent price for a mural cover of 1 m ^{2} is thus of 5.59€ when using standard bales.

To facilitate comparisons between insulation materials, products must be compared at an equivalent level of thermal performance, regardless of their respective thicknesses and thermal conductivities. In other words, insulation materials must be compared based on their price per m² for a standard thermal performance. An R of 5 m².K/W is typically used in the literature (CEREMA 2017)[10]. We thus convert the sale price per m² for R = 7.12 m².K/W to an equivalent for a standard thermal performance R = 5 m².K/W by multiplying 5.59€ per m² by 5/7.12, which gives a price of 3.93€ per standard bale.

Applying the same methodology to the **optimised bale**, assuming that the price of straw (0.15€ per kg) and density (100 kg/m^3) are the same, but taking into account the fact that optimised bales have a lower thermal conductivity than standard bales, the following prices are computed:

- price per *optimised bale* (R = 8.41 m².K/W) : 2.63€;
- price per mural *m²* for R = 5 m².K/W : 3.33€.

[10] CEREMA (2017) *Les coûts des matériaux biosourcés dans la construction – Etat de la connaissance* 2016, DREAL de Bretagne

In summary, optimised bales are cheaper than standard bales per m² for any given level of thermal performance simply because they have a lower thermal conductivity while being produced in the same conditions (same cost of straw).

Characteristics			
	optimised bale	standard bale	unit
length	1	1	m
width	0.47	0.47	m
thickness	0.37	0.37	m
area	0.47	0.47	m²
volume	0.1739	0.1739	m^3
density	100	100	kg/m^3
mass	17.39	17.39	kg
thermal conductivity	0.044	0.052	W/mK
thermal performance	8.41	7.12	m².K/W
thickness for R = 5 m².K/W	0.26	0.26	m
cost of straw	0.15		€/kg
price of a bale	2.63	2.63	€
price of a bale per m² for R = 5	3.33	3.93	€/m²

Table 2: Characteristics and prices of standard vs. optimised bales

5. Small-scale scenario

5.1 Production company's value chain

To assess the unit cost and sale price of the insulation material, the following small-scale scenario has been chosen. A local small company sources wheat straw from local farmers and stores it. Baling twine and packaging products (plastic wraps, europallets, carboard boxes) are also bought. The manufacturing process is simple: wheat straw is compressed into the final product – the optimised straw bale[11] - thanks to a special hydraulic press. Baling twine binds the straw bale. Bales are then packaged and piled on a europallet and wrapped in plastic. As with the large-scale scenario, the final product is stored and then sold directly on the premises to local construction professionals or to straw merchants.

Many other indirect costs must be included to comprehensively assess production costs. The workshop is equipped with various tools, machinery, equipment and furniture that are essential to the manufacturing, packaging and storing stages. The company also incurs overhead costs such as rent, ICT expenses, office supplies, insurance and accounting fees, advertising expenses and also utilities (electricity, gas, water, telephone and internet) to support its activities. Finally, various taxes and contributions must be paid by the company and as such represent a cost.

5.2 Representative company

The simulation exercise focused on a small, fictitious company based in France. It is argued that the cost estimation results for France also roughly apply to the UK context. In real terms (i.e. once the £ to € exchange

[11] See part 3 for a description of prototype characteristics

rate is accounted for) the price of identical raw materials, machinery, tools and equipment is quite homogeneous between France and the UK, given that they are both part of the European single, common market. However, other costs such as labour costs, rent, utilities and taxes may differ more significantly between France and the UK, for various institutional and contextual reasons. By adapting these prices to the UK context, one may precisely estimate unit production costs and sale price.

The legal structure selected is a *Société Coopérative d'Intérêt Collectif* (SCIC), i.e. a company where each member of the general assembly holds one vote regardless of his capital share, and which gathers three types of partners: salaried employees, beneficiaries (e.g. clients, suppliers etc.) and a third type of partner (e.g. company, financer charity etc.). SCIC companies need to comply with specific regulations which indirectly affect the amount of taxes they will have to pay. Between 57,5% and 100% of profits must be allocated to indivisible reserves. This share is deduced from the company's corporate tax.

Ideally, the local small company could be an existing straw merchant looking to diversify its activities by manufacturing straw-based insulation materials. This situation would be advantageous for two reasons:

- As a straw merchant, the company would better control several dimensions of the supply of straw bales, which is seasonal, and additionnally often subject to undesirable fluctuations, in terms of volumes, prices and quality;
- Under-exploited assets such as storage and manufacturing space, tools, equipment and machinery could be mutualised between the two activities (straw trade and insulation material manufacturing). Similarly, labour and intangible assets (e.g. experience, expertise, local network of partners and clients…) could be shared. This would bring down the company's overall unit costs by spreading fixed costs over more activities. However, this assumption was not taken into account in this scenario.

5.3 Cost breakdown

5.3.1 Feasible output and labour

It was assumed that the company employs a total of 19 full-time workers: 1 support worker specialised in administrative and business-related tasks (supply chain, sales etc.), and two teams of 9 workers that work in two 7-hour long shifts (morning and afternoon for example). These workers manufacture optimised bales thanks to the hydraulic presses, and are also in charge of repair, maintenance, storage etc. Each worker will work for about 217 days a year, if all days off are deduced and taking into account a 5% absenteeism rate. This represents a total of 1,519 effective hours annually per worker.

During each shift, the team of workers spends 6 hours operating hydraulic presses, and 1 hour on other tasks (maintenance, preparation, cleaning, logistics). We assume a 1-to-1 relationship between the number of workers and hydraulic presses. Given that it takes 0.133 hours (8 minutes) to produce 1 prototype (including 2 minutes of compression by the hydraulic press), 810 optimised bales can be produced every day. This translates into 226,233 bales per year, which is equivalent to 39,341,92m^3, or around 3,934 tonnes (though this can vary depending on humidity).

5.3.2 Variable costs

5.3.2.1 Labour costs

Let's assume that each worker earns a gross salary of 1,600€ per month, which amounts to 19,200€ annually. This is slightly higher than the minimum wage in France (1,522€). Employer contributions are excluded from this figure, as they will be included later in the "Taxes" part. However, it has been established that the factory opens 252 days per year, after deducting the 104 days of weekend and the mean of 10 national holidays during the week per year. Therefore, regarding the total number of man-days worked, we reach a full time equivalent of 23,59 workers. Since employer contributions have been excluded from this figure, as they will be included later in the "Taxes" part, the total cost of the workforce for the company amounts to 452,928€ per year.

5.3.2.2 Consumables

The two consumables used are standard rectangular straw bales and baling twine. Each optimised bale requires 18 kg of straw and 18 metres of twine.

This translates into 4,072 tons of straw per year. The price of straw is 0.15€/kg[12] for a standard small bale that weighs between 12 and 15 kg, when it leaves the farm. Annually, this amounts to 615,600€. Straw bales are stored in a dedicated storage space.

4,072 km of twine are required every year to tie the bales, representing a total cost of 28,719.66 €.

5.3.2.3 Packing consumables

8 optimised bales can be stacked on a europalette, therefore 28,279 europalettes must be purchased every year, given total output, for a total cost of 565,582.50€ Each europalette is wrapped in plastic to protect the bales, partly from humidity as their moisture content must remain below 20% to meet professional rules that apply to straw-based construction[13] The annual cost of packing plastic is 25,507.77€. The plastic wrapped europalettes are stored and readily available when an order arrives.

5.3.3 Fixed costs

5.3.3.1 Manufacturing equipment

The hydraulic press is the main piece of machinery used in the production process. Optimised bales are obtained by compacting standard, rectangular straw bales oriented in the right way into a wooden box with the right dimensions, as shown in Table 2. 654 kN/m² of compressive pressure is applied for about 2 minutes[14]. The wooden box has some slots to easily bind twine around the bale.

Assuming that the wooden box costs 50€ and that it must be replaced every 2 years due to wear and tear, it costs 25.00€ per year. A hydraulic press[15] with a force of 100 tonnes costs 3,428€ upfront, which amounts to 342.8€ annually when linearly amortised over 10 years[16]. Given the 1-to-1 relationship between hydraulic presses and workers, 9 hydraulic presses are needed, which represents an annual (amortised) cost of 3,085.35€.

We further assume that the hydraulic presses must be repaired every year for a cost of 3,280.50€ (maintenance, repairing the hydraulic cylinder, changing the stem).

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12 Agricultures & Territoires, Chambre d'agriculture de l'Oise (2018) Barèmes fourrages 2018 HT, Accessed on 27/05/19: http://www.fdsea60.fr/media/2891256/baremes-2018.pdf

13 CEREMA (2015) *Rapport d'étude ACV / FDES conforme aux exigences de la norme NF EN 15804* – Remplissage isolant en bottes de pailles (issues de l'agriculture conventionnelle) conformément aux règles professionnelles de construction en paille CP 2012

14 Platt S., Walker P., Maskell D., Laborel-Préneron A. (2019) Re-baling straw for better insulation*, 3rd International Conference on Bio-based building material*, June 26th – 28th 2019 Belfast (UK)

15 Holzmann WP100H Hydraulic press, 100 tonnes of force. Accessed on 27/05/19: https://www.bricozor.com/presse-hydraulique-puissance-100-tonnes-wp100h-holzmann.html?gclid=CjwKCAjwq-TmBRBdEiwAaO1enxBmUvgmy7C99_X39H7KhIX9zhuMzsq7Kku5pH9sWJ8e_KjJ-7_P1BoCOR8QAvD_BwE

16 Reference periods over which equipment is amortised is based on fiscal amortisation data. Accessed on 27/05/19 at: https://www.compta-facile.com/les-amortissements-comptables/

Finally, the workshop must be equipped with various tools to facilitate manufacturing and maintenance of machines (including a handsaw to cut standard bales), for an annual cost of around 191.69€, assuming amortisation over 5 years.

Figure 3: Hydraulic press built and used by the University of Bath to produce prototypes

5.3.3.2 General workshop equipment

Several other machines, tools, pieces of equipment and furniture are necessary to support the manufacturing process. While it is difficult to compile an exhaustive list of all these items, we quantified some major ones and use them as a proxy for the workshop equipment costs in general.

Packing equipment (2 packing/wrapping machines, 2 wrapping tools and 2 pallet trucks) costs 563.14€ annually (amortized). In terms of furniture, we assume that 8 worktables and 4 closets for tools must be purchased, thus representing 693.74€ annually when amortised over 10 years.

2 industrial hoovers and 2 high-pressure cleaning machines are used as a proxy for cleaning expenses. They amount to 142.98€ every year (amortised).

In total, these additional expenses add up to around 1,399.85€ per year.

5.3.3.3 Office: rent, ICT, supplies

Total workshop area is estimated to be equal to 470.2 m². This comprises:

- 115.2 m² for the actual workshop fitted with the hydraulic press, the worktable and the closet for tools.
- 1400 m² of storage space: half for raw materials, and the other half to store the output.
- 10 m² of furnished office space. The office is used when the employee works on business, sales, supplies and administration management activities.

- 30 m² for communal spaces, such as toilets, bathroom and a kitchen.
- Another 45 m² can be added to account for corridors and other spaces.

Given that the average rent for commercial spaces in the Seine-Maritime *département* in Normandy is about 5€/m²/month according to the website Cessionpme.com[17], total rent over a year amounts to 96,012.00€ annually.

The worker will need an office space fitted with a desk, chair, closet, and various office supplies and stationaries to carry out more managerial and administrative tasks. These costs add up to 80.04€ per year (furniture-related expenses are amortised).

Finally, the office will have to include IT equipment (computer, printing machine, telephone, etc.). Annual IT expenses have been estimated at 6,491.50€.

5.3.3.4 Utilities

Utilities include:

- Water consumption for 1 full-time worker is estimated to be around 25 m^3 year thanks to Eau de Paris'[18] online calculator. This comes at a total yearly cost of 2,305.92€.
- Gas consumption for heating all areas in the workshop except storage is equal to 9,009 kWh/year according to ADEME (2014)[19], which estimates that a typical storage area or workshop consumes between 35 and 55 kWh/m²/year of gas for heating. The annual gas bill is equal to 763.73€;
- Electricity consumption, which is split between the electricity requirements of the 9 hydraulic presses[20] (427,580.37 kWh per year) and general consumption related to lighting, small equipment and appliances used in the workshop (25 kWh/m²/year) adds up to around 467,585.37 kWh per year. Electricity expenses represent 40,798.37€ a year;
- Internet access and telephone bills, which cost 180€ per year.

5.3.3.5 Other fixed expenses

A typical company must have a budget for fixed expenses such as insurance fees and accountancy fees. While these costs can vary significantly depending on the number of hours an accountant is hired or on the various options included in the insurance contract, we estimate that they come at a total annual cost of 27,200€, for a company with 19 employees.

We assumed that the equivalent of 5%[21] of turnover was dedicated to advertising (so 143,000€ per year), given that the company sells optimised bales directly to construction professionals.

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[17] CessionPME (2019) accessed on 28/05/19 : https://www.cessionpme.com/annonce,location-entrepot-bureaux-saint-romain-de-colbosc-76430,1716181,A,offre.html. For any real estate advertisement, at the bottom of the web page, the median rent displayed is from the same *département.*

[18] Eau de Paris's website (2019) Calculez votre consommation d'eau. Accessed on 06/08 : http://www.eaudeparis.fr/calculez-votre-consommation-deau/

[19] ADEME (2014) Atelier type n°10 : atelier de stockage, *Ateliers industriels : fiches descriptives des ateliers-types*. Accessed on 28/05/19 : https://www.ademe.fr/sites/default/files/assets/documents/atelier-de-stockage-atelier-type-n10.pdf

[20] Based on Y. Yao's figures (2018) *Life-cycle analysis on bio-based construction materials*, Msc. Thesis defended à University of Bath for the Msc in Innovative Structural Materials at the Architecture and Civil Engineering Faculty.

[21] This is a standard figure for a B to C company, mentionned at the marketing budgetization of a firm (2019). Accessed on 28/05/19: https://www.business-marketing.fr/budgetisation/.

The question of financing is beyond the scope of this study. However, it seems reasonable to assume that the owner of the company would take a loan to buy the 9 hydraulic presses upfront. Annual interests on this 10-year, 31,303.54€ loan are estimated at 15.65€, with a real interest rate of 0.5% (the nominal rate is 2% for a SME, to which can be subtracted the expected inflation rate over the next 10 years, which is 1,5%).

5.3.3.6 Taxes

In France, companies are required to pay three taxes: the *impôt sur les sociétés*, the *cotisation foncière des entreprises* and the *cotisation sur la valeur ajoutée des entreprises*. The latter two taxes constitute the *contribution économique territoriale* and their rates partly depend on the geographic location of the company.

To compute the *impôt sur les sociétés* owed by the company to the state, we assumed that 57,5% of accounting results would be allocated to *réserves impartageables* (indivisible reserves), because this is the minimum amount required by law for companies with the SCIC status. Projected turnover was estimated to be equal to 2,830,740.41€. As a result, the taxable fiscal result (344,064.86€) is part of the two lowest brackets, where the tax rate is 15% and 28% respectively, so the tax to be paid every year would be 91,382.56€.

The *cotisation foncière des entreprises* is levied on the yearly rental value of the workshop. Because the tax rate is determined at the municipal level, it somewhat varies across localities. Therefore, for simplicity, we apply the average local tax rate in the Seine-Maritime *département* (Normandy), which is 19%, and we assume that the localisation coefficient is equal to 1. Additionally, the company benefits from various tax breaks, because it is a newly created (no tax on the first year, 50% tax break the following year), industrial company (30% tax break). As a result, the company must pay 10,070.22€ per year in tax.

The third tax owed is the *cotisation sur la valeur ajoutée des entreprises*. Since projected turnover is above 500,000€, the company is eligible to this tax. However, the company benefits from a tax break on the 1st year of its creation, which implies that over a given period of 10 years, it will only pay 37,737.69€ per year on average.

Variable costs						
Input category	Input name	Quantity	Unit	Unit cost	Unit	Annual cost in €
Consumables	Straw	4072194	kg	0,15	€/kg	615600,00
	Twine	4072194	m	0,01	€/m²	28719,66
Packing	Plastic wrap	447941	m²	0,06	€/m²	25507,77
	Europallets	28279	europallets	20,00	€/europallet	565582,50
Labour	Labour	23,59	full-time worker	1600,00	€/hour (gross)	452928,00
	Support staff	*1*				
	Workers	*18*				

Fixed costs						
Input category	Input name	Quantity	Unit	Unit cost	Unit	Annual cost in €
Manufacturing	Hydraulic press	9	machines	3478,17	€ (upfront)	3310,35
	Repair and maintenance	9	interventions	364,50	€/year	3280,50
	Various tools					191,69
Workshop equipment	Packing equipment					563,14
	Workshop furniture					693,74
	Workshop machinery					142,98
Office	Rent	1600	m²	5,00	€/m²/month	96012,00
	ICT expenses			0,5%	of turnover	13158,45
	Office supplies	1	sets	430,80	€ (upfront)	80,04
Utilities	Electricity	467585	kWh	0,09	€/kWh + fixed cost	40798,37
	Gas	9009	kWh	0,07	€/kWh + fixed cost	763,73
	Water	590	m^3	3,91	€/m^3	2305,92
	Telephone & internet	1	package	180,00	€/year	180,00
Other expenses	Insurance fees			17000,00	€/year	17000,00
	Accounting fees			10200,00	€/year	10200,00
	Advertising expenses			5%	of turnover	131584,50
	Interests on loan	31303,53	€ loan	0,5%	real interest rate	15,65
Tax	IS			91382,56	€/year	91382,56
	CFE			10070,22	€/year	10070,22
	CVAE			37737,69	€/year	37737,69
	Employer's contributions			104456,52	€/year	104456,52

Table 3 : Summary of variable and fixed costs for the optimised bale under the small-scale scenario

Finally, the company has to pay employer contributions (*cotisations patronales*) on salaries to finance the French social security system. For a full-time worker earning a monthly gross wage of 1,600.00€ and employed by the company described in this study, the employer will pay 369.00€ (i.e. 23%) every month, according to the official online calculator[22]. Therefore, total employer contributions are equal to 104,456.52€ annually. A summary of the variable and fixed production costs is presented below in Table 3.

[22] Pôle Emploi (2019) Estimation du coût d'un salarié. Accessed on 29/05/19: https://entreprise.pole-emploi.fr/cout-salarie/

5.3.3.7 Unit production cost

In sections 4.3.2 and 4.3.3, all the costs that shall be incurred by the company to produce optimised bales over one year were described and quantified. The sum of all these costs adds up to 2,264,823.02€ annually.

Total yearly feasible output was also estimated in section 5.3.1, where it was determined that 226,233 optimised bales could be produced in one year given our assumptions.

Unit cost is simply computed as total costs divided by total output for a given year:

$$unit\ cost\ in\ € = \frac{total\ costs}{total\ output} = \frac{variable\ costs + fixed\ costs}{total\ output}$$

Thus, each optimised bale costs 10.01€ to produce according to the simulation performed on the basis of the data available and the assumptions made.

To facilitate comparisons with conventional insulation materials sold on the market, this figure can be converted into unit production costs per mural m² by dividing it by the area of the optimised bale (0.47 m²). This gives us a unit production cost per mural m² of 21.30€, for a thermal resistance of 8.41 m².K/W associated with a thickness of 0.37 m.

To reach a standard thermal resistance R = 5 m².K/W, given a thermal conductivity of 0.044 W/mK, the optimised bale's thickness must be 0.22m. Thus, unit production costs for an optimised bale with R = 5 m².K/W are equal to 12.66€ per m².

5.3.3.8 Margin, markup and sale price

To find the final selling price of each optimised bale, the margin is simply added to the unit cost. Selling price and margin (or markup) are generally jointly determined.

For example, once the unit production costs are known, it can be decided that each optimised bale will be sold at 12.51€, in which case the margin ratio is 20% (3.20€ unit margin), since:

$$margin\ ratio\ in\ \% = \frac{turnover - total\ costs}{turnover} \times 100 = \frac{sale\ price - unit\ cost}{sale\ price} \times 100$$

Similarly, it can be decided to apply a 25% markup on the unit production costs of the optimised bale to obtain a selling price of 12.51€, since

$$markup\ (in\ \%) = \frac{margin\ rate}{1 - margin\ rate}.$$

Margin is expressed relative to the selling price, while markup is expressed relative to unit production costs, as a percentage that must be applied to unit costs to derive the selling price. Thus, margin, markup and sale price are all inextricably linked. The choice of their value depends on several factors, the main one being the company's market power. Market power refers to the ability for a company to raise and maintain its sale price above the price that normally would prevail in a more competitive market environment. A company with strong market power can effectively increase prices without losing too many customers to competitors (thereby increasing its turnover).

Market power depends on many determinants such as the size of the company's market share, market structure (regulations, barriers to entry, relationships between upside and downside companies and competitors etc.) and the firms' long-term strategy (advertising, strategic behaviour, collusion etc.) for example. Thus, the degree of market power depends both on the sector and on the company itself.

Given that the company that being modelled does not fall in a specific sector (since it would ideally be a straw merchant producing and directly selling insulation materials), the average margin rate that prevails in one sector cannot be straightforwardly applied. For simplicity, a 20% margin rate (equivalent to a 25% markup on unit production costs) was chosen, based on mean margin rates in the following two sectors[23] that are closely related to the activity considered:

- *Commerce de gros de produits agricoles bruts et animaux vivants* (wholesale trade of raw agricultural products and live animals): 33%[24]
- *Artisanat commercial* (commercial craftsmanship for companies with fewer than 10 full-time workers): 7.1%[25].

A 20% margin rate is equivalent to a 25% markup on unit production costs. This yields a final selling price, excluding VAT, of:

- 12.51€ for a single optimised bale;
- 26.62€ for 1 m² with R = 8.41 m².K/W;
- 15.83€ for 1 m² with R = 5 m².K/W.

The key results of the economic assessment of the small-scale scenario are presented in the table below.

Total costs per year in I	2264823,02
Total output per year	226233,00

Unit cost in I per optimised bale	10,01
Unit cost in I per m² for R = 8.41 m².K/W	21,30
Unit cost in I per m² for R = 5 m².K/W	12,66

Gross margin rate in %	20%
Markup rate in %	25%
Sale price in I of an optimised bale for R =	12,51
Sale price in I per m² for R = 8.41 m².K/W	26,62
Sale price in I per m² for R = 5 m².K/W	15,83
Turnover in I per year	2830740,41

Table 4: Key results of the economic assessment under the small-scale scenario

[23] For m = margin rate; p = selling price and c = unit production cost, we have: $m = \frac{p-c}{p} \times 100 \Leftrightarrow p = \frac{1}{1-m} c \Leftrightarrow price = (1 + markup) \times unit\ costs$, where $markup\ (in\ \%) = \frac{margin\ rate}{1-margin\ rate}$

[24] INSEE (2016) Caractéristiques comptables, financières et d'emploi des entreprises - Ratios comptables au niveau groupe, *ESANE*. Accessed on 04/06/19 : https://www.insee.fr/fr/statistiques/3560263?sommaire=3560277

[25] INSEE (2016) Caractéristiques comptables, financières et d'emploi des entreprises – Ratios, par taille d'entreprise, *ESANE*. Accessed on 04/06/19 : http://agreste.agriculture.gouv.fr/enquetes/entreprises-agroalimentaires/statistiques-structurelles-sur-les-752/

6. Comparison with conventional insulation materials

Figure 4 thereafter compares the sale price (excluding VAT) in € per m² of conventional, bio-based and waste-based insulation materials, including the optimised straw bales produced under the two scenarios considered, for a thermal performance of R = 5 m².K/W. Comparison prices are all derived from CEREMA (2017). These prices are those that a final consumer would face in a shop.

Mineral wool, glass wool and standard straw bales are among the cheapest insulation products available on the market in France. Bio-based insulation materials such as hemp and flax wool, hemp wool, wood fibre and sheep wool, and waste-based insulation materials (recycled cotton wool and cellulose wadding) are sold at about 20€/m².

The optimised straw bale produced under the small-scale scenario (i.e. a straw merchant that has a re-baling unit) is more expensive than any other type of insulation materials, except expanded cork. This scenario does not appear as price competitive. This can be largely explained by the higher unit production costs of the straw-based insulation material, since even if the margin were zero, the optimised bale would still be the second most expensive insulation material in this list. The parts of this report will investigate the breakdown of production costs and explore potential cost-minimising strategies.

On the other hand, when the optimised straw bale is produced by modified agricultural balers directly in the field (i.e. large-scale scenario), the price of the straw bale is drastically lower. Figure 4 shows that an optimised straw bale produced under these conditions would be cheaper than any other type of insulation material, including standard straw bales.

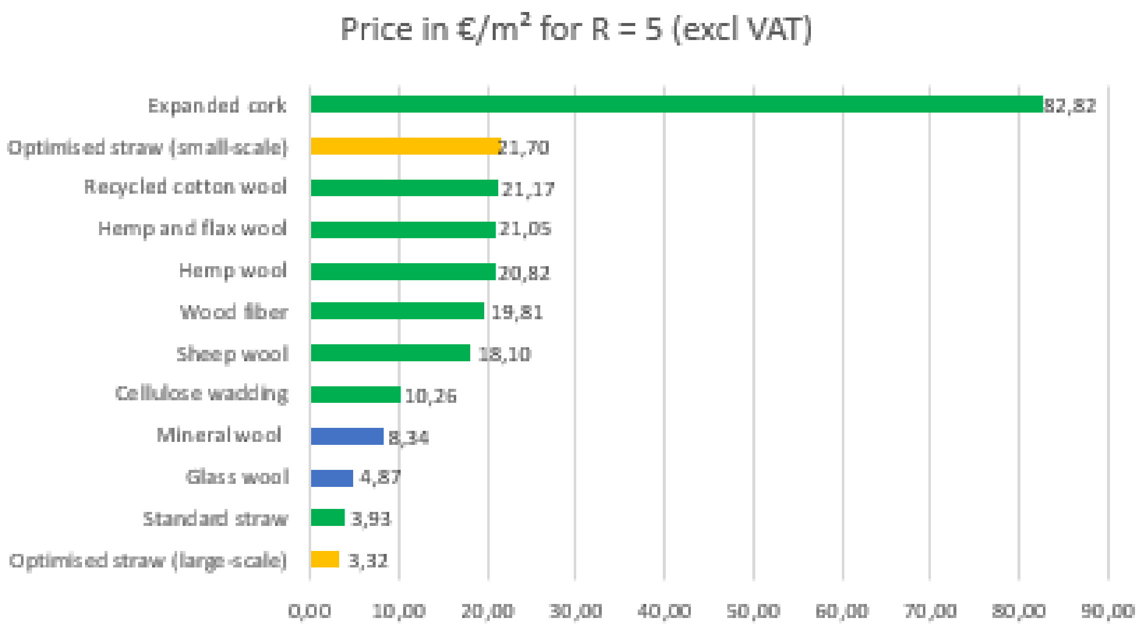

Figure 4 : Comparison of conventional, bio-based, and waste-based insulation materials with optimised bales (produced under the small-scale and large-scale scenarios)

7. Cost-minimizing strategies

By comparing the unit costs associated with the two alternative production scenarios (small vs. large scale), it appears that producing optimised bales thanks to modified agricultural balers is more efficient than doing so with a fixed, re-baling workshop. This result holds if one agrees with the assumptions described in each scenario. In particular, it has been assumed that a manufacturer of agricultural balers would be willing and capable of producing modified balers that would be sold at the same price as conventional balers, in the long run. It has been argued that modifying a baler would not be a particularly challenging process given the relative technical simplicity of such machines.

Although the small-scale production process is less competitive from a cost perspective, it can be optimised in different ways in order to reduce unit production costs. Figure 5 thereafter breaks down total annual production costs into major cost categories. It is apparent that the production process is highly labour-intensive, since almost 17% of costs are associated with labour (wages), while manufacturing, machinery and workshop equipment represent less than 1% of costs. The only expensive piece of machinery is the hydraulic press, which costs around 3,310.35€ annually. Raw materials and packing costs (equipment and packing consumables) together account for almost half of total costs.

This distribution of costs suggests that cost-minimising strategies should in priority focus on labour costs, raw materials and packing costs:

- The company could try to obtain better deals with its suppliers of raw materials and packing consumables to reduce those costs;
- Labour costs could also be decreased by automating lengthy tasks (e.g. preparing, cutting and setting up straw bales into the hydraulic press);
- Labour productivity could rise by reducing the amount of time spent on each manual task. This could be achieved by improving training, the organisation of the workshop, the sequence of tasks etc.

As fixed costs represent a small share of total costs compared to variable costs, economies of scale are limited, and hence unit costs cannot be decreased significantly. In other words, increasing output per year will not drastically reduce unit production costs because fixed costs cannot be "spread" over a larger output. Moreover, fixed costs are in fact not completely constant: they rise slightly with the number of workers and machines, as the surface of the workshop must increase, more furniture and equipment must be purchased, bills increase (utilities, insurance etc.), and more tax has to be paid. This can be seen in figure 6 which shows the relationship between the total number of workers (which is proportional to the number of hydraulic presses) and unit production costs. According to the present model, increasing the number of workers (and hence of machines) does not significantly diminish unit costs once the company employs more than 19 workers.

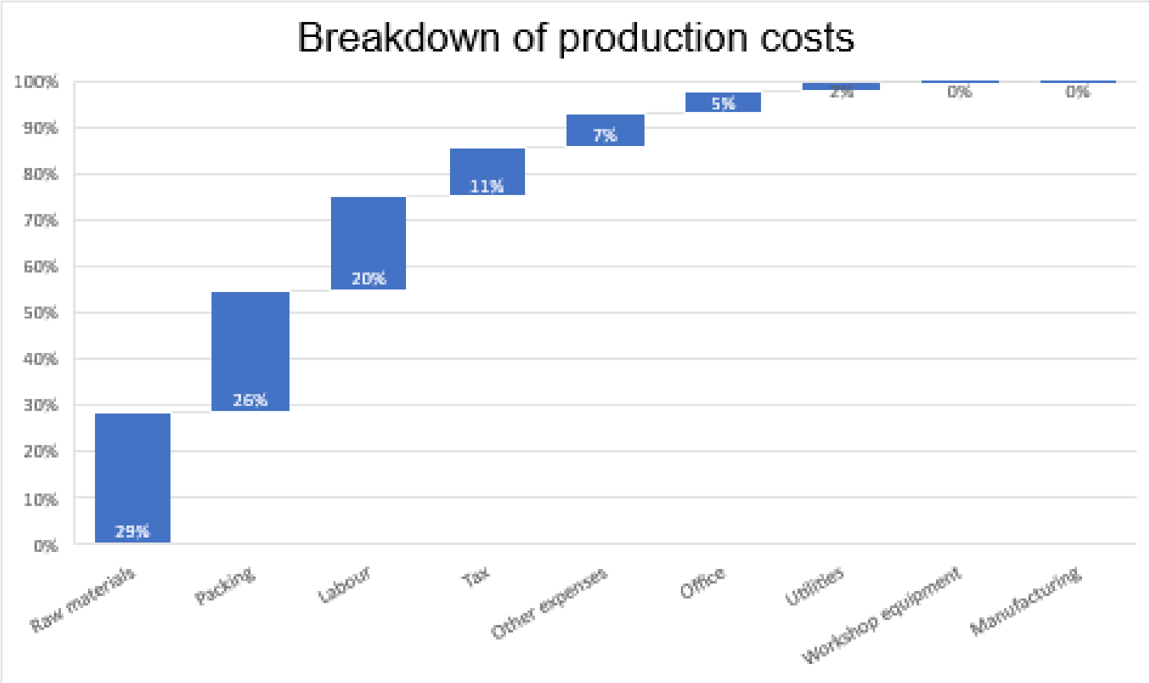

Figure 5: Breakdown of production costs for the optimised bale under the small-scale scenario

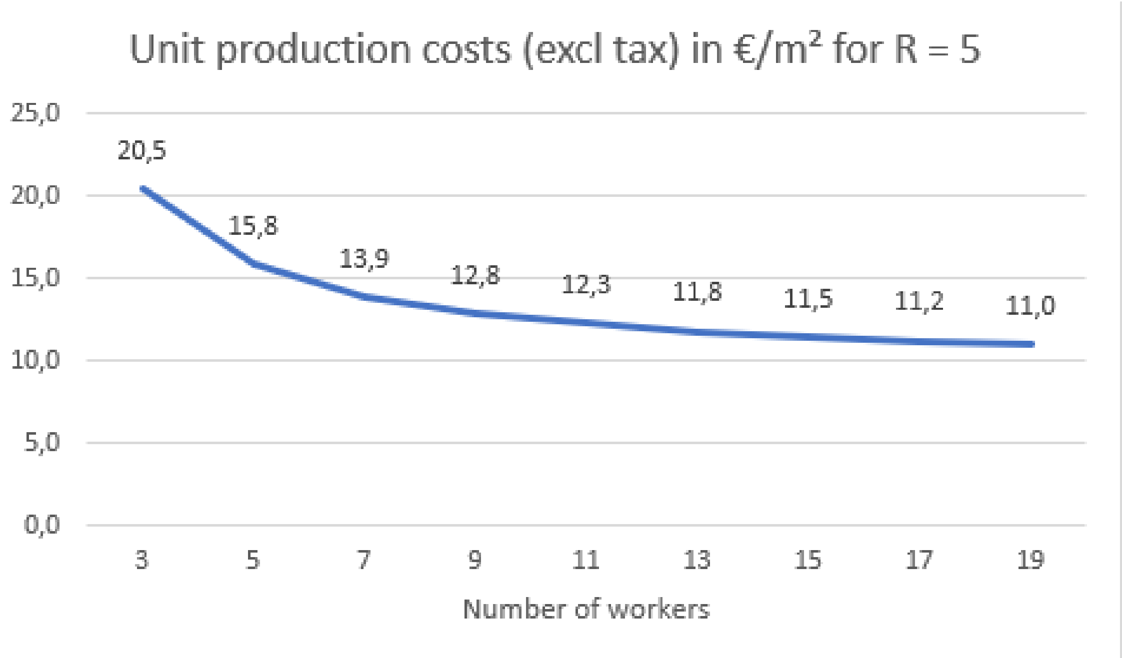

Figure 6: Economies of scale associated with the small-scale scenario: as the number of workers and machines increases, unit production costs fall

In summary, economies of scale are limited under the small-scale scenario, so large-scale production is not an attractive solution to improve the price-competitiveness of optimised bales since it does not drastically reduce costs On the other hand, enhancing labour productivity to increase output per hour per worker appears as a key strategy to minimise production costs.

8. Conclusion

The University of Bath has developed a manufacturing process that re-orientates the straw stems of a standard agricultural bale in a thermally optimal way. These optimised straw bales have a lower thermal conductivity than standard bales and are thinner. They can be produced in two different ways that were explored in the present report in two distinct scenarios: in the **large-scale scenario**, optimised straw bales are produced by **modified agricultural balers** directly in the field, while in the **small-scale scenario**, optimised bales are manufactured by **re-baling existing, standard straw bales** in a workshop thanks to a hydraulic press. In the small-scale scenario, the company that manufactures optimised bales would ideally be a straw merchant seeking to diversify its activities and selling optimised bales directly to construction professionals. In the large-scale scenario, a manufacturer of agricultural balers would produce and sell modified balers to farmers who would then produce optimised bales for sell to construction professionals.

These two different scenarios yield different results in terms of economic performance, according to the cost-estimation model developed, to the data available and to the hypotheses made in the present assessment. Optimised bales would be priced at **3.33€ per m²** for a thermal performance R = 5 m².K/W (commonly used comparison unit) under the **large-scale scenario**, that is, cheaper than any other type of conventional or bio-based or waste-based insulation material, including standard straw bales for construction. On the other hand, in the **small-scale scenario**, optimised bales could potentially be sold at **21.68€ per m²** (also for a thermal performance R = 5 m².K/W). These two prices include a 20% margin. Our analysis shows that the large-scale scenario, where standard agricultural balers are modified to directly produce optimised bales, would be preferable to the small-scale scenario in terms of economic performance. However, several strategies to reduce the unit production costs associated with the small-scale scenario were identified, focusing on labour productivity and raw materials mainly. Economies of scale are limited in this scenario because fixed costs represent a small proportion of total costs.

To estimate the unit production cost and final price of optimised straw bales under the two scenarios, a simple model was built on a spreadsheet that measures all the inputs and associated costs required to produce the optimised straw bales. It should be noted that the present simulation exercise relies on certain assumptions and on the available data, hence results and prices presented in this report should not be taken at face value. Rather, they give an indication of the distribution and magnitude of the various costs associated with the production process and provide a basis for exploring cost-reduction and massification strategies. The spreadsheet-based model that was developed is a simulation tool that can easily be modified to explore how changes in production parameters affect unit costs.

9. Limitations

The results presented in this report should be treated with caution, as they are estimates derived from a simple modelling exercise. Cost and price estimates are inaccurate because some of the data we use and some of the assumptions and calculations we have made are imprecise. These issues are inherent to any modelling or forecasting work. One should bear in mind that the straw-based insulation material remains at the prototype-stage, it is not yet produced or commercialised. The goal of this economic assessment was simply to produce a first approximation of production costs, and hence of the selling price, to compare it with competing insulation materials, and to explore cost-reduction strategies.

Below are some reasons why production costs might be underestimated and/or overestimated.

Production costs may be overestimated:

- Unit input costs might be reduced if raw materials, packages, machinery etc. are bought in large quantities to earn discounts.
- If a straw merchant decides to produce straw-based insulation materials, he or she could reduce costs by mutualising some equipment, machinery or buildings among the two activities and thus exploiting them fully.
- The production process could be further optimised to improve labour productivity. For example, the hypothetical 1-to-1 relationship between the number of workers and hydraulic press may be too conservative. Perhaps two workers could realistically operate three hydraulic presses. Improvements of this kind could significantly increase labour productivity and drive unit production costs down.

Production costs may be underestimated:

- Due to time, resource and data constraints, the modelling exercise is not perfectly exhaustive. Some cost categories and components may be missing (e.g. some tools, equipment etc.). However, the most significant and relevant ones have been accounted for.
- In the large-scale production scenario, it is assumed that modified agricultural balers would be sold at the same price as conventional agricultural balers. This will happen only if expected demand for modified balers is large, and if a manufacturer finds it profitable to meet (or create) this demand for modified agricultural balers. Moreover, modified and standard balers were assumed to operate in a similar way, and thus at the same cost. Again, this might not necessarily be the case if for example modified balers are slower than conventional ones.

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