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Application of optimisation, building energy simulation and life cycle assessment to the design of an urban project

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Abstract

The building sector is the economic sector of the EU that has the highest final energy consumption. In response to concerns about climate change, energy security and social equity, most countries plan to substantially reduce energy demand and greenhouse gas emissions. Moreover, 55 % of the world's population lives in urban areas, a proportion that is expected to rise to 68 % by 2050. Finally, there are effective catalysts to improve environmental performance at the scale of urban projects. For these reasons, environmental impacts of the neighbourhood have to be minimised using reliable tools offering economically viable solutions.

This paper presents a multicriteria optimisation methodology that has been developed to reduce both investment and environmental costs of buildings. The life cycle assessment methodology used in this study enables the evaluation environmental impacts over the whole life cycle of buildings. The optimisation of an individual building and the simultaneous optimisation of several buildings were carried out considering various criteria such as environmental impacts and construction cost, in the case of a 5-hectare urban project.

A genetic algorithm was implemented in order to identify Pareto-optimal solutions associating a life cycle assessment tool to building energy simulation. The first step was to implement the NSGA-II algorithm and a comparison with the NSGA-III algorithm is considered in perspective.

Results present optimal Pareto fronts minimising investment costs and CO₂ emissions of buildings. In this way, a decision-making aid is proposed to urban planners.

Key Innovations

- A framework to determine the trade-off between buildings' investment cost and environmental impacts at the scale of urban projects with a focus on greenhouse gas emissions is developed
- A multi-objective evolutionary algorithm is integrated to building energy simulation and life cycle assessment tools
- The framework is used to test the applicability in a case study

Practical Implications

- A decision-making aid intended for designers at earliest stages of buildings and urban projects is proposed

Introduction

EU's nationally determined contribution, under the Paris Agreement, pledges a 55 % economy-wide reduction in greenhouse gas emissions by 2030 compared to 1990, across all 28 Member States. The building sector is EU's economic sector that has the highest final energy consumption. It represents 40 % of all EU's energy consumption and 36 % of EU's greenhouse gas emissions. Improving building energy and environmental performance is a key to reach the Paris Agreement objectives.

Present decisions influence environmental impacts of next decades due to the long lifetime of infrastructures. Until now, environmental strategies focused on direct energy consumption targeting a reduction of energy consumption and, more recently, CO₂ emissions relating to building occupancy (heating and domestic hot water production). However, the environmental evaluation of buildings should also include the manufacture stage and the materials' end of life in order to identify more comprehensive environmental impacts.

The decisions that have the highest influence on performance are taken in early design phases. This study corresponds to the recommendation stage before the launch of architectural design competitions. On the other hand, the scale of the urban project makes it possible to integrate additional leverage actions, for example concerning district heating. Ecodesign is one of the most efficient methods used to reduce energy and environmental impacts of buildings (Oyarzo and Peuportier 2014). Decision support tools developed at the building scale are particularly relevant through the multicriteria and multistage approach of life cycle assessment (LCA) methodology. LCA enables the environmental evaluation of projects over the whole life cycle of buildings, from raw material extraction to the end of life of the buildings.

Neighbourhood ecodesign is addressed in the scientific literature but there is a lack of tools helping in the design of high performance neighbourhoods (Oliver-Solà et al. 2011). However, some rare tools exist to assess

neighbourhood environmental impacts (Popovici and Peuportier 2004). Lotteau et al. (2015) noticed the heterogeneity between communications regarding this topic, but do not mention an assessment combining both economic and environmental impacts.

In order to reach as many stakeholders as possible, decision support tools have to propose economically feasible solutions. This communication presents a new approach merging neighbourhoods LCA, investment cost and multicriteria optimisation. It helps designers to find trade-off between both economic and environmental aspects. In this communication, only CO₂ emissions are presented but the LCA tool calculates other environmental impacts.

The first part of this communication presents the LCA methodology, the optimisation issue and their application to buildings. A multicriteria environmental optimisation is developed and then applied on a case study. CO₂ emissions and investment costs are minimised to give an optimal solution in order to provide a decision-making aid.

Methods

Life cycle assessment

LCA methodology allows to evaluate environmental impacts of products, systems and processes, taking into consideration all substances emitted to and extracted and from the environment over their whole life cycle. This methodology is divided into four stages: Objectives definition, flow inventory, environmental impact assessment and interpretation of results (ISO 14044 2006). LCA proposes a global approach identifying the highest environmental impacts, thereby avoiding a transfer of pollution in time throughout the life cycle, from an indicator to another or from a place to another (for instance electric cars reduce urban impacts but the impacts of battery manufacturing and power plants are increased). The flow inventory depends on the choice of the database, in particular on the number of available, reliable and updated data. Different impact categories are then established and all flows are classified in a set of potential impacts, expressed as environmental indicators. The LCA tool used in this study considers 12 environmental indicators including damage on human health and ecosystem quality. Two indicators in particular are addressed in this work: cumulative energy demand, analysing primary energy consumption of the project in kWh, and greenhouse gases emissions in kg of CO₂eq.

LCA of neighbourhoods

LCA is applied at an urban project scale in order to address current sustainable construction issues. This methodology is tailored to the environmental assessment of complex systems, such as neighbourhoods, due to its multicriteria and multistage approach. Scientific literature includes research works dealing with LCA of buildings and current studies emerging on the scale of urban projects (Popovici and Peuportier 2004), (Oliver-Solà et al. 2011). However, there is a lack of tools

designed to develop urban projects with high environmental performance responding to problems such as bioclimatic design, urban density and mobility. Urban aspects influence thermal properties such as heating and cooling loads that highly contribute to most of the environmental impacts of old buildings and neighbourhoods in European climates. Public transport and district heating profitability are influenced by density; this parameter has a significant impact on the environment, in particular for new neighbourhoods. Environmental impacts of districts depend on many factors, including urban morphology, materials quantity, vegetation area, energy equipment and building compactness. Design parameters such as the number of storeys or the length of buildings can also influence the performance. The life cycle assessment methodology application is therefore justified by the need to take into consideration all these numerous parameters in order to assess environmental impacts of a neighbourhood and develop a decision aid tool.

LCA of buildings

Ecodesign of buildings enables to considerably reduce environmental impacts, as Oyarzo and Peuportier (2014) showed, carrying out LCA of housing in Chile.

Building LCA includes the following main stages:

- Construction stage, including extraction of raw materials, manufacturing and transport of building materials and on-site works.
- Use stage related to energy consumption, water use, waste production and transport during the occupancy of the building.
- Renovation stage, corresponding to replacement of end of life products and equipment.
- End of life stage, according to building deconstruction, waste transport and treatment.

Building energy simulation and life cycle assessment tools included in the Pleiades software and the international database ecoinvent 3.4 were used in this study. An hourly production mix is considered to take into account the hourly variation of electricity production (Roux et al. 2016).

Limits of the methodology

Many studies (Hollberg and Ruth 2016; Lotteau et al. 2015) highlighted that LCA methodology has to be applied during the earliest stages of the projects in order to help stakeholders in decision-making. However, LCA focuses on quantifiable impacts of environmental quality and does not take into account investment cost and other more subjective criteria as aesthetic or quality of life. A multicriteria optimisation could include more parameters. This work aims at developing minimisation of both investment costs and greenhouse gas emissions.

Optimisation issue

An optimisation process aims at establishing a set of solutions minimising or maximising some objectives and comparing them until no better solution is found, while respecting a set of constraints. The goal of a single objective optimisation problem is to find the best

solution for a specific criterion, such as energy consumption, or investment cost. It can be extended to several potentially conflicting objectives. There is then no longer a single solution but a set of optimal solutions. This is a multi-objective optimisation. As an example, such a problem including k objectives and two constraints (G, H) can be defined as follows:

$$\begin{aligned} \text{Minimise} \quad & f_m(x), & m=1,2,\dots,M; \\ \text{with} \quad & g_j(x) \geq 0, & j=1,2,\dots,J; \\ & h_k(x)=0, & k=1,2,\dots,K; \end{aligned}$$

$x \in \Omega$

where Ω is defined as the set of feasible solutions. Non-dominated solutions then form a front. A solution $x^{(1)}$ dominates a solution $x^{(2)}$ in the sense of Pareto if and only if following conditions are verified:

- The solution $x^{(1)}$ is at least as good as the solution $x^{(2)}$ on all the objectives.
- The solution $x^{(1)}$ is strictly better than the solution $x^{(2)}$ on at least one objective.

The Pareto front is defined as the set of non-dominated solutions. Figure 1 introduces the notion of domination on the Pareto sense; solutions A and B are both non-dominated, they belong to the Pareto front. The solution C is dominated; it does not belong to the Pareto front.

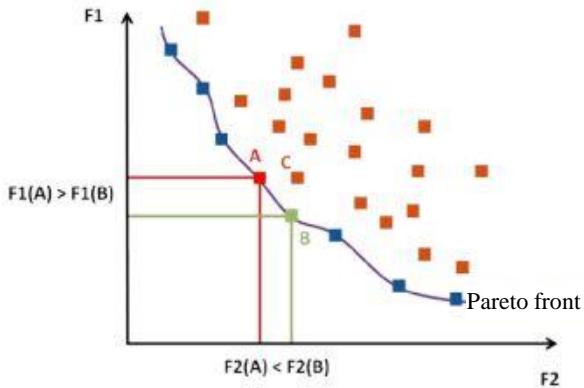


Figure 1: Illustration of a multicriteria (F1, F2) optimisation result, source: (Recht 2016)

A stochastic methodology was chosen for its ability to deal with non-linear problems and to find global extrema. Genetic algorithms are part of this methodology and are popular due to the fact that provide a set of solutions instead of a single solution. These algorithms are inspired by the theory of the natural evolution of species. Once the population is initialised, the algorithm starts the following generational loop (Deb et al. 2002):

- Evaluation of a set of solutions.
- Sorting the best solutions according to non-domination and selection for reproduction.
- Crossing of the parameters of the selection and mutation of each solution at a specified probability.
- Selection for replacement.

Iterations are stopped when the stop criterion appears. The evolutionary algorithm NSGA-II (Non-Dominated Sorting Genetic Algorithm) implements effective elitist

strategies regarding the quality of solutions and the extension of the front (Deb et al. 2000).

Approach

The study aims to provide a decision support for a multi-objective project intended for building stakeholders. The cost function of the optimisation is the minimisation of CO₂ emissions and investment. These criteria were chosen in order to address the current needs of designers, trying to balance environmental and economic costs of the projects. Results are presented with a bi-dimensional Pareto front without weighting in order to provide a multicriteria decision-aid. Buildings are modelled using the software Pleiades. Then, building energy simulation and life cycle assessment are carried out. The Amapola module integrated in Pleiades was used in order to carry out the optimisation. Environmental evaluation is performed at each generational loop. Multicriteria environmental optimisation was performed on a case study, and the methodology was initialised with a random drawing of a Latin hypercube sample.

The building energy simulation includes physical models regarding solar gains, heat transfer through walls, ventilation and thermal mass, as well as scenario based models of occupants' behaviours. Energy consumption includes space heating and cooling, hot water production, ventilation, lighting, electricity for domestic appliances, computers etc. Building simulation considers shading, for example shadow due to other close buildings so that interacting between buildings is accounted for.

Life cycle assessment evaluates environmental impact including the fabrication of materials and products, construction stage, energy and water consumed in the use stage, replacement of components and end of life. Environmental data are issued from ecoinvent database adapted to the French electric mix. Waste is treated as appropriate. Windows, wood or polystyrene are burned at their end of life, whereas concrete and metals are recycled or landfilled.

Regarding urban scale aspects, specific assumptions are considered such as transport between home and work, household waste and water management at the urban scale. Moreover, district heating is accounted for, considering 54% of heat supplied from a biomass system and 46% from natural gas plant.

Originality of the framework

Some recent developments (Kiss and Szalay 2020) compare different environmental indicators through multi-objective optimisation without considering investment cost. Other studies (Ascione et al. 2019) focus on investment or operational cost of buildings and energy consumption or combined CO₂ emissions, relating to the use stage of building life cycle. (Bre, Roman, and Fachinotti 2020) chose to implement an artificial neural network combined with the NSGA-II algorithm in order to perform multi-objective optimisation with low computing time. This method was applied to optimise the energy efficiency and thermal

comfort of an actual dwelling in order to get the best trade-off between heating and cooling performance.

The proposed methodology contains two main novelties; the first one consists of the possibility to satisfy both environmental and economic criteria in an optimisation. Environmental impacts are calculated with the life cycle assessment methodology, taking into account environmental impacts over the whole life cycle of the buildings. The economic criterion does not correspond to the global building cost but to the difference compared to the initial project. Part of the building components can thus be considered through this choice of methodology (only the modified ones, as compared to the initial project). Indeed, many parameters concerning the structure remain unchanged, therefore their cost doesn't influence the final decision. The second improvement concerns the implementation of multi-objective optimisation at the multi-building scale, as one step towards the neighbourhood scale. A model reduction technique allows the use of a precise simulation for the evaluation while reducing the computation time.

Case study

A Paris suburban neighbourhood construction project is used to illustrate these developments. The urban project of 5 hectares includes offices, dwellings, hotels, a student residence and commercial buildings. The project is part of a global environmental quality ambition and was chosen for its diversity in terms of infrastructures, and its social, environmental and cultural objectives. As this communication presents a multi-building scale optimisation procedure, two buildings of the urban project were specifically chosen: a residential building and an office building, both located in the heart of the district. The considered optimisation criteria are the greenhouse gas emissions expressed in CO₂ equivalent emissions and investment cost. The main characteristics of the case study are represented in table 1, and 3D representations of the collective dwelling and the office building are presented in figure 2 and figure 3 respectively.

Table 1: Main characteristics of case study buildings

Use	Office	Dwelling
Height	98 m	47 m
Area	33400 m ²	6977 m ²
Ground area	1270 m ²	552 m ²
Number of storeys	26	15
Initial cost	4 521 750 €	1 607 650 €

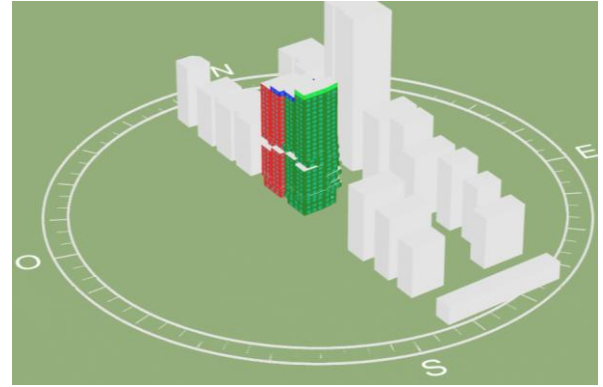


Figure 2: 3D representation of the office building

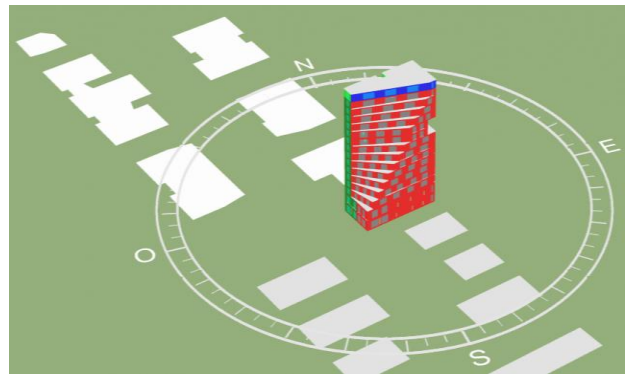


Figure 3: 3D representation of the collective dwelling building

Results

Results of the multicriteria environmental optimisation are presented with a Pareto front for both case study buildings individually at first, and then as a whole. Both buildings are divided into four thermal zones according to the orientation and energy loss surface. This choice corresponds to a trade-off between calculation costs and results precision. The functional unit selected is a residential building of 6977 m² and an office building of 33400 m² with a defined level of comfort, considering heating, domestic hot water, ventilation and specific electricity consumptions.

Table 2: Initial composition of case study walls

Wall	Material	Thickness (cm)
External wall	Particle board	2
	Glass wool	15
	Concrete	20
	Plasterboard	1.3
Ground floor	Expanded polystyrene	15
	Concrete	20
	Tiling	1
Internal wall	Concrete	20
Intermediate floor	Concrete	20
Roof	Pure bitumen	0.5
	Polyurethane	15

	Concrete	20
	Plasterboard	1.3

Search space

Table 2 both buildings have the same initial wall composition with a wall insulation variation from 15 cm to 20 cm. A district heating and a heat pump as cooling system are considered. A dynamic mix (Roux et al., 2016) for electricity production is implemented. The rate of summer discomfort was taken into account in order to avoid exceeding the high temperature limit set at 27 °C.

During meetings with the decisions makers (i.e. municipality, urban planner and consulting engineers), it was decided to optimise main design parameters in this early phase: insulation thickness, type and size of windows (i.e. glazed percentage in relation to the area of facade) were chosen in this first step. Investment cost relating to these parameters was established according to data collected in previous projects. The search space is described table 3. The optimisation was performed with 100 individuals and 20 generations. This setting provides diversification and intensification in the optimisation results. Economic criterion is presented as a “delta

Collective dwelling building optimisation

An environmental optimisation of collective dwelling building, whose 3D representation is illustrated in figure 2, was performed. Figure 4 represents the Pareto front evolution of this building optimisation for 20 generations. Figure 4 shows the greenhouse gases emissions and delta investment. This last criterion corresponds to the difference of investment cost as compared to the initial cost of the building.

The optimal Pareto front is represented in light blue in figure 4. It corresponds to the Pareto front of the twentieth generation of the multi-objective optimisation. Results show that the value of CO₂ emissions changes from 8.15 to 8.55 kg of CO₂eq./((m².year) whereas the initial building emitted 11 kg of CO₂eq./((m².year). The initial cost of the parameters studied of the building is 1,6 M€, corresponding in the figure 4 to 0 €/m² of Delta investment cost. The optimal Pareto front provides a set of solutions between 100 and 175 €/m² cheaper than the initial building. Two thirds of optimal solutions correspond to more than 20 cm of wall insulation (glass wool) and a lower insulation thickness in roof and ground floor. Low-carbon solutions correspond to triple-glazed windows whereas small investment cost solutions correspond to double glazing.

investment” which corresponds to the variation between solution and the initial cost.

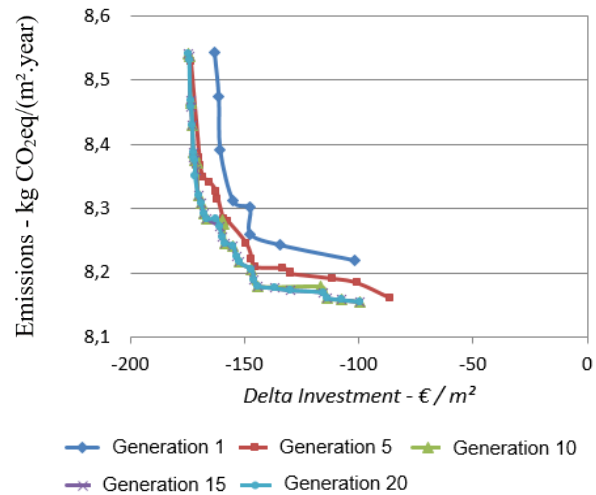


Figure 4: Evolution of Pareto front of the residential building optimisation over the generations

Table 3: Change values and corresponding prices

Finally, the whole set of solutions suggests a low opening rate, coinciding with small windows.

Office building optimisation

The environmental optimisation of the office building was performed and results are presented in figure 5.

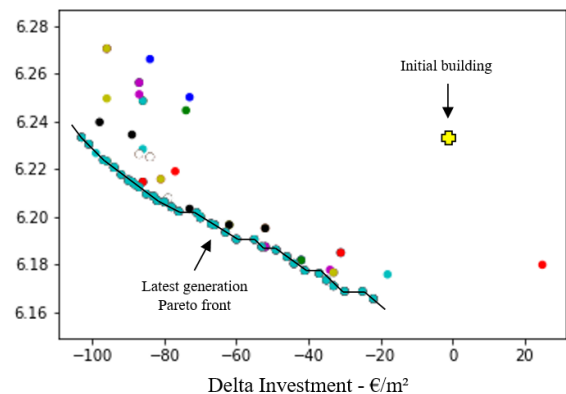


Figure 5: Pareto front evolution of office building optimisation, over the 20 generations

Component	Change	Price
Glass wool in external walls	From 7 to 30 cm	From 103 to 112 €/m ²
Expanded polystyrene in ground floor	From 7 to 30 cm	From 37 to 65 €/m ²
Polyurethane in roof	From 7 to 30 cm	From 63 to 109 €/m ²
Windows	Double glazing - triple glazing	450€/m ² - 615 €/m ²
Opening percentage	20, 25, 30, 35, 40, 45, 50 %	

Figure 5 shows a less obvious evolution of Pareto front regarding the office building as compared to the previous case study. The optimal Pareto front is clearly represented, but the evolution over the generations is less clear. Greenhouse gas emissions change from 6.16 to 6.24 €/m² in the set of optimal solutions. This variation is low but coherent with the position of the yellow point representing the initial building. The most contributing life cycle stage is the use stage. This is particularly due to specific electricity consumption relative to offices (for computers, lighting etc.), assumed to be 16 W/m², i.e. over 80% of total electricity consumption.

On the other hand, gains regarding investment cost are possible, up to 100€ per square meter.

The optimal Pareto front contains more homogenous solutions than the previous case study. All solutions indicate 15 or 20 cm of glass wool (in walls), and 7 cm of polystyrene and polyurethane. The size and type of windows of a solution depend on its position on the Pareto front.

Multi-building optimisation

A third optimisation was then performed grouping both buildings. Building energy simulations and environmental evaluations are performed individually and then grouped at each generation.

The multi-building optimisation assumes a population of 100 individuals over 20 generations. Pareto front of 5 generations are presented on figure 6. Results of each criterion are divided by the total area of both buildings and the lifetime of the buildings.

This combined optimisation considers simultaneously both buildings and leads to different solutions than individual optimisations. The first distinction relates to insulation thickness in particular in external walls. A majority of the optimal set of solutions contains a large thickness of glass wool as walls insulations, between 15 and 25 cm of expanded polystyrene in the ground floor and a little less polyurethane as roof insulator. Solutions relative to low investment cost use double-glazed windows whereas solutions relative to low CO₂ emissions contain triple-glazed windows.

The Pareto front evolution is different from previous optimisations: the optimal front contains more values

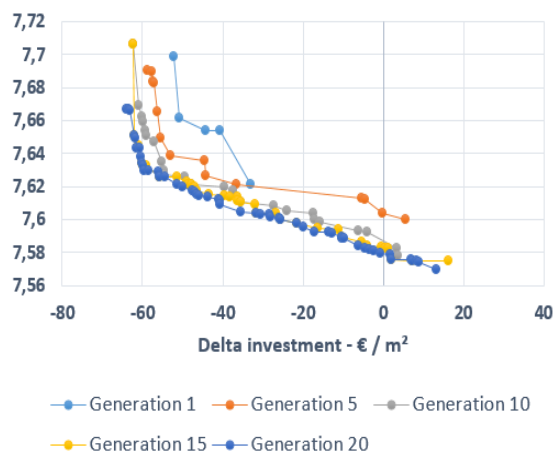


Figure 6: Pareto front evolution regarding two objectives optimization of case study buildings

and we can observe a stronger difference between the Pareto front of different generations. That refers to a slower convergence of the algorithm with both buildings. Appropriate setting of the algorithm parameters is very important in order to reach an optimal Pareto front with reliability.

The evolution of the Pareto front according to the generations indicates that the stop criterion is well adapted to the case study; the convergence of the set of solutions can be observed from the fifteenth generation. The front presents a diversity and a sufficient number of solutions. This implies that the algorithm and its setting are adequate.

Discussion

The previous section introduced the developments of an optimisation procedure and its application, from a building scale to a multi-building scale. In the following, two main points observed during the application of this work will be detailed, followed by the advantage of multi-building optimisation.

Convergence of Pareto front

It was decided to run the optimisation methodology over 20 generations in order to obtain a large number of solutions and a diversified front. This assumption came from a study regarding the evolution of a Pareto front of the collective dwelling building optimisation. The optimal front was not reached after 5 generations, and 10 generations results had too few data. Results show a convergence from 15 generations and the number of 20 generations was selected to avoid local optima. The optimal front of the office building optimisation does not show the importance of this large number of generation, but the general result grouping both buildings indicates that the set of solutions converges between the fifteenth and the twentieth generation.

Convergence seems slower when both building are evaluated at the same time. A specific survey on computing time would be useful on this subject, while considering time savings and reliability according to data preparation and results analysis. Data input and results interpretations are both stages of the procedure which can be significantly simplified by developing a unique procedure.

This study could be improved by implementing another stopping criterion based on the hypervolume instead of the number of generations, which requires a preliminary study.

Optimal set of solutions

Optimisation results show that CO₂ emissions can be reduced by 0.5 kg of CO₂eq./m²/year in the multi-building case. This value is consistent due to the high initial level of performance of the buildings. Heating and cooling loads of solutions are low, but the energy performance of the building envelopes does not modify the specific electricity consumption. This consumption is particularly high in the office building. This implies that the use stage contributes the most to greenhouse gas

emissions compared to the rest of the building's life cycle.

The high environmental performance of buildings may explain the slight reduction of CO₂, even if an uncertainty analysis would be useful to go further in the results interpretation. The development of the tools aims at suggesting alternative solutions as an aid to decision-making regardless of initial conditions.

Results show that the optimisation of insulation thickness, type and size of windows can significantly reduce the investment cost of an urban project without deteriorating its environmental performance, in particular regarding CO₂ emissions.

Interest of multi-building optimisation

Optimisation results are different regarding the time of convergence of the algorithm and selected solutions. We can observe a slight difference in the performance values. Individual optimisations may correspond to local optima. It would therefore be useful to extend the methodology at the neighbourhood scale.

Optimization is used as a design aid interacting with an architect. For instance, the variation interval of window size has been fixed by the decision maker, integrating aesthetical concern. It would be possible to account for a supplementary aspect in the multicriteria optimization, corresponding to a daylighting performance that can also be evaluated by Pleiades (calculation based upon Radiance).

This application indicated the usefulness of working at different scales to save time and get more precise and appropriate results. The tool developed in this framework presents a possibility to reduce CO₂ emissions and investment cost after the analysis of an optimal set of solutions, and could be improved adding more environmental or comfort indicators.

Conclusion

This communication presented recent developments regarding multicriteria environmental optimisation of buildings at different scales. Environmental evaluation has to be performed from the early design phases of an urban project in order to be used as an aid when the most important decisions are taken.

The analysis of a case study showed that multicriteria optimisation leads to different optima for different scales. First of all, an association of life cycle assessment and optimisation provides a significant decision aid to building stakeholders. The addition of a cost indicator reinforces the usefulness and broad dissemination of the approach. Until now, scientific literature contained little studies relative to environmental optimisation over the whole life cycle of urban projects. This communication showed the interest of environmental and economic optimisation of a building and development at the urban project scale.

In perspective, it would be useful to extend the study to more environmental criteria like water use, damages to health and to biodiversity. Increasing the number of criteria could impact the computation time of the process, due to the needed convergence of the algorithm.

For an optimisation with four or more criteria an improved algorithm NSGA-III could be implemented in order to compare results quality and speed of convergence with NSGA-II. A constraint regarding the discomfort rate could be added as an input of the algorithm in order to avoid overheating in summer. Finally, further work will take into account a district heating network, with heat supplied by wood and gas boilers. Such improvements, once implemented, will allow to extend this multi-building scale to a district scale.

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