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A SYSTEMATIC METHODOLOGY FOR SENSITIVITY ANALYSIS IN LIFE CYCLE THINKING CONTEXT APPLIED TO HEMP-BASED INSULATION PRODUCTS FOR BUILDINGS

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Abstract
This work aims at using a global sensitivity analysis (SA) approach within the frame of life cycle assessment (LCA) for providing information to the actors of system in a product's life cycle. More precisely, the coupling of life cycle thinking and sensitivity analysis methods aims to systematically check the influence of input parameters of a foreground process controlled by a given economic actor. Amongst others issues, the developed method must be able to identify trends and effects for each input parameter on each environmental indicator considered. An application of the methodology proposed is realized to the industrial transformation of hemp into insulation products for buildings. The most influential parameters on the considered environmental impact categories are identified including the technological action levers that economic actor can control. Finally, this work results in a set of recommendations towards an eco-design approach for industrial actor in order to reduce the environmental impacts generated by his activity.

Keywords:
Bio-based material, Environmental management, Fiber processing, Industrial system, Inventory modeling, Morris analysis, Sobol indices

1 INTRODUCTION

Life Cycle Assessment (LCA) is a quantitative eco-design tool well recognized and useful for the assessment of environmental impacts of a product or service. However, environmental management approaches are required in addition to LCA approach for improving the environmental performances. The two approaches are linked even if they are different and do not target the same objectives. On the one hand environmental management aims at improving environmental performances inside a production site, by acting on efficient parameters. On the other hand, LCA aims at assessing environmental impacts over the whole life cycle of a product. This work presents a novel approach to conducting a Life Cycle Management (LCM) based on LCA approach providing information to the actor of a foreground system inside the product's life cycle.

The methodological approach developed by Andrianandraina *et al.* [2014] aims at checking and accurately assessing the influence of parameters of the foreground system within the frame of LCA, assuming that a foreground process is defined as the part of the system related to decisions, i.e. to possible choices of an actor able to act on the system [Tillman 2000]. The combination of sensitivity analysis (SA) and LCA methods proposed by Andrianandraina *et al.* [2014] and applied in this article must be able to: (i) include foreground process modeling and thus avoid the assumption of proportionality between inventory data and reference flows; (ii) quantify influences of foreground processes' parameters (and possibly interactions between parameters) (iii) identify effects and trends for each parameter on each indicator in order to determine the most favorable direction for parametric variation. Finally, the developed method must result in the identification with confidence of the technological action levers by considering uncertainty and variability sources involved inside the modelling of the chosen foreground system. The action levers to be found must be technological options that economic actors of the considered sub-system can control or vary. For each LCA environmental impact indicators considered, the effects and trends of the variability of each action levers should be quantifiable and identifiable. Finally, note that another methodology to account for the uncertainties and to identify the parameters inducing most of the uncertainties in the prospective LCA results is described by Padey et al. [2014].

The proposed method was first applied to the agricultural production phase of hemp crop as the first step of the production of a hemp-based insulation material for buildings [Andrianandraina et al. 2014, Ventura et al. 2013]. In the present work the industrial transformation phase of hemp straw into insulation material is examined.

2 METHODS

2.1 Sensitivity analysis methods

Let us consider an analytical or computational model $y = f(x)$ between an output variable y and a vector of input variables $x = (x_1, x_2, \dots, x_n)$. Within a sensitivity analysis framework some local and qualitative methods can be used versus global and quantitative ones for evaluating the influence of input parameters x on the output y of the model considered. In this work we successively use one method of each type.

The local and qualitative method used is the Morris analysis [Morris 1991] which consists of evaluating a coefficient of variation called elementary effect (EE) such that

$$EE_i = \frac{f(x_i + \Delta x_i) - f(x_i)}{\Delta x_i} \quad (1)$$

with Δx_i a pre-defined step, for each input variable x_i. It ensues two measures computed over a number *r* of repetitions for evaluating the effects of each x_i : the average μ_i and the standard deviation σ_i of the elementary effects. Furthermore, the average of absolute elementary effects such that

$$\mu_i^* = \frac{1}{r}\sum_{k=1}^{r} \left| EE_i^{(k)} \right| \quad (2)$$

is computed as a third sensitivity measure more useful than μ_i since negative and positive elementary effects can eliminate each other in a non-monotonic models [Campolongo 2007]. By displaying a chart of the standard deviation σ_i versus the average μ_i^*, the Morris method allows to class the effects of input parameters as (i) negligible, (ii) linear and additive, (iii) non-linear or in interactions with other parameters.

The global and quantitative method used is the Sobol analysis [Sobol 2001] which provides some sensitivity index for quantifying the contribution of input variable x_i to the variance of y. Thus, based on analysis of variance decomposition, the first order sensitivity indice for x_i is given by

$$S_i = \frac{V(E(y|x_i))}{V(y)} \quad (3)$$

Similarly, some second order sensitivity index can be calculated for evaluating the contribution of the interaction between two variables to the variance of y. At last, the overall contribution of x_i to the variance of y when taking into account the interaction with the other variables $x_{j,j\neq i}$ is measured by the total order indice calculated as follows:

$$ST_i = 1 - \frac{V\left(E\left(y|x_{j,j\neq i}\right)\right)}{V(y)} \quad (4)$$

2.2 LCA-SA methods

The coupling procedure between SA and life cycle thinking contains five steps (Fig. 1).

In the first step, the goal and scopes of the study are defined similarly to classical LCA: that includes the boundaries of system, the functional units, the identification of sub-systems and processes. In this step, the system of a product's life cycle is analyzed in terms of interactions between economic actors, leading to a partition into separate sub-systems related to each other by variable functional units. In the second step, for the chosen foreground system relative to the actor being considered, the elementary processes are identified with the models providing the inventory of inputs and outputs flows. In the third step, all input variables are characterized with their distribution probabilities and are grouped in several categories corresponding to the actor's action possibilities [Ventura et al. 2012]: the variables with a direct control are defined as *technological* ones (corresponding to the potential action levers), the variables with a possible indirect control or no control (constraints) are defined as *contextual* ones, and the modelling variables not controlled by the economic actor are defined as *methodological* ones. In the fourth step, local and global sensitivity analysis methods are successively conducted. First, the Morris method (Step IVa) is applied as a screening SA to rank influential parameters, identify their variation trends, and reduce the number of parameters considered in the subsequent step. Secondly, the Sobol method (Step IVb) is employed as a global SA to quantify the influence of each influential parameter on the considered impact category, as well as interactions between influential parameters. Finally, the last step (Step V) consists in an interpretation of the results by implementing the scenario corresponding to higher and lower impacts. In this step, the (technological) action levers are identified and potential scenarios towards an eco-design approach are proposed for each economic actor.

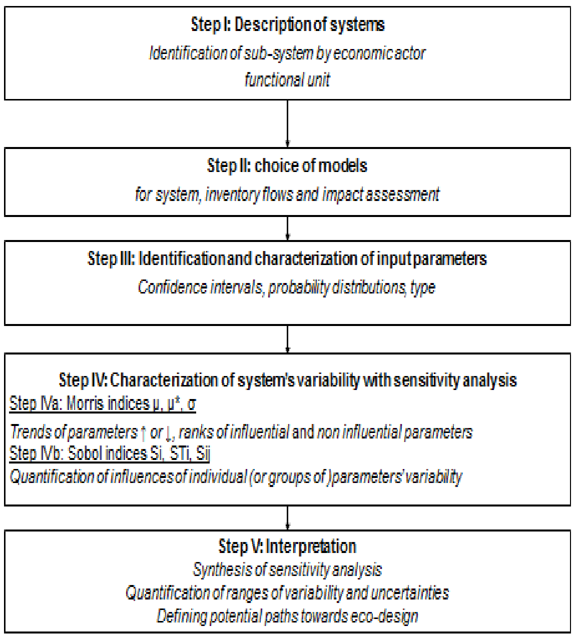


Fig. 1 : Steps involved in the combined LCA-SA method.

System definition (Step I)

In our case study the foreground system is the hemp industrial transformation. The first stage of hemp crop production system is taken into account and was previously studied by Andrianandraina et al. [2014].

The hemp cultivation provides the hemp straw which is first transformed in two raw materials: core (about 55%) and bark (about 20%) [van der Werf et al. 1994]; there is also a third co-product (dust, about 15%) but which may or may not be valorized. These raw materials are secondly transformed into insulation products for buildings.

The previous work on agricultural sub-system modeled the *production and harvesting of one kilogram of hemp straw.* In the present work the functional units are *to supply one square meter (m^2) of insulation board with a thermal resistance of 2.44K.m^{2}w^{-1} for a typical duration of 50 years* and *to supply one square meter (m^2) of wall with a thermal resistance of 2.36K.m^{2}w^{-1} for a typical duration of 100 years,* respectively for production of insulation board and hemp concrete.

Models for system (Step II)

Two types of models are required: physico-chemical and decision models. The modeling of industrial production process is concerned with the physic-chemical models for inventory flows of the chosen foreground sub-system, and decision models are those related to choice of a scenario or to methodological decisions such as the choice of an allocation method.

Two steps are distinguished in the industrial transformation. First, the hemp straw undergoes a primary transformation which consists of a mechanical separation of hemp bark from hemp core. Various fiber processing scenarios are available to which correspond some consumptions of electricity, diesel and propane. Based on the scenario considered a range of variation of the different consumptions is defined. A second transformation is conducted for the bark and core separately: hemp bark is combined with polyester resin to obtain an insulation board, and hemp core is used as granulate combined with a binder to obtained hemp concrete [Inies database, Tran Le et al. 2010].

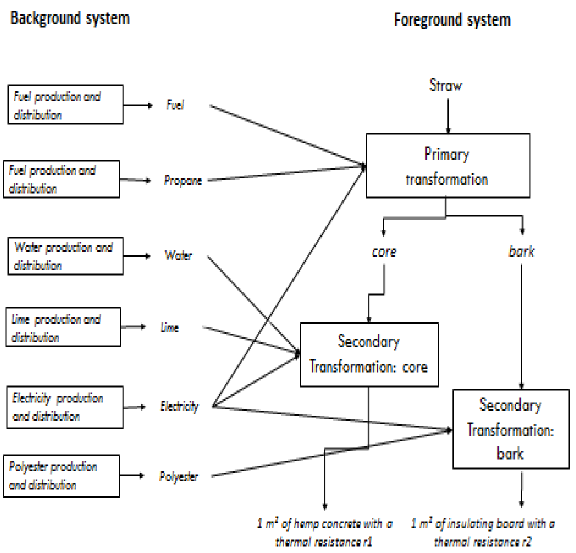


Fig. 2 : LCI modeling for industrial transformation.

Some decision models are also required in the modeling of industrial transformation system of hemp straw. Indeed, a model allocation impacts between co-products is useful when considering each product separately. Herein a partitioning allocation is applied. Thus, a qualitative parameter named *allocation method* is introduced having coded values set to 1 for mass allocation and set to 2 for economic allocation. A decision model *is* also required in the agricultural system modeling since hemp crops can either produce only straw, or both straw or seed according to the chosen type of cultivar. Therefore, a qualitative parameter *Crop production scenario* was introduced with coded values set to 1 for the production of straw only and set to 2 for the production of both straw and seed. For the transformation processes, based on the fact that hemp dust may be considered or not as a co-product, a qualitative parameter denoted *Hypothesis on hemp co-products* is introduced reflecting how allocation coefficients are calculated: coded values are set to 1 when considering only two hemp co-products (bark and shiv) and set to 2 when considering three hemp co-products (bark, shiv and dust).

Decision models for choosing the number of co-products or the type of partitioning allocation used in the agricultural and industrial sub-systems are schematized in Fig 3. They involve mass ratios and prices per unit of product that are considered as *contextual parameters.*

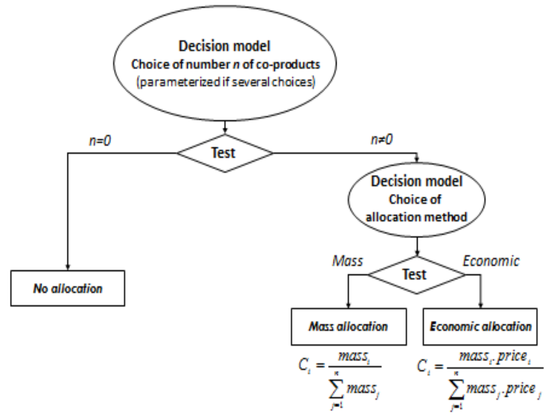


Fig. 3: Scheme for partitioning allocation used in agricultural and industrial sub-systems for this case study (with mass$_i$ and price$_i$ the mass and price of product i).

Characterization of input parameters (Step III)

Input parameters need to be characterized before conducting sensitivity analysis: their reference values (default, or recommended), their range of variation, and their probability distribution functions were collected from the literature, or obtained by expert judgments. The probability distribution function was assigned as follows: a uniform discrete distribution was set for all qualitative or quantitative integer value parameters, a uniform continuous distribution was set for parameters for which only the range of variation was known, triangular distribution was set for parameters with existing recommended values and for which range of variation was known, and normal distribution was set for parameters described by their mean value and standard deviation.

Tab.1 Parameters used to connect the agricultural and primary transformation sub-systems. Column headings: parameter name, unit, variable type, Probability distribution function, variation range and default value.

Parameters	Unit	Type	Distribution	Variation range	Default value
Straw yield	kg/ha	Tech.	Uc	6000-9500	7000
Seeds yield	kg/ha	Tech.	Uc	800-1200	1000
Seed price	€/kg	Tech.	Uc	0.5-1	0.75
Straw price	€/kg	Tech.	Uc	0.09-0.12	0.105

Uc:Uniform continuous; Tech: Technological.

Tab. 2 Parameters used for primary transformation sub-system. Column headings: parameter name, unit, variable type, Probability distribution function, variation range and default value.

Parameters	Unit	Type	Distribution	Variation range	Default value
Transport	km	Tech.	Uc	300-500	400
Quantity of electricity	kWh	Tech.	Uc	79-107	93
Quantity of diesel	kg	Tech.	Uc	0.5-4.82	2.41
Fraction of photovoltaic electricity	%	Tech.	Uc	0-15	7.5

Uc:Uniform continuous; Tech: Technological.

Tab. 3 Parameters used for secondary transformation sub-system. Column headings: parameter name, unit, variable type, Probability distribution function, variation range and default value.

Parameters	Unit	Type	Distribution	Variation range	Default value
Including or not hemp dust as co-product	n.u.	Meth.	Ud	Including, not including	Not including
Mass of hemp shiv per ton of straw	kg	Cont.	Uc	384-576	480
Price of hemp core	€\kg	Cont.	Uc	0.16-0.24	0.20
Quantity of hemp core	kg	Tech.	Uc	9-13	11
Quantity of hydraulic lime	kg	Tech.	Uc	19-29	23.75
Quantity of water	kg	Tech.	Uc	28-42	35
Quantity of electricity for hemp core	kWh	Tech.	Uc	1.5-2	1.8
Mass of hemp bark per ton of straw	kg	Cont.	Uc	280-420	350
Price of hemp bark	€	Cont.	Uc	0.28-0.42	0.35
Quantity of hemp bark	kg	Tech.	Uc	2.11-3.16	2.64
Quantity of polyester	kg	Tech.	Uc	0.28-0.5	0.36
Quantity of electricity for hemp bark	kWh	Tech.	Uc	25-31	28

n.u=without units; Uc:Uniform continuous; Ud:Uniform discrete; Tech: Technological; Methodological: Meth; Contextual: Cont.

Characterization of system's variability (Step IV)

For Morris indices, we discretized each input parameter in ten values and set the number of trajectories (with a number of elementary effects computed for each parameter) = 30. For Sobol indices, we ran 500 bootstrap replications of size 5,000 from an initial sample size = 10,000. We then estimated a Sobol index confidence interval by considering the 5% and 95% percentiles. For both insulation products studied separately, the Morris and Sobol methods were successively applied at the level of impact indicators and the results presented here concern the study per parameter.

3 INTERPRETATION (STEP V)

3.1 LCA approach

In the following part of this article, we do not detail the results corresponding to all considered impact categories but we focus on the *climate change and Cumulative Energy Demand (CED)* impact categories for which parameters from industrial transformation phase are most influential. However, a few general observations can be pointed out from both Morris and Sobol SA results, for all impact categories, for both insulation products.

First, for almost all parameters, the ratio σ_i/μ_i^* is found in the interval [0.1;0.5] showing possible interactions and/or non- linearity of the effects of these parameters [Morris 1991]. Second, the methodological parameter *allocation method* has a preponderant influence for the hemp concrete product, for almost all environmental impact categories. However, we do not find this influence for the insulation board product. For hemp concrete, the impacts are distributed more evenly between hemp co-products (bark, core and, when relevant, dust) by economic allocation in contrast to mass allocation (Tab. 5). Economic partition is thus more favorable to hemp concrete. For insulation board, the favorable influence of economic allocation already pointed out for hemp straws in agricultural sub-system, remains preponderant and thus balances its unfavorable effect at the step of primary industrial transformation. Furthermore the qualitative parameter hypothesis on hemp co-products (reflecting the inclusion or not of hemp dust as a co-product), is not influential found but has a negative average value μ_i which is favorable to including a third co-product since this reduces the impacts of the other co-products.

Finally, depending on the impact category considered, some parameters that had a considerable influence for the agricultural production phase still remain influential after including the industrial transformation phase.

Production of insulation board

For the insulation board almost all environmental impacts are generated during the hemp crop production phase, except for climate change and CED (Tab. 4).Considering climate change, two technological parameters from the industrial sub-system are found to be the most influential: the quantity of polyester consumed (51%) and the quantity of electricity for transformation of hemp bark (12%). One influential technological parameter comes from the agricultural sub-system: the crop production scenario (15%). The two parameters from industrial sub-systems have an increasing trend in contrast with the parameter from the agricultural sub-system which has a decreasing trend. For CED, the technological parameters from industrial sub-system are entirely responsible of the variation on this impact category: the quantity of electricity consumed for hemp bark transformation (95%), the fraction of photovoltaic electricity (31%) and the quantity of polyester (9%) are the most influent parameters. Between these three parameters the fraction of electricity from photovoltaic source is the one having a decreasing trend traducing that increasing this parameter is favourable to CED impact category. For acidification, eutrophication, human toxicity, ecotoxicity and land competition impact category not presented here, some parameters from agricultural sub-system are the most influential as the type of mineral fertilizer on acidification or the contextual environmental parameter clay content of the soil on eutrophication [Andrianandraina et al. 2014]. In particular, variations of human toxicity and ecotoxicity are essentially due to the variations of technological parameters related to agricultural engines. However, for ecotoxicity, the quantity of electricity for hemp bark transformation (11%) is ranked as the second influential parameter (Table 4).

Tab. 4 Tendency, mean value of Sobol first and total order indices values for most influent parameters on impact categories related to production of insulation board, technological parameters from industrial sub-system in italic.

Impact categories	Parameters	Tendency	S_i	ST_i
Climate change	*Quantity of polyester*	↗	51%	51%
	Crop production scenario	↘	15%	27%
	Quantity of electricity consumed for hemp bark (secondary transformation)	↗	12%	12%
Ecotoxicity	Engine release year	↘	24%	31%
	Quantity of electricity consumed for hemp bark (secondary transformation)	↗	11%	11%
	Working speed	↘	10%	18%
	Rating motor	↗	6%	9%
Cumulative energy demand	*Quantity of electricity consumed for hemp bark (secondary transformation)*	↗	95%	96%
	Fraction of photovoltaic electricity	↘	31%	33%
	Quantity of polyester	↗	9%	9%

Tab. 5 Tendency, mean value of Sobol first and total order indices values for most influent parameters on impact categories related to production of hemp concrete technological parameters from industrial sub-systemn in italic.

Impact categories	Parameters	Tendency	S_i	ST_i
Climate change	*Quantity of hydraulic lime*	↗	50%	50%
	Crop production scenario	↘	5%	9%
	Quantity of hemp core	↗	3%	3%
Ecotoxicity	Engine release year	↘	28%	39%
	Allocation method	↘	10%	21%
	Working speed	↘	8%	16%
	Engine rated power	↗	7%	10%
Cumulative energy demand	*Quantity of hydraulic lime*	↗	20%	20%
	Allocation method	↘	11%	27%
	Hypothesis on hemp co-products	↘	7%	7%

Production of hemp concrete

Similarly to the production of insulation board, the influence of parameters from the industrial sub-system on impacts essentially emerge for climate change and CED categories for producing hemp concrete. More precisely (Tab.5), the quantity of hydraulic lime has a dominating influence (50%) on climate change; and is also found in a first rank (20%) for CED followed by the allocation method (11%) and the assumption on hemp co-products for including or not hemp dust as a co-product comes third (7%).

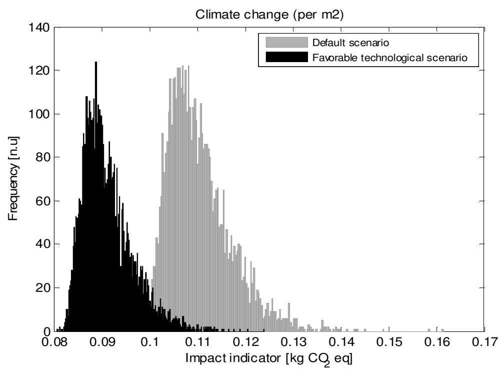
For acidification, eutrophication, human toxicity, ecotoxicity and land competition not presented here, parameters having a major influence are in general the same as for the one of the insulation board: they emerge from agricultural sub-system. The main difference comes from the allocation method which has a significant influence. For example, the choice between mass or economic allocation for producing hemp concrete is the second most influential parameter for various environmental impacts as ecotoxicity or CED (Tab. 5).

3.2 Implementations of scenarios

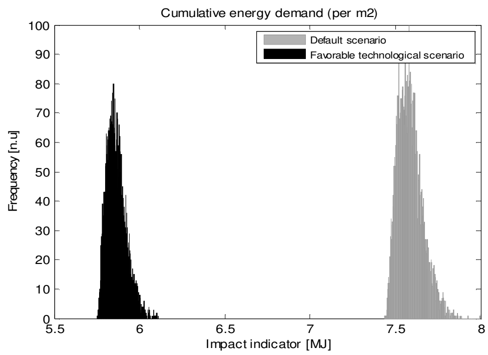
For both products, the significant influence of technological parameters on environmental impact categories provides some technological options for reducing these impacts. This part is focused on climate change and CED impact categories for which parameters from the industrial sub-system are found the most influential.

LCA with default and favorable technological parameters

After identifying all key technological parameters (Tab. 4 and 5), we can recalculate LCA results to assess environmental impacts either with a favorable set of parameters or an average default set of parameters, using a Monte Carlo simulation (considering a sample size of 5,000). The default set of parameters is calculated by setting all influential technological parameters from industrial sub-system at their default value and all influential contextual and methodological parameters according to their probability distribution (Tab. 1-3). The favorable set of parameters is calculated by setting all influential technological parameters from industrial sub-system at their most favorable values (with the influential contextual and methodological parameters set identical to the default scenario, i.e. according to their probability distribution). All non-influential technological parameters are set at their default or recommended value. Note that all parameters from agricultural sub-system are set according to their probability distribution in the two options since we are interested in technological action levers regarding the industrial actor. We also computed the percent relative

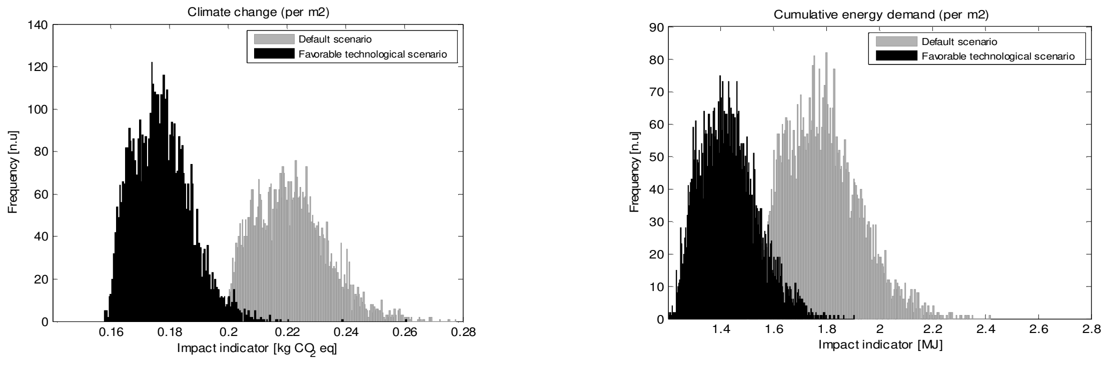


(a)



(b)

Fig. 4 : Climate change (a) and cumulative energy demand (b) impacts per year of the default scenario versus the favorable technology scenario for production of insulation board.



(a) (b)

Fig. 5 : Climate change (a) and cumulative energy demand (b) impacts per year of the default scenario versus the favorable technology scenario for production of hemp concrete.

variation from the mean value. For all the impact categories considered, the best improvement is obtained for CED in Fig. 4 (b), where variations in the quantity of consumed electricity for hemp bark during the secondary transformation, combined with the fraction of electricity from photovoltaic source are essentially responsible of all the variation. For this impact category, the probability distributions related to the default and favorable scenarios have a small variability and there is no overlapping at all. For climate change in Fig. 4 (a) (and the other impact categories not presented here), there is a reduction from 13% to 20% of mean value of the environmental impact. However, the probability distributions related to default and favorable scenarios more or less overlapping and the reduction of the variability may not be significant in some cases.

For producing hemp concrete, the best impact reduction is found for the favorable set of technological parameter on climate change (Fig. 5 (a)), where the variation of quantity of hydraulic lime has a dominating influence (50%). For CED and the other impact categories, there is a reduction of around 20% but an overlap of the probabilities distributions is observed (Fig. 5 (b)).

Potential scenarios towards eco-design

This sub-section presents a set of technological recommendations which are potential scenarios towards an eco-design approach for industrial actor based on identified technological action levers. For the insulation board, the quantity of polyester, the fraction of photovoltaic electricity as well as the quantity of consumed electricity consumed during secondary transformation are the technological action levers available for the economic actor to reduce impacts on climate change and CED. Hence, it turns out to be better for climate change and CED to reduce the quantity of polyester and electricity, on the one hand, and to increase the fraction of photovoltaic electricity, on the other hand. However, reduction of polyester quantity may affect thermal conductivity of the insulation product, and the full assessment including the use phase would help to define limits for which this reduction can be acceptable. It would also be interesting to investigate the modeling of polyester production process and define conditions for best performances. Other options for the industrial actor are the use of some alternative binder materials such as starch [Tran Le 2010] or cellulose. However further investigations are required to verify if using these new materials would allow to reduce impact on climate change. Concerning the photovoltaic production of electricity, the industrial actor would need to install a photovoltaic system of 82,500 m² (assuming that 10,000 tons of hemp straw and the corresponding quantity of hemp bark are transformed per year) in order to achieve a 15% fraction.

For hemp concrete, it turns out to be better to reduce the quantity of hydraulic lime for climate change and CED. This result is in accordance with the work of Boutin et al. [2006]. Similarly to polyester production process, it would be interesting to model the hydraulic lime production process. Moreover, some studies on the hemp concrete processing would allow to the industrial actor to minimize the hemp concrete density and, consequently, the quantity of hydraulic lime while ensuring a good thermal resistance. Indeed, the density depends on the projection distance or the compaction process when using the projection or mixing method, respectively. Deeper investigations are required for taking into account some variations in technical characteristics (such as density, thermal resistance) of the insulation products depending of implementation processes.

At last, our study reveals that most technological options depend on farmer’s decisions during hemp crop production through the influence of parameters such as the characteristics of agricultural engines or the crop production scenario.

4 CONCLUSION

The systematic method applied in this work is useful to propose various action possibilities for the actor of a foreground system involved throughout a product’s life cycle. Furthermore, this approach is also useful for integration into eco-design approaches, i.e. it could easily be complemented by cost models. However it has the disadvantage to be very consuming in term of computation time of models. Moreover, it is going to become more and more time consuming especially as for pursuing our study we added the sub-systems and, consequently, the models of the different actors involved during a product life cycle. Thus, some future prospects will be of interest such as tools for reducing calculation costs by model reduction or faster methods. Further investigations are needed on the interaction between the different parts of system.

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