DESIGN OF MULTI-STORY TIMBER BUILDING USING MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION

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ABSTRACT: This paper presents a design method for multi-story timber building with consideration of regulatory constraints. The objective is to optimize in the same time thermal, structural and environmental objectives taking into account the industrial feasibility. This work aims to develop a preliminary design tool that integrates both, optimization step and decision making support. To set up this method and the appropriate tool a case study is developed and will be implemented.

KEYWORDS: Multi-story timber building, Multi-objective optimization, Energy simulation, Structural analysis, Environmental impact, Multidisciplinary Design Optimization, Particle Swarm Optimization (PSO)

1 INTRODUCTION

Wood is a low environmental impacts material with a dry and rapid implementation in the building process, facilitated by a potential high prefabrication level. However in France, timber building is still underdeveloped with a building incorporation rate of 10% against 15% in Germany and 35% in Scandinavia and North America [1]. Furthermore, a lack of knowledge in timber building, especially for multi-story slows its development [2]. To expand multi-story timber building there is a need to develop design methods with regulatory constraints consideration.

Although the benefits of using wood are accepted by the building trade, a lack of confidence persists regarding fire safety, acoustics, stability and durability of timber frame constructions [3]. Recently, multi-story timber structures are emerging worldwide [4-6]. These good examples demonstrate the technical and economic feasibility of such buildings.

Building is a complex system, subject of multidisciplinary design studies generally considered by technological fields. Building envelopes design is guided by different disciplines including structural engineering, energetics, environment, lighting, and acoustics. In order to develop optimized building design considering thermal, structural and environmental objectives, it is necessary to increase design understanding tradeoffs involved. This makes it a challenging multi-objective optimization problem.

Usually, in multi-objective optimization building problems, one of the two strategies below is used as detailed on [7]: one is optimizing a weighted function including the different objectives and the other is the multi-objective optimization with Pareto front. The first strategy leads to a single solution while the second one leads to a set of optimal compromise between objectives, maintaining a clear view on results significance which is its major benefit. Well adapted to this strategy, the use of metaheuristic techniques to optimize multi-objective building design problems is growing over the years [8]. As studied on [9,10], the aim is often to optimize building considering conflicting design objectives such as energy consumption, cost, comfort and environmental impact (Fig. 1). However, very little research associates structural objectives or constraints to sustainable building optimization.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Choices of optimization objective function [7]}
\end{figure}

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[7], [8] and [9] underline and conclude on the necessity to develop tools, for sustainable building design, that integrate both, building physic simulation and optimization process. However, optimization process can lead to a large computational burden especially when detailed simulation models are used. Such tools have to reduce computation time, to be accurate, and to support decision making.

Firstly the methodology will be presented. Optimization approach and algorithm will be defined. Secondly, the toolbox would be specified. It consists to a preliminary design tool incorporating thermal metamodels generation, sensitivity analysis and optimization process. Finally, a case study will be presented, objectives to optimize defined and initial results discussed.

2 METHODOLOGY

2.1 OPTIMIZATION APPROACH

First, the overall approach is to perform a search process through the multi-objective optimization. Then, a decision process is implemented through a multi-criteria analysis.

Multi-objective optimization is divided into six steps:

1. **Objectives selection**: technological, environmental and social objectives are initially selected.
2. **Identification of significant variables**: significant design variables are selected by theory, sensitivity analysis and expertise.
3. **Establishment of influence graph**: the relationships between objectives and variables are established and represented as influence graph.
4. **Explanation of links between variables and objectives**: it consists in assembling knowledge and implemented necessary research to explain the relationships between variables and objectives.
5. **Modeling of each objective function**: objective functions are designed as explicit qualitative function or algorithm.
6. **Implementation of the multi-objective optimization method**: optimization calculation by the use of a metaheuristic and Pareto front adapted to the variety of objective functions and to the heterogeneity of variables.

Multi-criteria decision process is the second part of the approach. It aims to choose, according to several criteria and specific context, the most adapted solution from the previously obtained set of optimal solutions:

1. **Choice of decision criteria**: economic, preferential and expertise criteria are selected.
2. **Implementation of the method of multicriteria decision**: The appropriate method that implements the decision maker preferences and the desired output kind (classification, categorization ...) is applied.

The multicriteria decision process will not be addressed in this work. Currently two works on multi-criteria analysis applied to wood frame buildings were identified: one is the overall scale of the building [10] and the other is across the wall [11].

2.2 OPTIMIZATION ALGORITHM

Metaheuristic methods like genetic algorithm (GA), ant colony (AC), particle swarm optimization (PSO) are well adapted to multi-objective optimization. Developed by Kennedy and Eberhart [12], PSO, like other metaheuristic methods, finds a set of optimal solutions to a difficult optimization problem. This method, motivated by the simulation of social behavior, has proved to be very efficient in multi-objective optimization including continuous and discrete decision variables. Like GA, the system is initialized with population and searches for optima by updating generations. However unlike GA, PSO has no evolution operators such as crossover and mutation. PSO while traversing the search space is focused on optimum, whereas GA explores the search space and then can takes more time to find the optimum. Optimization tools for building design have to reduce computation time, especially when detailed simulation models are used. Multi-objective PSO technique is especially and fully suitable for our problem where five objectives have to be optimized with continuous and discrete decision variables.
The original procedure for implementing PSO is simple and easy to implement six steps algorithm [12]:

1. Initialize a population of particles with random positions and velocities on n dimensions in the problem space.
2. For each particle calculate the fitness (the function to optimize in n variables).
3. Compare particle’s fitness with the fitness of its best position ever visited (pbest). If current value is better than pbest, then it becomes pbest.
4. Identify the particle in the neighborhood with the best fitness; it becomes the leader of the neighborhood.
5. Change the velocity and position of particles according to velocity and position updating rules (3) and (4).
6. Loop to step 2. Until the end condition is met, usually a sufficiently good fitness or a maximum number of iteration.

For a search in an n-dimensional space search where the particles movements are synchronized, at the tth iteration, for the ith particle, the position and position change (velocity) vectors are respectively represented as (1) (2) [13]:

\[ X_i^t = (x_{i,1}^t, x_{i,2}^t, \ldots, x_{i,n}^t) \]  
\[ V_i^t = (v_{i,1}^t, v_{i,2}^t, \ldots, v_{i,n}^t) \]  

The position and position change (velocity) updating rules are given as below:

\[ x_{i,j}^{t+1} = x_{i,j}^t + v_{i,j}^{t+1} \]  
\[ v_{i,j}^{t+1} = w v_{i,j}^t + c_1 r_1 (p_{i,j}^t - x_{i,j}^t) + c_2 r_2 (g_j^t - x_{i,j}^t) \]  

Where \( i = 1, 2, \ldots, p \), \( j = 1, 2, \ldots, n \), \( p \) is the number of particles (the size of swarm), and \( n \) is the dimension of search space; \( x_{i,j}^t \) is the position of the particle \( i \) and \( v_{i,j}^t \) its velocity; \( w \) is called inertia weight, it is used to control the impact of the previous history of velocity on the current one; \( r_1 \) and \( r_2 \) are uniformly distributed random numbers between 0 and 1; \( c_1 \) and \( c_2 \) are positive acceleration constants; \( p_{i,j} \) is the value of \( j \)th dimension of the best position ever visited by \( i \)th particle; \( g_j \) is the value of \( j \)th dimension of global best position ever visited by all particle in the swarm.

3 OPTIMIZATION-SIMULATION TOOLS

The PSO optimization process will be performed using the Ted© tool (Tool for Ecodesign) [12]; structural and environmental objectives will be modeled using analytic functions that can comprise continuous and discrete decision variables. EnergyPlus 7.2 (DOE, U.S Department of Energy) will be used for energy and comfort simulation; and corresponding metamodels will be generated and used as objective functions to be implemented in Ted© (Fig. 2).

**Figure 2: Components and their relationships for simulation-based optimization**

An important task is to reduce the computation time required to get the optimal solutions when detailed simulation models are used. The issue could be addressed by metamodeling techniques which approximate a simplified function relationship between the simulation results and the input variables. Metamodels based on polynomial chaos (PC) [14] have the advantage to deduct Sobol indices [15] of the output from its coefficients with almost no additional cost [16]. The Sobol indices are used in global sensitivity analysis as a tool for ranking the input random variables of a model according to their weight in the variance of the model response. The use of PC from an EnergyPlus model was used in [17] to evaluate the spread of uncertainties by coupling with the OpenTURNS© tool, which integrate a PC toolbox [18].

Let a numerical model, \( f \), having \( n \) input parameters gathered in an input vector \( \mathbf{X} = (x_1, x_2, \ldots, x_n) \), and a scalar output \( Y \):

\[ Y = f(\mathbf{X}) \]

\( \mathbf{X} \) follows the joint probability density function. The polynomial chaos expansion enables to approximate the output random variable of interest \( Y \) by the new output random variable of interest \( \tilde{Y} \). A truncated polynomial chaos to order \( k \) is as follows

\[ Y \approx \tilde{Y} = \sum_{k=0}^{k} \alpha_k \psi_k \circ T(\mathbf{X}) \]

where \( T \) is an isoprobabilistic transformation which maps the multivariate distribution of \( \mathbf{X} \) into the multivariate distribution \( \mu \), and \( \psi_k \) is a multivariate polynomial basis which is orthonormal according to the distribution \( \mu \) and \( \alpha_k \) are the polynomial coefficients to compute in order to minimize the difference between the variable of interest \( Y \) and its polynomial approximation.

The determination of the Sobol decomposition and sensitivity indice is immediate as soon as the PC expansion of \( f \) is known. The Sobol indice \( S_u \) of \( f \) are approximated by [16]:

\[ S_u \approx \tilde{S}_u = \sum_{k=0}^{k} \alpha_k^2 \left< \psi_k^1, \psi_k^1 \right> \]

\[ \sum_{k=0}^{k} \alpha_k^2 \left< \psi_k^1, \psi_k^1 \right> \]
4 CASE STUDY

4.1 DESCRIPTION

The case study (Fig. 3) is a three-story office building with an objective the optimization of the building envelope composition. Architectural geometry, location and use are fixed parameters. Timber structure is a discrete variable. Three options will be considered during the optimization process: beam to beam, cross laminated timber (CLT) and timber frame structure. Glulam beams, mixed (timber and concrete), concrete and CLT floors would be also considered as discrete variables. Others variables concern the building envelope such as insulation level, glazing, beam cross section. The envelope composition will vary according floors level.

![Figure 3: Case study building](image)

4.2 OBJECTIVE FUNCTIONS

Currently, five objectives to optimize have been selected in our problems.

**Heating needs:** It is the energy demand to keep the building at a setpoint temperature $T_{set}$ during the winter. The objective is to minimize the gap between the desired $H_d$ and obtained heating needs $H_n$ as follows (8). If the objective is simply to minimize the needs for heating while $H_d=0$. $H_n$ must be bellow a fixed value $H_{\text{max}}$.

$$F_1 : \min(\text{abs}(H_n - H_d)) \quad \text{and} \quad H_n \leq H_{\text{max}}$$

(8)

**Summer comfort:** The degree-hour $DH$ is summation of the building thermal zones integral operative temperature degrees $T_o$ higher than a comfort temperature $T_c$ during an hourly simulation period with occupancy $p_{occ}$. The comfort temperature depends on the type of building. The objective is to minimize $DH$. $DH$ must be bellow a fixed value $DH_{\text{max}}$.

$$DH = \sum \text{zones} \left( \int (T_o - T_c) dt \right) \text{ when } T_o > T_c$$

(9)

$$F_2 : \min(DH) \quad \text{and} \quad DH \leq DH_{\text{max}}$$

(10)

**Floor vibration comfort:** Three comfort levels 1, 2, 3 and 4 respectively, very good, good, acceptable and unacceptable are fixed. Comfort level, $F_v$, have to be minimized.

$$F_3 : \min(F_v) \quad \text{and} \quad F_v \neq 3$$

(11)

**Global warming potential (GWP):** The objective is to minimize de $GWP$ related to the envelope during the building life cycle (Pre-Use, Use, Replacement and End of Life). The pre use and replacement emissions of the raw material extraction and materials manufacturing are calculated based on the mass of each material in the building construction. The end of life emission related to the demolition and disposal transportation to landfill and recycling center are also calculated based on the mass of each material in the building construction. Finally the use emission related to the envelope is determined by first calculating the heating needs during the building life cycle. Then heating needs are multiplied by the efficiency of the heating system and the local electricity emissions factor.

$$F_4 : \min(GWP)$$

(12)

**Embodied energy:** The objective is to minimize embodied energy $E_{en}$ of the envelope during the building life cycle. It is determined similarly to the $GWP$.

$$F_5 : \min(E_{en})$$

(13)

In longer term acoustic insulation, lighting autonomous and structural cost would be implemented to the optimization.

4.3 STRUCTURAL AND SIZING CONSTRAINTS

**Floor height:** The floor height is limited to a maximum value defined by the variables.

**Wall thickness:** The wall thickness is limited to a maximum value defined by the variables.

**Structural constraints:** Solutions must meet the normative requirements of Eurocode 5 [19-20] or, for CLT as the recommendations of FPInnovations [21]. Preliminary design calculations will be performed to check the viability of solutions regarding to the ultimate limit state (ULS) and the serviceability limit state (SLS).

4.4 VARIABLES

Two types of variables are considered in this optimization model: continuous variables as insulation thickness and discrete variables as kind of floor. Continuous variables are box constraints with boundary values and discrete variables give a predefined set of alternatives.

When generating metamodels, it is possible to extract the total Sobol indice $STi$. $STi$ express the responsibility of each parameter in its range of variation correlated with the others on the output variation.

For instance, for heating needs, 10 parameters have a greater influence on 24 studied parameters (Fig. 4): the wall insulation thickness ($x_0, x_1, x_2$) and conductivity ($x_6$), wall CLT thickness ($x_3, x_4, x_5$), windows $U$-value ($x_{11}$, $x_{12}$) and south window solar factor ($x_{14}$) (Table 1). These influential parameters have to be taking into account during the optimization process. Other parameters may be fixed
according to the designer choice. It is important to notice that the parameters influence ranking largely depends on their field of variation. Therefore it must be chosen carefully.

Figure 4: Design parameters influence for heating according to total Sobol indice

Table 1: Parameters description

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>First story wall insulation thickness</td>
</tr>
<tr>
<td>x1</td>
<td>Second story wall insulation thickness</td>
</tr>
<tr>
<td>x2</td>
<td>Third story wall insulation thickness</td>
</tr>
<tr>
<td>x3</td>
<td>First story wall CLT thickness</td>
</tr>
<tr>
<td>x4</td>
<td>Second story wall CLT thickness</td>
</tr>
<tr>
<td>x5</td>
<td>Third story wall CLT thickness</td>
</tr>
<tr>
<td>x6</td>
<td>Wall insulation conductivity</td>
</tr>
<tr>
<td>x7</td>
<td>First story wall cover panels thickness</td>
</tr>
<tr>
<td>x8</td>
<td>Second story wall cover panels thickness</td>
</tr>
<tr>
<td>x9</td>
<td>Third story wall cover panels thickness</td>
</tr>
<tr>
<td>x10</td>
<td>Cover and ceiling panels density</td>
</tr>
<tr>
<td>x11</td>
<td>North windows U-value</td>
</tr>
<tr>
<td>x12</td>
<td>South windows U-value</td>
</tr>
<tr>
<td>x13</td>
<td>North windows solar factor</td>
</tr>
<tr>
<td>x14</td>
<td>South windows solar factor</td>
</tr>
<tr>
<td>x15</td>
<td>First floor insulation thickness</td>
</tr>
<tr>
<td>x16</td>
<td>CLT density</td>
</tr>
<tr>
<td>x17</td>
<td>Floor concrete cover density</td>
</tr>
<tr>
<td>x18</td>
<td>Roof insulation thickness</td>
</tr>
<tr>
<td>x19</td>
<td>Roof CLT thickness</td>
</tr>
<tr>
<td>x20</td>
<td>Roof insulation conductivity</td>
</tr>
<tr>
<td>x21</td>
<td>Ceiling panels thickness</td>
</tr>
<tr>
<td>x22</td>
<td>Floor CLT thickness</td>
</tr>
<tr>
<td>x23</td>
<td>Floor concrete cover thickness</td>
</tr>
<tr>
<td>x24</td>
<td>Natural ventilation rate</td>
</tr>
</tbody>
</table>

For degree-hour 11 parameters have a greater influence on 25 studied parameters (Fig5): the wall cover and ceiling panels thickness (x7, x8, x9, x21) and density (x10), CLT density (x16), floor CLT and concrete cover thickness (x22, x23), window solar factors (x13 and x14) and natural ventilation rate (x24) (Table 1).

For the same range of variation, only one parameter (x14) influences both heating needs and degree-hour. Parameters that concern external floors insulation have no influence for both, heating needs and degree-hour (x15, x18, x19, x20). This is mainly due to the poor external floor surface ratio compare to wall and intermediate floor surface on this case study.

Figure 5: Design parameters influence for degree-hour to total Sobol indice

4.5 EXPLOITATION OF RESULTS

Analysis of the resulting set of solutions can be difficult, particularly when there are a large number of objectives and decision variables to consider. In addition to the Pareto front, use of a parallel coordinate plot [22] (Fig. 4) will enable to selectively visualize impact of decision variables on the objectives and to support decision-making.

Figure 6: Parallel coordinate plot

In [23], another method has been developed to analyse the solutions obtained from a multi-objective optimisation. Solutions are ordered by one objective and correlations between design variables are evaluated.

5 CONCLUSIONS AND PERSPECTIVES

To expand multi-story timber buildings with multidisciplinary design, a multi-objective optimization method is proposed. The methodology aims the preliminary design of the building where architectural geometry, location and use are fixed parameters. It includes the optimization of structural, energy and environmental objectives though the minimizing of energy needs, thermal discomfort, CO₂-equivalent emission and embodied energy of the building and the maximizing of floor vibration comfort. Structural constraints are considered by preliminary design calculations.

A preliminary design tool with optimization step and decision making support is being developed. This tool integrates building physical simulation and optimization process. To save valuable time, detailed simulation models are replaced by metamodels. In addition, they enable to perform a sensitivity analysis almost instantly. Non-influential parameters would be fixed according to the designer.
On-going work on environment and structural objectives will complete the optimization process. Also integration of discrete variables concerning the structure kind has to be performed.

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