MULTI-CRITERIA OPTIMIZATION OF A WOOD BASED FLOOR

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One of the major goals of the European project "Silent Timber Build" is to develop new prediction tools for wood based building components such as walls and floors in order to be able to optimize their performance. Indeed, a multi-criteria optimization process can avoid oversized systems and in the end lack of competitiveness. In this paper, massive wood (such as CLT) based floors are considered and the class of evolutionary algorithms, particularly well-suited to discrete search spaces as well as multi-objective optimization, is chosen to solve given optimization problems. Floor treatments above (such as floating floor, added mass, etc...) and below (such as suspended ceiling) base floor are considered in the optimization process. Moreover, it is of important interest to improve the low frequency impact sound performance of such floors since it is a critical point regarding lightweight structures acceptance by inhabitants. In this work, the objective functions in are based on acoustic performance single number quantities associated with airborne and impact sound insulation that include the low frequency range. They are constructed in using recent results on inhabitant perception. Then, it will be investigated if the optimization algorithm applied to such floors, that belong to a finite number of admissible combinations, tends to converge towards designs displaying the highest bending stiffness, the highest mass per unit area, etc...
Keywords: wood based floor, optimization, airborne sound, impact sound

1. Introduction

In this paper, we focus on optimal design of building systems. That is to say, seeking for the best system among admissible configurations. As systems consist of the assembly of industrial products, most parameters can only take discrete values (thickness, physical properties, etc) and such problem is equivalent to a combinatorial problem. However, due to the potentially huge number of combinations, a relevant strategy has to be used.

Moreover, a problem which goes beyond the scope of this work is to define objective performance indicators for acoustic comfort which is by definition subjective with respect to inhabitant perceptions. Standard objective criteria are defined from the comparison of experimental measurements and reference curves down to 100 Hz [1], [2], later extended to low frequencies down to 50 Hz in using weighted summation of the low third octave band energy content. However, in regard to the very low frequencies, down to 20 Hz, the agreement between standard single values and subjective perception is discussed [3]–[8], in particular with respect to impact noise comfort prediction. Consequently, most recent findings about this topic [6], [7] will be used in order to construct tailored fitness functions.

Another problem, related to the optimization strategy itself, lies in the continuous against discrete representation of the search space [9]. In particular, in the framework of lightweight building construction, systems are made up of engineered industry products whose dimensions and characteristics belong to standard numbers. More, in the general case, primary or secondary frames are constituted of a discrete number of stiffeners. Then, a variation from one configuration to another can be an increment in the number of stiffeners. By way of consequence, due to the non-continuous mapping from the search space of the configurations to the objective performance of an element, derivatives cannot be defined. Moreover, beside airborne sound insulation performance and impact sound insulation performance, one can imagine additional criteria, such as mass or cost minimisation for example. An additional constraint for the optimization strategy must be its ability to handle multi-objectives. Following, the class of evolutionary algorithms, which are particularly well-suited to discrete search spaces and multi-objective optimization problems, is chosen to treat the robust optimization problem. An extensive literature survey of such a class of algorithms can be found in [10].

First, the global structure and concepts associated with such algorithm are briefly introduced. Then, applications to the optimal design of CLT (Cross Laminated Timber) based systems are presented. In particular, optimal choice of cement screed/resilient layer is sought. In this paper, objective functions (linked to airborne and impact sound insulation performance) are constructed from the resolution of wave propagation problems in multi-layered systems in using AcouSYS software meanwhile the optimization algorithm is implemented within in house *ad hoc* code.

2. Optimization strategy

In this work, no significant improvement nor contribution to evolutionary algorithm theory was undertaken. Thus, concepts of Section 2.1 are rather classical [9], [10] and only briefly introduced to help the reader situate this work among others with a self-contained paper.

2.1 Genetic algorithm

Evolutionary algorithms inspire from early Darwinian concepts such as survival and reproduction of the fittest on one hand and non-directed mutation of individuals on the other hand. From an initial population, only the best individuals will survive, reproduce and mutate from a generation to another. Thus, algorithms inspired by such concepts involve the following general structure [9], [10], with the usual terminology:

- **Initialization** of the individuals constituting the first generation
- **Evaluation** of the individuals with respect to a fitness function
- **Selection** of the parents for the future generation
- **Reproduction** of the parents, through cross breeding, elitism or mutation

As it was mentioned within the introduction, the admissible designs are such that most design parameters can only take discrete values (number of stiffeners, standard product thickness, etc.) and the optimization problem is consequently equivalent to a combinatorial problem. Then, design parameters are naturally well suited for a change of variables to a binary representation because no continuous mapping needs to be defined. That is to say, a finite sequence of bits is enough to describe any admissible configuration. A system, or “individual”, is completely described by the knowledge of a bit string of fixed length such that for example:

Design parameter	p_1	p_2	…	p_n
“Genotype”	0 1 0 1	1	…	0 1

Initialization process yields the first generation, consisting of a given number *P* of individuals all described by a unique bit string. Then, individuals are evaluated and ranked with respect to fitness functions (here linked to airborne and impact sound insulation performance or thickness). When considering a single-objective, ranking individuals is straightforward. However, when considering multiple objectives, one individual can be the best with respect to one objective and another individual the best with respect to another objective. This situation occurs when objectives are in competition with each other. Then, without additional constraint, there is no unique solution to the optimization problem but rather a family of optimal solutions. This family is made up of nondominated individuals, in the sense that any other individual of the given generation that would be superior with respect to one fitness function would be inferior with respect to the second fitness function. Solving the optimization problem is then equivalent to finding Pareto fronts. Going back to the ranking process, Pareto fronts are successively identified among the individuals of a given generation. Then, the individuals that belong to a same front are tied for the rank of the front. Figure 1 illustrates the process for a two-objectives maximisation problem.

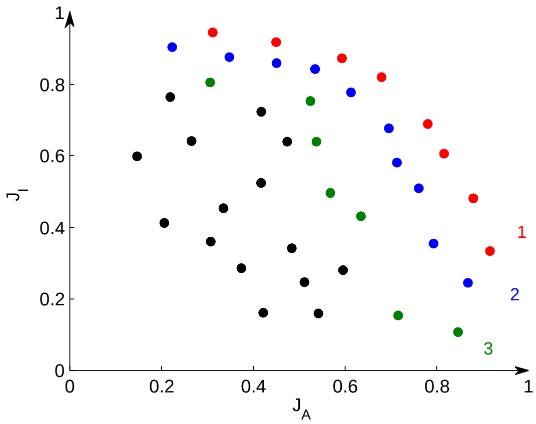

Figure 1: Schematic ranking process for a two-objectives maximisation

The selection of parents for the next generation is performed using tournaments of size *T*. This popular selection procedure is arbitrarily selected among other possibilities, but has the advantage of not being too much of an elitist selection. Indeed, depending on the size of the tournament (concept of selection pressure), intermediate individuals can survive and maintain some level of diversity among the population. However, in order to ensure that the best individual survive, an elite ratio among the children is introduced such that part of the next generation is constituted of the best individuals from the preceding one. Following, the creation of the remaining individuals for the next generation takes place in two steps: crossbreeding and mutation. In regard to crossbreeding, part of the parents (defined by a crossbreeding ratio) mix their genotypes, using once again a random uniform selection of the “alleles”, or group of bits, respectively associated with each design parameter. Such process can be schematically depicted as

Parent 1	**1 1 0 0**	0	…	1 1
Parent 2	0 1 0 1	**1**	…	**0 1**
Children	**1 1 0 0**	**1**	…	**0 1**

Regarding mutations, remaining parents are submitted to so-called bit-flips (from 0 to 1 or 1 to 0) that happen when the realisation of a uniform random variable with support [0,1], associated with a given bit, surpasses a threshold fixed by a mutation rate. Then, as soon as the creation of the new generation is completed, the evaluation takes place again until a maximum number of generation or any other exit criterion is reached.

The resulting genetic algorithm consequently depends on multiple parameters such as the population size, tournament size, elite ratio, crossbreeding ratio and mutation rate. The tuning of such parameters with respect to the optimization problem determines the global efficiency of the algorithm in its ability to find an optimal design and avoid local minima within a satisfying computational time.

2.2 Fitness functions

The problem of the definition of an objective function for the evaluation of the acoustic performance of lightweight systems, within the framework of an optimization problem, refers directly to the problem of the definition of single number quantities for the rating, from experimental data, of those systems. In the standards respectively associated with the definition of single number quantities for airborne and impact sound insulation [1], [2], single numbers R_w and L_w , resulting from the reference curve methods, are corrected with respect to a frequency band B using the respective adaptation terms C_B and $C_\mathrm{I,B}$. Thus, in the frequency band B the performance is rated by the quantities $R_\mathrm{w} + C_\mathrm{B}$ and $L_\mathrm{n,w} + C_\mathrm{I,B}$. By construction, the latter directly consist in the weighted summation of the energy content with respect to the third octave band that belong to B. Then, according to [1], [2], such single number quantities can be written as

$$R_\mathrm{w} + C_\mathrm{B} = -10\ \log_{10}\left(\sum_{b\in \mathrm{B}} 10^{(W_{b,A}-R_b)/10}\right), \tag{1}$$

$$L_\mathrm{n,w} + C_\mathrm{I,B} = 10\ \log_{10}\left(\sum_{b\in \mathrm{B}} 10^{(L_{n,b}-W_{b,I})/10}\right), \tag{2}$$

where $W_{b,A}$ and $W_{b,I}$ respectively are frequency dependent weighting coefficients. According to the values of $W_{b,A}$ given in the standard [1], the single number $R_\mathrm{w} + C_\mathrm{B}$ is mostly dependent on the higher third octave bands in B. Furthermore, the value of $W_{b,I} = 15$ dB for the whole frequency band is given in the standard [2]. Results presented in [6], [7] showed that single values resulting from such weighting coefficients, in particular in regard to impact noise, cannot discriminate good designs from worse, in a way which is consistent with inhabitant perceived performance. Adapted weighting coefficients were consequently introduced in regard to impact noise, such that the adequation of the resulting single number quantities was improved with respect to inhabitant perception.
Thus, in order to focus to low frequency problems associated with airborne sound insulation, it is proposed to introduce a fitness function J_A , computed over the frequency band B = [20,200] Hz in the spirit of Eq. (1) but without coefficients. Let g_i be the genotype associated with individual "i", $J_\mathrm{A}(g_i)$ is an objective performance indicator of the design indexed by g_i such that

$$J_A(g_i) = -10\ \log_{10}\left(\sum_{b\in \mathrm{B}} 10^{-R_b/10}\right). \tag{3}$$

Moreover, in regard to impact sound insulation performance, weighting coefficients adapted from [6], [7] are used. The fitness function J_I is the defined over the frequency band B = [20,200] Hz as

$$J_I(g_i) = -10\ \log_{10}\left(\sum_{b\in \mathrm{B}} 10^{(L_{n,b}-W_{b,I,Akulite})/10}\right), \tag{3}$$

where $W_{b,I,Akulite}$ coefficients are given in Table 1. It should be noted that a minus sign in Eq. (3) is used so that maximising J_I is equivalent to minimizing impact noise.

Table 1: $\boldsymbol{W_{b,I,Akulite}}$ coefficients

Frequency band [Hz]	20	25	31.5	40	50-200
$W_{b,I,Akulite}$	7	9	11	13	15

3. Applications

In the following, two applications are successively considered. The first one regards an optimal choice of products (plasterboards, cavity depth, CLT thickness, resilient material, and cement screed thickness) for a basic layout shown in Fig. 2. The aim is to maximize functions J_A and J_I respectively associated with airborne and impact sound insulation performance. In the second application, the same optimal choice of products is sought; but with a third objective which is to minimize the total thickness h of the system.

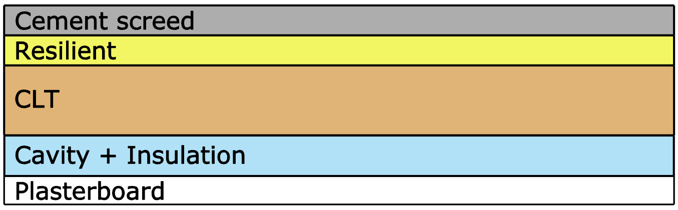

Figure 2: Basic layout for system 1

In this application, admissible values for each design parameter are given in Table 2. For this relatively simple problem, the dimension of the associated search space (or number of admissible combinations) is consequently $n = 4 * 8 * 4 * 2 * 2 = 512$. In most cases, fitness functions are evaluated in using a model of the system's behaviour. Such a model can be complex and computationally demanding. Thus, a fast exploration of the search space requires the least possible evaluations of fitness functions.

Table 2: Design parameters

Cement screed thickness	40 mm		60 mm		80 mm		100 mm	
Resilient stiffness	0.5 MPa	1 MPa	2 MPa	3 MPa	5 MPa	7 MPa	9 MPa	11 MPa
CLT thickness	95 mm		115 mm		160 mm		200 mm	
Cavity depth/insulation thickness	60 mm				120 mm			
Plasterboard	1 plasterboard (12.5 mm)				2 plasterboards (25 mm)			

In this work, airborne sound reduction index and impact noise levels are computed in using AcouSYS software. Systems are modelled as infinite homogeneous stacked layers and finite dimensions are taken into account with spatial windowing [11]. The numerous remaining physical parameters associated with the different layers are rather classical and taken from the software database. They are not listed here for reasons of conciseness and results are analysed from a qualitative point of view.

3.1 Preliminary investigations

In order to illustrate and discuss various points, the performance of all 512 admissible configurations are first evaluated in a systematic way. This is not a prerequisite of the optimisation methodology and is undertaken purely for analysis. Figure 3 shows the distribution of the design parameter values function of the normalised performance. The worst designs with respect to objective functions J_A and J_I define the zero references meanwhile the best ones define the upper references.

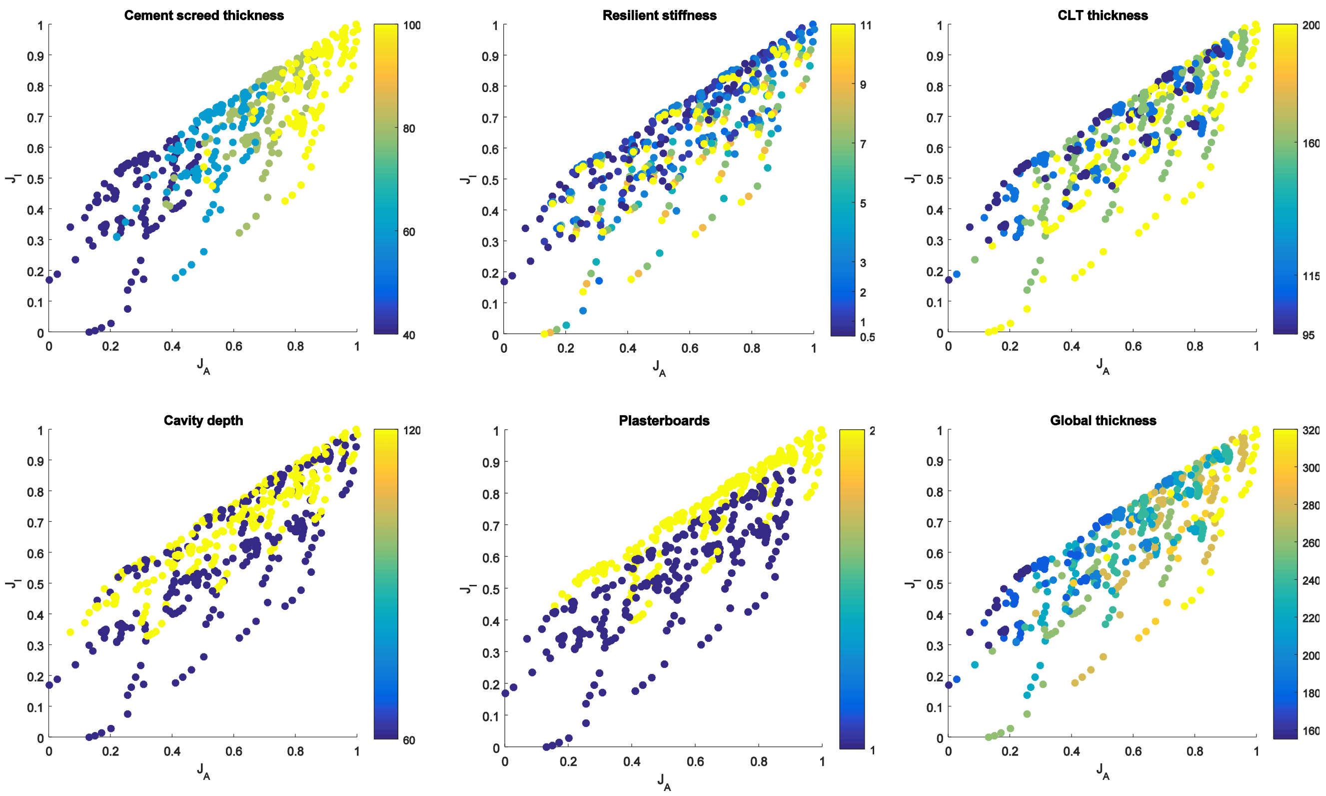

Figure 3 : Distribution of the design parameters function of the normalized performance among all 512 admissible configurations

Thus, the first observation is that airborne and impact sound insulation are not competing objectives. It is possible to improve one without worsening the other. In fact the Pareto front comes down to two close designs for which only the resilient stiffness differs.
Moreover, it can be observed that increasing cement screed thickness globally shifts up the whole performance meanwhile it is possible to obtain good performances with diverse values of resilient stiffness and CLT thickness. Indeed, it can be seen that the associated values are spread out among various levels of performance. Moreover, if a good airborne insulation performance can be obtained with a 60 mm cavity and a single plasterboard, the best impact sound insulation performance can only be attained with a 120 mm cavity and a double plasterboard. Finally, it can be seen that overall, the very best performance is attained for high thickness. However, maximum thickness doesn't guarantee the best performance as the appropriate resilient material has to be selected.

3.2 First optimization

In this application, the configuration that maximises airborne and impact sound insulation is sought. The genetic algorithm is then used to explore the search space. An initial population of 40 individuals is created. Selection is performed through tournaments of size 10. The 4 best individuals of every generation are kept for the next one. Finally, 4 children are per generation are result from a random mutation. Thus, a little less than a tenth of the number of admissible configurations is initially evaluated. Moreover, the selection pressure is quite high as the best parents are selected among quarters of the population.

Figure 4 shows the evolution of objective performance with generations of the algorithm. In order to evaluate the ability of the algorithm to converge towards global optimal solutions, the normalisation is performed with respect to the best and worse configurations resulting from the Section 3.1. The first generation is randomly selected to map the search space and then, the algorithm is able to find new designs whose performance gets better and better. After the fourth generation the algorithm stops as the population diversity is low and only slow mutations can contribute to the creation of new designs. Over the course of the algorithm, 60 unique configurations were evaluated. That is to say that 60 unique vibro-acoustic problems were solved with this strategy in place of 512 for a naïve approach.

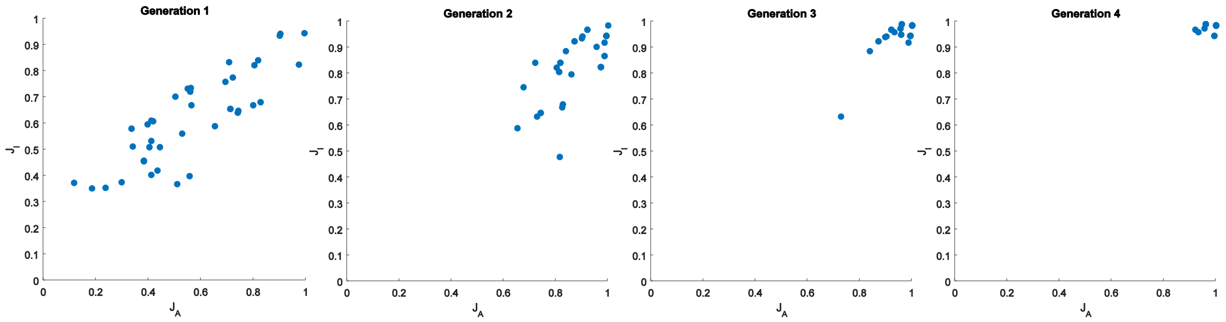

Figure 4 : Evolution of the performance among algorithm generations

3.3 Second optimization

In this application, a third objective is considered. Now, the best airborne and impact sound insulation is sought but for a minimal thickness. From Figure 3 we already know that an objective of maximal acoustic performance will compete with an objective of minimal thickness. Thus, the Pareto front associated with this multi-criteria optimization will consist in a surface portion surrounding the three-dimensional point cloud whose coordinates are the three objective performances. It is then necessary for the designer to know Pareto equivalent configurations in order to make the final choice or compromise.

a) (b)

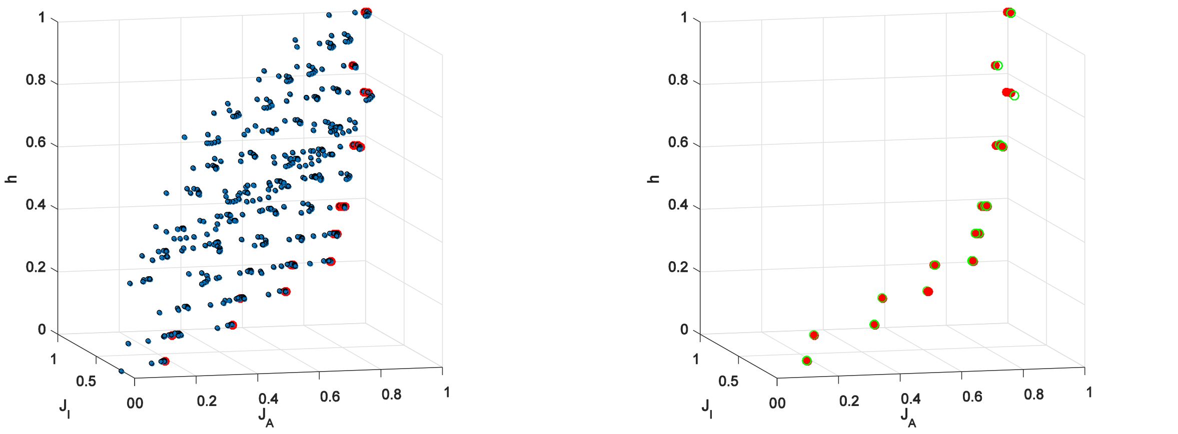

Figure 5 : (a) three-dimensional point cloud associated with the three objectives for the 512 admissible configurations, red dot denote the Pareto front; (b) exact (red) and estimated through optimisation (green) Pareto fronts

Figure 5 (a) shows the three-dimensional point cloud of the 512 configurations evaluated in Section 3.1 with Pareto equivalent configurations denoted with the red dots. The thickness is normalised with respect to the lower admissible values, which defines the zero, and the highest. It can be seen how the Pareto front allows to select the best possible configuration, as soon a final constraint (such as a given thickness) is added. Then, the optimisation algorithm is used to try to find the Pareto front.

Exact same algorithm parameters than in Section 3.2 are used. Figure 5 (b) compares the Pareto front found by the algorithm and the exact one. Not every exact Pareto equivalent configuration has been found but the algorithm provides a quite good estimate of the contour surface. Over the course of the algorithm, 86 unique configurations were evaluated with this strategy in place of 512 for a naïve approach.

4. Conclusions

A strategy was presented for the multi-criteria optimization of a wood based floor. Objective performance indicators were constructed in order to tackle the low frequency range. Applications were presented to illustrate the relevance of the strategy in comparison with direct naïve approach.

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