# Development of a multi-criteria decision support tool for sustainable building retrofits

*Zaid Romani* [a], *Abdeslam Draoui* [b], *Francis Allard* [c].

[a] LaRAT, National School of Architecture of Tetouan, Morocco, z.romani@enatetouan.ac.ma.

[b] ETTE, Faculty of Sciences and Technology of Tangier, Abdelmalek Essaadi University, Morocco, adraoui@uae.ac.ma.

[c] LaSIE, La Rochelle University, France, francis.allard@univ-lr.fr.

**Abstract.** The existing building stock represents a major challenge for a successful energy transition and achieving zero carbon territories. Several thermal simulation tools have integrated optimization modules for building design and retrofit. However, in these tools there are problems of convergence towards local optimum and the unknown computation time. Indeed, we propose in this research work a tool allowing an optimal choice of building envelope to achieve a sustainable building retrofit by integrating 16 criteria representing the heating energy needs as well as economic and environmental criteria. This tool is based on thermo-aeraulic dynamic simulation using TRNSYS and CONTAM software, the metamodeling based on the design of experiments method and polynomial regression as well as three multicriteria analysis methods such as weighted sums, Min Max and Pareto optimality. Using this tool, the calculation time of the optimization process and the uncertainties of the results are known. Thermal comfort considered as a social criterion is studied in the post-processing. A real-life existing building located in La Rochelle city (France) was chosen as a case study. The results show that the tool developed allows a rapid choice of building envelope technical solutions and to get a compromise between all criteria studied.

**Keywords.** Building energy retrofits, Sustainable building, Multicriteria optimization tool.
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## 1. Introduction

Currently, and in parallel with the health crisis of Covid 19 and the technological development that humanity is experiencing, the energy production and consumption are also at the center of public debates. They represent one of the essential subjects in international politics and societal discourses.

According to the International Energy Agency [1], the building and construction industry together represent actually the most energy-consuming and polluting sector in the world. Indeed, this sector is responsible for more than a third of final energy consumption and almost 38% of direct and indirect $CO_2$ emissions (this percentage represents the highest value of $CO_2$ emissions ever recorded) [1]. This consumption continues to increase due to the use of energy-intensive devices and the rapid growth of the buildings floor space [2]. It should be noted that to get involved in the mitigation of global warming, it will be necessary to achieve zero-carbon building stock by 2050 through the reduction of direct $CO_2$ emissions by 50% [3].

The implementation of energy efficiency strategies in buildings makes it possible to reduce a colossal share of the total expenditure of countries around the world [4], to mitigate the harmful impacts on the environment [5], to abolish energy poverty [6] and improve the comfort conditions of occupants [7]. Moreover, these strategies must be affordable by the population.

In this regard, we are faced with a multi-criteria problem (economic, social and environmental criteria). In addition, meeting these criteria must last over time to ensure climatic resilience. Therefore, a sustainable building implies considering, in the design process and during the rehabilitation, the life cycle of the building by evaluating these economic, social and environmental impacts from the extraction of the raw material to its deconstruction.

In the sketching stage of building retrofit, energy simulations with some parametric studies are insufficient to achieve an optimal choice among the technical solutions that exist on the market. To achieve this objective, research work proposes the coupling of optimization and multicriteria analysis methods with building energy simulation software [8, 9]. This coupling consists in the use of programming languages (such as Matlab, Python, etc.) integrating mathematical optimization methods. To make this coupling more practical, recent tools have been developed with user-friendly interfaces to perform multi-criteria optimization [10, 11]. However, the large majority of optimization algorithms used in these tools presents several drawbacks such as the high computation time (in the case of several combinations) and the possibility of converging towards a local optimum.

To remedy these issues, in this research work, we present a multi-criteria decision support tool for sustainable building retrofit. It is based on the development of metamodels from the design of experiments method and polynomial regression as well as the TRNSYS and CONTAM software to predict the heating energy needs. Considering the fast calculation using these metamodels, they are then used in a combinatorial process by integrating environmental and economic criteria. The best compromise is obtained through three multicriteria analysis methods.

## 2. Calculation process

It is often difficult to find the best trade-off among the passive technical solutions that contribute to the sustainable building retrofit. The tool proposed in this work is based on a calculation process that we have already developed [12]. This calculation process integrates the development of the heating energy needs metamodel, the evaluation of the economic and environmental criteria on the building life cycle, the comparison between three multicriteria analysis methods as well as a post-processing to reduce indoor overheating in summer. The calculation process of this tool is presented in Figure 1.

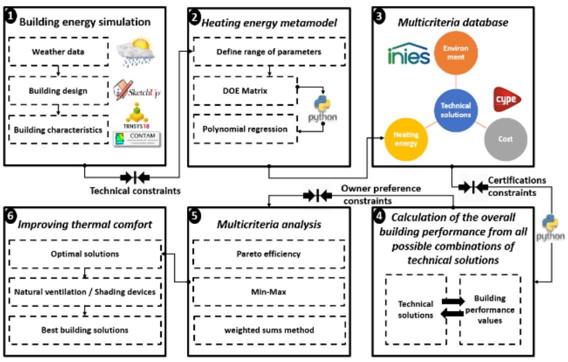


**Fig. 1** - Calculation process proposed to get the best technical solutions for sustainable building retrofit [12].

In the first step of the calculation process, it is necessary to draw the building and define the characteristics of the building project which will be the object of the rehabilitation as well as the climatic data. In order to carried out the dynamic thermo-aeraulic simulations, the building modeling is achieved using the TRNSYS 3d and CONTAM coupling software. Technical constraints may exist and must be taken into account. For example, if it is not possible to change the coating of the exterior facade, the solar absorption coefficient will be fixed.

The passive building envelope parameters considered in our tool as variables are presented in Table 1. A variation interval of these parameters has been defined. The maximum values represent the envelope characteristics of the existing building which are generally the least efficient solutions. The minimum values represent effective solutions that exist in the construction market.

**Tab. 1** - Passive building envelope parameters considered as variable in the tool developed [12]

| Parameters | Symbol | Range | Unit |
|---|---|---|---|
| Transmission coefficient of external walls | $U_{ew}$ | [0.15-EBV] | $Wm^{-2}\cdot K^{-1}$ |
| Absorption coefficient of external walls | $\alpha_{ew}$ | [0.05-0.95] | - |
| Transmission coefficient of the roof | $U_{rf}$ | [0.15-EBV] | $Wm^{-2}\cdot K^{-1}$ |
| Absorption coefficient of the roof | $\alpha_{rf}$ | [0.05-0.95] | - |
| Transmission coefficient of the floor | $U_{fl}$ | [0.15-EBV] | $Wm^{-2}\cdot K^{-1}$ |
| Transmission coefficient of the windows | $U_{w}$ | [0.4-EBV] | $Wm^{-2}\cdot K^{-1}$ |
| Solar factor of the windows | g-value | [0.05-0.95] | - |
| Absorption coefficient of the frame | $\alpha_{f}$ | [0.05-0.95] | - |
| Infiltration rate (4 Pa) | $Q_{4\text{-}Pa}$ | [0.1- EBV] | $m^3\cdot h^{-1}\cdot m^{-2}$ |
| Transmission coefficient of the thermal bridge | $\psi$ | [$10^{-2}$- EBV] | $Wm^{-1}\cdot K^{-1}$ |

EBV: Existing building value

In the second step, in order to reduce the computation time resulting from the dynamic thermo-aeraulic simulations in the optimization process, metamodels are developed to predict the heating energy needs. This is achieved with a limited number of simulations determined by the design of experiments method (D-optimal design) and a full quadratic polynomial regression [13]. Python programming language is used to automate the TRNSYS and CONTAM simulations. Thereafter, the calculation of the building energy needs will be carried out from the metamodel developed without recourse to dynamic thermal simulation.

The next step is to generate a multi-criteria database of technical building solutions existing in the building market and their associated economic and environmental databases. The environmental criterion is made up of twelve indicators (Table 2) calculated over the life cycle of the building based on the French database (INIES) [14]. INIES database integrates the environmental characteristics of construction products available on the construction market in France. The economic criterion is a key element to assess the feasibility of construction projects. Three indicators used in our tool which are the initial investment cost, the payback time and the life cycle cost (Table 2). The cost of each technical solution is taken from the Cype software database [15].

**Tab. 2 -** Selected environmental and economic indicators

| Parameters | Unit | Symbol |
|---|---|---|
| Climate Change | (kg $CO_2$ eq.) | CC |
| Depletion potential of the stratospheric ozone layer | (kg CFC-11 eq.) | OPD |
| Acidification potential of land and water | (kg $SO_2$ eq.) | APLW |
| Eutrophication | (kg $(PO_4)_3$ eq.) | ET |
| Photochemical ozone formation | (kg $C_2H_4$ eq.) | POF |
| Abiotic resource depletion potential for elements | (kg Sb eq.) | ADPE |
| Abiotic resource depletion potential of fossil fuels | (MJ) | ADPF |
| Air pollution | ($m^3$) | AP |
| Water pollution | ($m^3$) | WP |
| Total use of renewable primary energy resources | (MJ) | TRPER |
| Total use of non-renewable primary energy resources | (MJ) | TNRPER |
| Use of net fresh water | ($m^3$) | UNFW |
| Initial investment cost | (€ or €/$m^2$) | CINV |
| Payback period | (year) | PBP |
| Life cycle cost | (€ or €/$m^2$) | LCC |

In the fourth step, using the Python programming language, the calculation of the set of criteria is performed for each combination of technical solutions. In this step, the user can give limit values not to be exceeded for each criterion in order to achieve a desired performance of the building (regulations, certification, etc.).

Three multi-criteria analysis methods are used and compared with the fifth step namely the weighted sums, the Min-Max and the Pareto optimality method [12]. In order to take into account user preferences, a weight is assigned to each criterion.

Once the choice of the optimal solution is made, the last step is to improve thermal comfort in summer. In our tool, a post-treatment was proposed to reduce the indoor temperature in the summer period. This objective will be achieved by the integration of two passive solutions such as natural ventilation and windows shading devices. The thermal comfort rate (TCR) is calculated as being the ratio of the hours of comfort (when the operating temperature exceeds the comfort temperature) and the hours of occupancy.

Thus, a package of optimal solutions allowing all the criteria to be met is obtained and which will guarantee the best compromise between all criteria studied and contributing to a sustainable building retrofit.

## 3. Tool application with a case study

The calculation process presented above has been transformed into a tool which can be used easily. The python code is linked through another VBA code embedded in an Excel file (Figure 2).

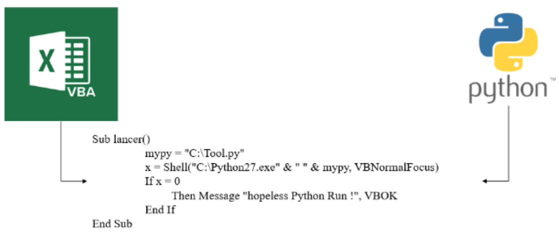


**Fig. 2 –** Python and Excel VBA code link.

The building case study is a real four-storey existing building with a total floor area of 960 $m^2$ (figure 3). It represents a typical French social housing built in 1954. It is located in La Rochelle city on the south-west Atlantic coast of France. This city is characterized by an oceanic climate.

**Fig. 3 –** Real building studied before rehabilitation.

Each floor consists of two T1 (one room) type apartments with a surface area of 26 m$^2$ and two T5 type apartments (4 rooms and one living room) with an area of 94 m$^2$. The ceiling height is 2.7 m. The large facades are oriented East-West and have large glass surfaces with a ratio of 30% and 20% respectively. This building is studied using the developed tool.

The different data entry steps are explained below:

The first window of the tool was devoted to introducing information about the project (Figure 4). A file name can be chosen according to the user. Then, it is possible to choose the climate data without going back to TRNSYS. In the TRNSYS/CONTAM file box, it will be necessary to put the link of modeling files. Users must enter the building lifespan to calculate the number of technical solutions replacements.

| General informations | |
|---|---|
| File name | Case 1 |
| Climate data | La Rochelle.tm2 (Tanger.tm2, Ifrane.tm2, Casablanca.tm2, Paris.tm2, Nantes.tm2, La Rochelle.tm2) |
| TRNSYS/CONTAM File | |
| Building lifespan (years) | |

| General informations | |
|---|---|
| File name | Case 1 |
| Climate data | La Rochelle.tm2 |
| TRNSYS/CONTAM File | D:\TRNSYS_CONTAM |
| Building lifespan (years) | 50 |

**Fig. 4 –** General information's windows of the tool.

The users can choose the metamodel type (linear, quadratic, linear with interactions, and full quadratic). In addition, the economic and environmental database has been fixed in this tool (Figure 5). There is also the possibility of integrating another database directly on another sheet of the same excel file.

| Multicriteria analysis methods and databases | |
|---|---|
| Metamodel type | Linear (Linear, Quadratic, Linear with interaction, Full quadratic) |
| Weighted sum method | |
| Min-Max method | Yes |
| Pareto efficiency | Yes |
| Cost database | Tool Data |
| Environmental database | Tool Data |

| Multicriteria analysis methods and databases | |
|---|---|
| Metamodel type | Linear |
| Weighted sum method | Yes |
| Min-Max method | Yes |
| Pareto efficiency | Yes |
| Cost database | Tool Data |
| Environmental database | Tool Data |

**Fig. 5 –** Second window of the tool concerning the metamodel type, multicriteria method used as well as the cost and environmental database.

The next window consists of introducing the minimum and maximum value as well as the construction constraints of each studied parameter (Figure 6). Depending on the location and orientation of the building studied, a number of windows with the same orientation must be fixed.

| Parameters studied | Min | Max | Constraints |
|---|---|---|---|
| External wall insulation thickness | 0 | 26 | |
| Absorption coefficient of external walls | 0.05 | 0.95 | |
| External roof insulation thickness | 0 | 27 | |
| Absorption coefficient of roof | 0.05 | 0.95 | |
| Floor insulation thickness | 0 | 26 | |
| Thermal bridges transmission coefficient | 0.01 | 1 | |
| Infiltration rate | 0.04 | 0.63 | |
| Window orientation no. | 1 | | |
| Transmission coefficient of windows no. | 0.1 | 4.3 | |
| Solar factor of window no. | 0.05 | 0.95 | |
| Absorption coefficient of window frames no. | 0.05 | 0.95 | |

**Fig. 5 -** Third window for entering the value of the building envelope parameters.

The last entry step is the choice of criteria (Figure 6). If one of the criteria is included in the multicriteria study, the user must put Yes in the choice box and put his weight according to the preferences of decision makers. The sum of the weights of all the criteria must be equal to 1.

| Criteria studied | Choice | Weight | Constraints |
|---|---|---|---|
| Heating energy needs | Yes | 6.25 | |
| Cooling energy needs | No | 6.25 | |
| The initial investment cost | Yes | 6.25 | |
| The payback period | Yes | 6.25 | |
| Life cycle cost | Yes | 6.25 | |
| Climate change | Yes | 6.25 | |
| Depletion potential of the stratospheric ozone layer | Yes | 6.25 | |
| Acidification potential of land and water | Yes | 6.25 | |
| Eutrophication | Yes | 6.25 | |
| Photochemical ozone formation | Yes | 6.25 | |
| Abiotic resource depletion potential for elements | Yes | 6.25 | |
| Abiotic resource depletion potential of fossil fuels | Yes | 6.25 | |
| Air pollution | Yes | 6.25 | |
| Water pollution | Yes | 6.25 | |
| Total use of renewable primary energy resources | Yes | 6.25 | |
| Total use of non-renewable primary energy resources | Yes | 6.25 | |
| Use of net fresh water | Yes | 6.25 | |

**Fig. 6 -** Fourth window of the tool which concerns the choice of criteria, their weight and constraints.

Once the data entry is completed, it is therefore possible to start the calculations by pressing the Run button. The tool will therefore automatically start the simulations developing the metamodel of the building studied. Then, the optimization will be carried out using the three multi-criteria analysis methods. The optimal values of each criterion will be displayed in a radar diagram as shown in the Figure 7.

Run

| Optimal values of the studied criteria | |
|---|---|
| Metamodel regression coefficient | 0.99 |

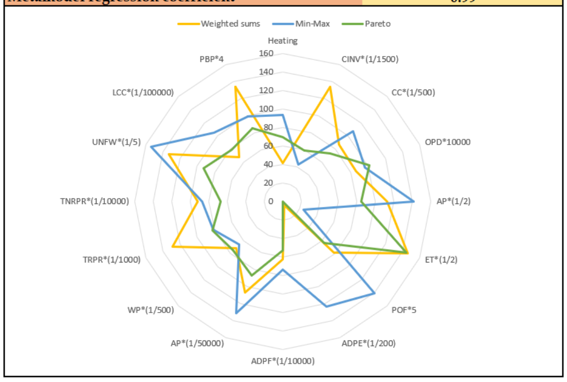


**Fig. 7 -** Display window of the results concerning the criteria and the precision of the metamodel.

The display of the optimal technical solutions for the rehabilitation of the building studied is shown in Figure 8. It indicates whether the value tends towards the maximum or the minimum depending on the range of variation chosen.

| Optimal technical solutions | |
|---|---|
| External wall insulation thickness (cm) | 18 |
| Absorption coefficient of external walls (-) | 0.5 |
| External roof insulation thickness (cm) | 14 |
| Absorption coefficient of roof (-) | 0.5 |
| Floor insulation thickness (cm) | 8 |
| Thermal bridges transmission coefficient ($W.m^{-1}.K^{-1}$) | 0.12 |
| Infiltration rate ($m^3.h^{-1}.m^{-2}$) | 0.5 |
| Transmission coefficient of windows Ouest ($W.m^{-2}.K^{-1}$) | 1.61 |
| Solar factor of window Ouest (-) | 0.56 |
| Absorption coefficient of window frames Ouest (-) | 0.5 |

**Fig. 8 –** Optimal building technical solutions obtained.

The last window (Figure 9) concerns a post processing in order to improve the indoor thermal comfort in summer and to avoid the overheating, especially in the case of the thermos flask.

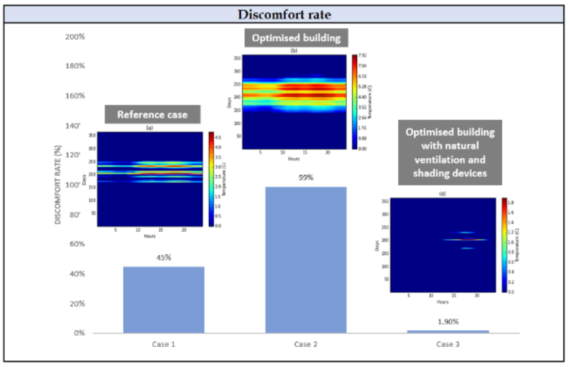


**Fig. 9 –** Display window of the post processing.

The tool displays the thermal discomfort rate and the difference between the interior temperature and a comfort temperature (26°C) with the discomfort rate which corresponds to 3 configurations: reference case (case 1), optimized building (case 2) and optimized building with natural ventilation and shading devices (case 3).

Using the tool developed, the time consumed to make 217728 combinations of technical solutions is approximately 8 minutes. By adding the time required to develop the metamodel, the total time is 326 minutes. If this combination study will be carried out only with TRNSYS and CONTAM software, the decision support becomes impractical because the calculation time of this combinatorial study is 303 days.

## 4. Conclusion

The energy transition must be accelerated in the building sector, which has significant potential in terms of saving and producing energy. However, this transition must be sustainable to protect the environment and future generations. In practice, builders need a multi-criteria decision support tools to get a sustainable technical solution instead of intuitive and harmful choices for the environment.

France will adopt new environmental regulations, the RE 2020, which will replace the 2012 thermal regulations. Indeed, the choice of technical solutions will be more complex with the introduction of environmental indicators. The tool that we have developed and presented in this work will have a significant benefit in terms of computing time, the relevance of the results in the case of a sustainable approach. This tool has several advantages:

- Carrying out multi-criteria analyses (economic, environmental and social) with the allocation of weights for each criterion;
- Flexibility in terms of the choice of building envelope parameters, criteria and constraints according to user needs;
- The speed of calculations compared to classical parametric studies;
- The integration of life cycle analysis into the calculation process;
- The assurance of reaching the overall optimum with control of the results uncertainties.

An improvement of the tool can be envisaged in order to take into account other criteria such as visual, acoustic and indoor air quality criteria. In addition, it will be necessary to optimize the integration of renewable energies.

## 5. Acknowledgement

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