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Multi-criteria decision modeling for the selection of timber in building structures

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ABSTRACT

Wood-based construction is becoming a real alternative for many types of buildings in France. This growth has entailed an extensive development of various wood types and methods in the construction industry. As a result, the design and conception of a building involve a decision with regards to the type of wood that will be used. Nonetheless, the contracting authority does not always have the tools necessary to support the choice of the best suited option. In this paper, we propose a multi-criteria modelling approach for evaluating the available alternatives using Life Cycle Analysis and Life Cycle Cost. We use a hierarchical model of values to define multi-dimensional criteria. We apply the sorting method ELECTRE-Tri B in order to aggregate the evaluations and classify the alternatives in terms of their desirability in a sustainable development context. We illustrate the workings of our approach on an example.

Keywords. Timber, Decision support, Multi-criteria analysis, Sustainable development, Life Cycle Analysis, ELECTRE-Tri.

INTRODUCTION

The use of wood in the construction industry is becoming more and more popular in France due to the perception that it is an environmentally friendly material. This decision to use wood can lead to complex choices because of the large number of alternatives available in terms of timber structures: solid wood or glued engineered wood, imported or local wood, a particular species or another, etc. Faced with these numerous possibilities, it can become difficult for a decision maker (owner, buyer) to make an informed choice. Often, the prerogative is left to the builder who may favour a solution that does not take into account the preferences of the decision maker, for example, by focusing on the financial aspects while neglecting the environmental aspect.

In this paper, a multi-criteria modelling and evaluation approach is proposed to help a non-specialist decision-maker choose the kind of wood that is most suitable for his future building structure (the most consistent with his goals and preferences). All the candidate alternatives considered meet the technical and regulatory constraints. This paper focuses on the multi-criteria evaluation of previously identified alternatives, on their comparison and classification in order to help the decision maker determine the most attractive option for him.

THE PROPOSED APPROACH

The proposed approach consists of three main phases: a technical assessment phase, an aggregation of low level technical data phase, and an alternatives classification phase (Figure 1). The first phase uses specialized tools to obtain technical evaluation data for the alternatives, such as Life Cycle Analysis (LCA) (Erlandsson & Borg, 2003; ISO, 2006; Udo de Haes, *et al.*, 2005). The second phase uses a multi-criteria sorting method, ELECTRE-Tri B (Yu, 1992) to aggregate the quantitative and qualitative data. The third phase uses the aggregated data to convey information to the decision maker by assigning each alternative to one of seven categories: A: excellent, B: very good, C: good, D: average, E: below average, F: bad, G: very bad. This is done by comparison to a reference option that is deemed acceptable on average.

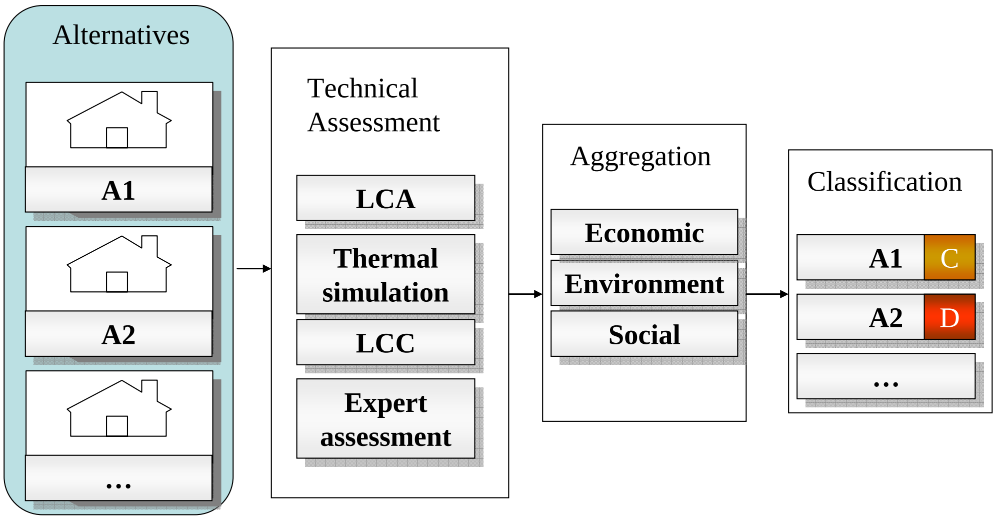

Figure 1. The proposed approach

The application of a multi-criteria evaluation method requires the definition of relevant criteria to assess the performances of the various alternatives. This definition stage is critical and requires considerable efforts in order to ensure the development of a pertinent decision analysis model. In this project, the alternatives are assessed with respect to the three dimensions of sustainable development: environmental (embodied energy, resource, etc.), economic (investment cost, maintenance cost, etc.) and social (aesthetic, employment opportunities, et.). As for time horizon, in addition to short-term aspects (investment, environmental impacts due to construction, etc.), long-term impacts (maintenance, end of life cost, etc.) are also considered. We present in Figure 2 the criteria's hierarchical structure composed of four levels and adapted from (Taillandier & Abi-Zeid, 2012). The environmental and the economic criteria are measured on a ratio scale while the social criteria are measured on a scale from 1 to 10 (10 being the best). The environmental criteria are measured on heterogeneous units while the economic criteria are all measured in euros.

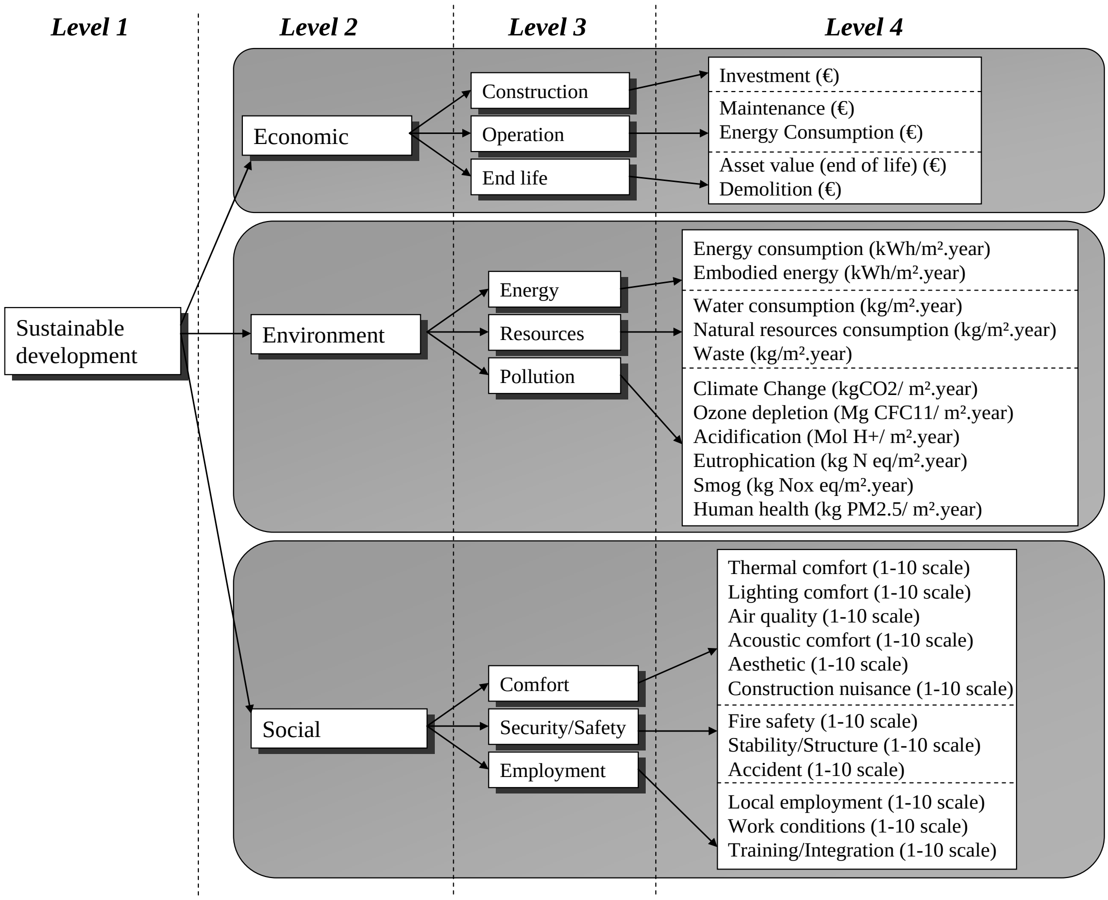

Figure 2. Criteria Structure

In order to obtain the necessary information for the assessment of the alternatives on each of the criteria, three methods are used: Life Cycle Analysis (LCA) (environmental dimension), Life Cycle Cost (LCC) (Arja, *et al.*, 2009; ISO, 2008) (economic dimension) and expert assessments (social dimension). However, these methods can yield a vast amount of technical data that are complex to interpret due to their number and to their highly specialised nature. An interpretation of this data is necessary in order to transform data into information and then into knowledge thereby supporting the decision-maker's process. Our objective is therefore to convert the raw data into legible categories that are easy to understand. This is done by aggregating the lowest level data (criteria of level 4) that are measured on heterogeneous scales with ELECTRE-Tri B (Yu, 1992).

ELECTRE Tri-B is a multi-criteria classification method based on the principle of assigning an object to predefined categories. In our case, a given alternative will be classified in one of seven ordered categories (A to G, A being the best). The evaluation data of an alternative is a vector consisting of the values of this alternative on the level 4 criteria. The idea behind ELCTRE-Tri is to compare each alternative's evaluation vector with the evaluation vectors representing the limits of the predefined categories called reference vectors (or reference profiles). These correspond to the upper and lower limits of the categories. Each alternative is compared with each reference vector in order to determine the closest category to which the alternative is assigned. Details of the method can be found in (Roy & Bouyssou, 1993).

The use of ELECTRE-Tri requires the definition of a number of method parameters reflecting the decision maker's values and preferences:

- Weights of criteria
- Indifference thresholds
- Preference thresholds
- Veto thresholds
- Cut threshold
- Reference profiles

The criterion weight reflects the importance of the criterion to the decision-maker, a higher weight implies a more important criterion. The preference threshold for a criterion is the smallest distance compatible with the preference of a higher evaluation over another evaluation on the given criterion. The indifference threshold is the level under which the difference between two criterion evaluations is not considered significant. The veto threshold reflects the threshold at which the difference between two values on a criterion disqualifies the vector of evaluations containing the worse performance on that criterion. When the difference between two values is above this threshold, the vector of scores of lower performance can never be considered better. The cut threshold allows us to compare two score vectors. The higher the threshold, the more criteria must support the superiority of V1 over V2.

In order to illustrate the working of the method, we use an example that consists of choosing the type of structure for a two storey house with 86 m² of living space. The house is to be located in Talence, near Bordeaux, France. Three alternatives for the structure are proposed:

- Alternative 1: Column/beam structure in solid wood with local specie (Douglas fir). Structural elements are prefabricated and assembled on construction site. Walls are also prefabricated and are composed of OSB (Oriented strand board) panels with a natural insulation (20 cm of Cellulose insulation) and a seal coat.

- Alternative 2: Walls of wood log (maritime pine) that are load bearing. An isolation is integrated (cellulose insulation) into the logs connections. An extra insulation is used (15 cm of cellulose insulation).

- Alternative 3: Prefabricated wood panel (European spruce), with integrated insulation (20 cm of cellulose).

The other elements of the house are otherwise identical in every point (same woodwork, same heating equipment, same foundations, same exterior joineries…).

Phase I - Technical assessment

The next step consists of assessing the different alternatives. In order to obtain these evaluations, the following tools are used:

- Life cycle analysis to measure resource consumption, grey energy, and pollution;
- Thermal simulation to measure energy consumption;
- Life cycle cost to evaluate the economic criteria;
- Expert judgment to assess social aspects (on a 1 to 10 scale).

The above assessment methods were chosen following a literature review with two objectives in mind: The methods had to make sense in a sustainable development perspective and had to be operational. This last point implies that for each method, documentation must be available, the associated implemented tool must be user-friendly, and it must have been previously applied in varied contexts. For expert judgement, a professor specialised in wood construction was called up.

Table 1 provides the technical assessment for the three alternatives and for a reference solution. The reference solution corresponds to a basic solution whose technical values meet average expectations for this kind of building. The technical values were obtained following a simulation of a standard house with the same function and characteristics (same living space, same roof…) as the three given alternatives, and by using the same tools (LCA, thermal simulation…). For the social dimension, the reference option was given a score of 5 for each criterion. Subsequently, experts assigned values of 1 to 10 to each alternative on each criterion of the social dimension. The differences in the scores of the alternatives may be explained by various reasons: the used materials (e.g. local employment), the construction process (e.g. work conditions) or the adaptation of design due to the different used technologies (e.g. thermal comfort).

Table 1. Technical assessments of alternatives

		Alt. 1	**Alt. 2**	**Alt.3**	**Ref.**
LCC	Investment (€)	118000	131 000	122 000	**108 000**
	Maintenance (€)	70 500	67 200	68 900	**45 560**
	Energy Consumption (€)	15 092	16 541	13 353	**12 077**
	Asset value (end of life) (€)*	30 450	35 550	22 412	**13 400**
	Demolition (€)	5 450	4 200	11 450	**22 210**
Thermal simulation	Energy consumption (kWh/m^2.year)	62.48	68.49	55.25	**50**
LCA	Embodied energy (kWh/m^2.year)	9.25	7.25	12.55	**19.57**
	Water consumption (kg/m^2.year)	32.12	22.56	27.55	**36.87**
	Natural resources consumption (kg/m^2.year)	22.45	23.55	23.36	**29.12**
	Waste (kg/m^2.year)	1.058	0.966	1.123	**1.512**
	Climate Change (kgCO2/ m^2.year)	3.57	4.25	3.77	**6.67**
	Ozone depletion (Mg CFC11/ m^2.year)	3.15E-09	2.56E-09	4.95E-09	**1.14E-08**
	Acidification (Mol H+/ m^2.year)	0.59	0.45	0.87	**2.55**
	Eutrophication (kg N eq/ m^2.year)	0.0002	0.00015	0.00022	**0.0015**
	Smog (kg Nox eq/ m^2.year)	0.0054	0.00059	0.0063	**0.0264**
	Human health (kg PM2.5/ m^2.year)	0.0149	0.0123	0.0156	**0.0223**
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Expert assessment	Thermal comfort*	6	6	8	**5**
	Lighting comfort*	7	7	7	**5**
	Air quality*	7	7	7	**5**
	Aesthetic*	7	8	7	**5**
	Acoustic comfort*	4	6	5	**5**
	Construction nuisance*	7	8	8	**5**
	Fire safety*	4	5	4	**5**
	Stability/Structure*	6	8	6	**5**
	Accident during construction*	7	6	7	**5**
	Local employment*	6	5	4	**5**
	Work conditions*	7	6	8	**5**
	Training/Integration*	5	7	5	**5**

** The criteria with an asterisk are to be maximized. All others are to be minimized.*

To make the information in Table 2 legible and interpretable by the decision maker, who is not a specialist, we use the reference option to obtain the relative performances of the alternatives. The assessment of a given alternative on each criterion is based on the comparison of its raw data value, obtained from the life cycle analysis, to the corresponding value of the reference option. Therefore, for the criteria measured on a ratio scale (all the criteria except the ones obtained by expert assessment), we compute a normalised distance D to the reference value where $D = (R\text{-}V)/R$ for the criteria to minimize, and $D = (V\text{-}R)/R$ for criteria to maximize. For example, energy consumption for Alternative 1 is 62.48 kWh/m².year and those of the reference is 50 kWh/m².year. Therefore, $D = (V\text{-}R)/R$ = (50-62.48)/50 = -0.25. The ordinal evaluations given by the expert are not transformed.

Phase II – Aggregation of technical data

In this phase we aggregate the evaluations on the fourth level criteria in order to obtain scores on higher level criteria. To aggregate the data associated with an alternative at lower level criteria into a value at a higher level criterion, we use two methods: The sum for commensurate cardinal criteria (economic) and ELECTRE Tri-B for the other criteria. In the application of the approach to our example, we use the weights presented in Table 2. As for the other parameters, they depend on the level at which ELECTRE-Tri is applied and are presented in the following sections.

Table 2. The various weights assigned to the criteria

Criteria	**Weight of each criterion**
Energy consumption, Climate change, Investment, Fire safety	5
Thermal comfort, Acoustic comfort	4
Natural resources consumption, Human health, Maintenance, Energy Consumption, Stability/Structure, Work conditions, Aesthetic, Construction nuisance	3
Asset value (end of life), Lighting comfort, Accident, Local employment, Embodied energy, Water consumption, Ozone depletion, Acidification	2
Demolition, Smog, Air quality, Training/Integration, Eutrophication, Waste	1

Aggregating the economic criteria

Since the economic criteria are all measured in euros, in order to go from fourth level to third level criteria, we simply use a sum where there is more than one criterion. For example, the value of the construction cost is that of the investment cost, the value of the operation cost is the sum of the maintenance and energy consumption costs, the value of the end of life costs is the difference between the demolition cost and the asset value at end of life. We then compare the values on the level 3 criteria with the corresponding values of the reference options. Subsequently, we compute the normalized distances for the construction, the operation, and the end of life costs. In order to make it easy for the decision maker to visualise the results we use a correspondence between a normalised distance to the reference option and a score as defined in Table 3. For example, for Alternative 1, the operation cost is 70 500€+15 092€=85 592€ and the operation cost for the reference value is 45 560€+12 077€=57 637€; so the normalized distance is (57 637-85 592)/57 637=-48% which corresponds to a category F. We also aggregate the economic criteria from level 3 to level 2 in the same fashion.

Table 3. The assignment of an ordinal score to a normalised distance

Score	A	B	C	D	E	F	G
Distance	50%	30%	15%	-15%	-30%	-50%	

Aggregating the Environmental criteria

In order to aggregate the energy criteria from level 4 to level 3, we use the same approach as for the economic criteria since the same measurement unit is used. Table 3 is also use to transform the normalised distance into a score (A to G). However, we use ELECTRE-Tri for the resources criteria and then for the pollution criteria based on the normalised distances computed for the fourth level criteria in order to obtain a score. We again apply ELECTRE-Tri to aggregate the 10 fourth level criteria to obtain a score for the level 2 environment criterion. In all cases, the indifference thresholds and the preference and veto thresholds used are the same for all the criteria and are equal to 0.01 and 0.1 and 1 respectively.

Aggregating the social criteria

The social criteria are measured on an ordinal scale from 1 to 10. In order to aggregate them from the level 4 criteria groups to the level 3 criteria we apply ELECTRE-Tri three times, once to get the score on the comfort level 3 criterion, once to get the score on the security/safety level 3 criterion, and once to get the score for the employment level 3 criterion. In order to obtain the score for the social level 2 criterion, we again apply ELECTRE-Tri using all the 12 fourth level social criteria. In all cases, the indifference thresholds and the preference and veto thresholds used are the same for all the criteria and are equal to 0 and 1 and 6 respectively.

Phase III – Classification

The last phase consists of classifying the alternatives based on all the fourth level criteria taken simultaneously. We therefore apply ELECTRE-Tri using the 27 level 4 criteria. The evaluation vectors for each of the alternatives consist of 16 normalised distances for the economic and environment criteria and of 11 scores on a 1-10 scale for the social criteria.

The weights, preference, indifference and veto thresholds are those used in phase II. The final result is the assignment of each alternative to one of the seven ordered categories from A to G. The results of our example are shown in Figure 3.

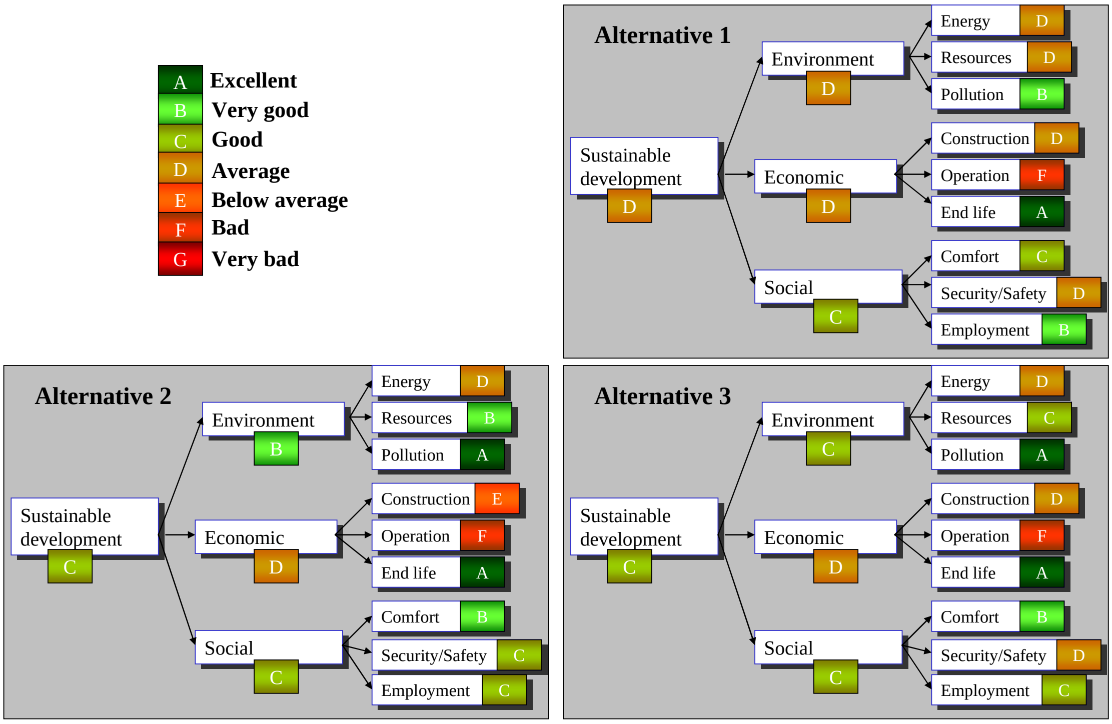

Figure 3. Classification results

Alternatives 2 and 3 have the best assignment (C: Good). But at the second and third criteria levels, we can observe that Alternative 2 seems more interesting on environmental aspect (due to a best resources safeguard) and on security criterion (C for Alternative 2 and D for alternative 3), but require a most important investment budget. Then, the choice between these two alternatives depends on the decision-maker preference and its capacity to gather the investment cost.

DISCUSSION

Our objective with the method we developed is to help a decision maker in the evaluation and selection choice of timber in a wood building structure. The multiple criteria defined allow us to portray adequately the situation by obtaining specialized technical data and translating them into meaningful information. It is very important that the decision maker clearly understand the meaning of the data obtained, and that he consider not only the final result, but also intermediate results in the criteria's hierarchy. The reading of hierarchical categories can provide useful information to explain the final classification of each alternative. However, many issues may be raised. For example, the relevance of the various criteria defined may give rise to discussions as we do not pretend that every decision maker will consider our list to be exhaustive and non-redundant. That list should be adapted to individual decision makers.

There are several important issues regarding the parameters used in our method. One can easily see that they are numerous and that they may be complex to define. Since the input parameters have a major impact on the scores obtained at the output, a sensitivity analysis is necessary in order to understand the extent of this impact. To ensure the robustness of the method, some efforts were made by using a stochastic approach in order to take into account uncertainties on parameters. However sensitivity on other parameters (deviation parameters) and on data (from LCA notably) have not yet been studied. Because of the limited space, we do not report these results in this paper.

LCA has in an important limitation with regards to data uncertainties and quality. This assessment method relies on many hypotheses (distance, material production process, etc.) and these hypotheses have a major impact on the results and are very difficult to validate. For example, an important parameter of LCA is the life duration of a building. Many studies use a life duration between 70 and 80 years (Kellenberger & Althaus, 2009), but this duration is theoretical and many buildings are demolished or renovated before this time (Erlandsson & Borg, 2003). This question is very important also for LCC, because it could have an impact on the ratio between construction and operation impacts (Öberg, 2005). A solution with a lower impact on construction but a higher impact on operation would be preferred if a shorter life time is considered. Notwithstanding these limitations, LCA and LCC still provide interesting information for environmental and economic assessment from a sustainable perspective.

Some of the technical criteria, namely the social dimension, were assessed by an expert on a scale from 1 to 10, and are subjective judgments. The choice of using expert assessments for the social criteria is open to question: It is relevant for the more subjective criteria (e.g. aesthetic) or for those that are an aggregation of several aspects (e.g. training/integration) or really difficult to assess precisely (e.g. air quality). But other criteria could be evaluated numerically by physical model or statistical analysis. For example, acoustic or thermal comfort could be assessed by numerical simulation (ambient sound level or interior temperature). Other criteria could be assessed by statistical studies (e.g. accident during construction). At the initial step of the method's development, we chose to use and expert scoring approach because of its simplicity, but it would be interesting to further evolve the method an improve the representativeness of the results, namely by including multiple experts opinions.

Another important point is the normalised distance from the reference option. The translation of a normalised distance into a score between A and G (Table 3) is the same for all criteria and yet, this is not quite appropriate. On some criteria, for example, investment cost, a normalised distance of 20% can be considered very important for the decision maker while for other more technical criteria, a distance will become significant only if it is of 10 fold order of magnitude (for example Ozone depletion). Further work on criteria impact modeling is necessary in order to define more appropriate distances and translate them into scores.

Furthermore, the use of a classification method such as ELECTRE-Tri B is interesting to help the decision-maker to understand the weaknesses and the strengths of each solution. However, it is an ordinal method that does not take into account the magnitude of the difference between two evaluations. The use of a method such as MACBETH (Costa & Vansnick, 1994) to construct interval scale value functions for each criterion can be an interesting complement, since it can lead to a global score and a ranking of the alternatives. The use of the two simultaneous methods could also help to reduce the influence of a method on the results.

CONCLUSION

In conclusion, we have developed a multi-criteria modelling and evaluation approach to help a decision maker in the choice of timber in a wood structure. The alternatives are evaluated on a technical level, followed by the aggregation of the data into information on higher level criteria. The end result is the classification of an alternative in one of seven ordered categories, A being the best and G the worst. In addition to the technical data obtained by various life cycle analyses, the proposed approach takes into account the preferences of the decision maker through the parameters used in the aggregation method. This is work in progress, and future research will address all the points raised in the discussion. Nonetheless, we believe that multi-criteria modelling and evaluation is a promising avenue to support decision makers with the selection of timber in a wood structure, especially in a sustainable development perspective.

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