PAPER • **OPEN ACCESS**

A Tool for Optimal Refurbishment Design of Low-Energy Buildings

To cite this article: I Salerno *et al* 2021 *J. Phys.: Conf. Ser.* **2042** 012164

A Tool for Optimal Refurbishment Design of Low-Energy Buildings

I Salerno[1], M F Anjos[1], K McKinnon[1] and E S Mazzucchelli[2]

E-mail: I.Salerno@sms.ac.ed.uk

[1] School of Mathematics, University of Edinburgh, Edinburgh, UK
[2] ABC Department, Politecnico di Milano, 31 Ponzio st., Milano, Italy

Abstract. We propose a model that aims to fulfill the following three necessities: the demand for refurbishing the existing built environment, the lack of a reliable means to help architects navigate among the numerous possible solutions for low-energy constructions, and the need for a multi-function tool to analyze buildings as complex systems. We introduce the Optimal Refurbishment Design (ORD) model that is a novel tool to help architects with the refurbishment of an existing building or the design of a new one. The ORD shows four innovative aspects. First, it opens the way to passive building design while focusing on affordable solutions. Second, its core component is based on mathematical optimization. Third, it simultaneously outputs optimal thermal mass and insulation of all the required elements in the building. Fourth, it automatically accounts for the user's needs and local regulations. Unlike most of the approaches in the Literature, the ORD's outputs are not limited by any pre-defined set of materials or strategies. We tested the ORD using a realistic study case of refurbishment, and found that the renovated house achieved the energy consumption of a Passive House by lowering its annual heating/cooling consumption by 23% with a payback period of less than 5 years.

1. The State-of-the-Art: Optimization Techniques for Building Design

The complex nature of a building system is well suited to the use of optimization techniques because they can handle conflicting objectives and each building's uniqueness. Nevertheless the application of optimization to real-world building design is still very limited. Some optimization methods are incorporated in software for building simulation, but they mainly integrate results coming from independent single-function analyses. Almost half of the models proposed to date are single-objective, and the majority of them minimize energy consumption. Other objectives sometimes considered are cost minimisation and comfort [1]. Most of the models in the literature are built ad hoc for a specific study case. For example Pernodet et al. [2] compare single-criteria approaches with global ones and show that the former do not give robust solutions. However their study has the following limitations: it runs static and over-simplified algorithms, it only considers heating demand, and it only works for a specific building and climate. Chantrelle et al. [3] present a 2-level model to tackle four criteria: cost, energy use, environmental impact, and comfort. Like [2], they consider existing genetic algorithms, and integrate an external simulator to calculate energy load. Their study has two main limitations: possible solutions are restricted to a pre-defined set, and the multi-criteria algorithm was not reliable for real-world applications. By contrast, Jin et al. [4] consider renovation strategies instead of individual parameters, but again the possible outputs are restricted to pre-defined solutions based on practical experience. Asadi and his team [5] present a combinatorial bi-objective optimization problem that defines a Pareto front. Its main limitation is the very simple thermal model of the building, which is static and assumes perfect heating efficiency. Indeed few optimization studies in the literature consider, or even mention, the thermal mass of the building.

2. The optimal refurbishment design model (ORD)

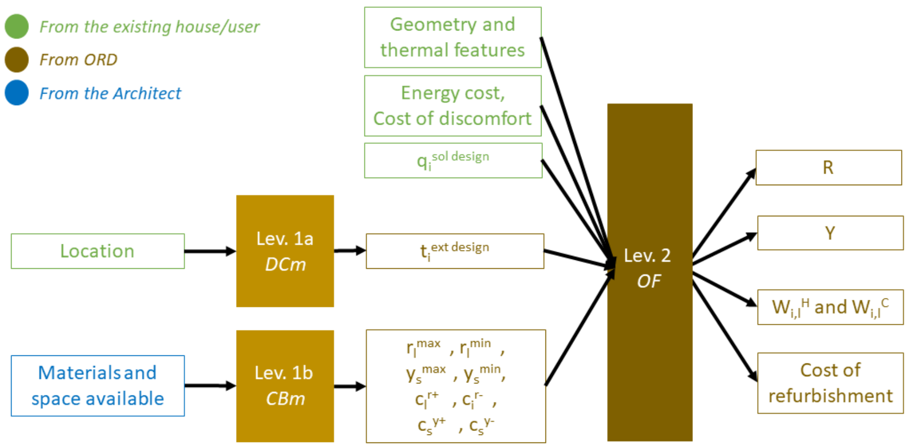

Figure 1: ORD structure

The ORD is a 2-level model whose structure is depicted in Figure 1. The ORD's levels are represented by golden rectangles (the optimization level in dark gold, the levels to prepare data in light gold). The white rectangles show input and output data of each level: green data come from the building/location's characteristics, gold are output from the ORD's level 1 and blue are given by the architect.) The multi-level structure makes it possible to overcome several of the limits of the state-of-the-art.

2.1. Level 1: Design Conditions and Materials

Level 1 consists of two parallel parts, the design condition maker and the cost and bound on materials maker. The two parts prepare data for the optimization framework.

2.1.1. Level 1a: Design Condition Maker (DCm) Level 1a tackles the issue of choosing relevant conditions for building refurbishment/design. It receives the building's location as input and it outputs the most representative hourly external temperature (t_i^{ext}) to be used in level 2. The DCm framework is based on the 2017 ASRHAE Handbook [6] that provides representative external temperatures and solar radiations for building energy system design. For a given location, ASHRAE gives weather information with associated probabilities throughout the year, on the base of 30 years of observations. The DCm outputs t_i^{ext} for two days: the first one is representative of heating conditions, and the second one of cooling. Specifically, for the heating day, the DCm considers the external temperature for which the building's location stays above that temperature during 99% of the hours of the year, and for the cooling day, the temperature for which the location stays above that temperature during 1% of the hours of the year. The DCm is built around the equation suggested in the ASHRAE regulation for the standard hourly profile.

2.1.2. Level 1b: Materials Cost and Bound Maker (CBm) Level 1*b* allows the ORD model to consider different building solutions and each material chosen by the architect/user. This makes the model adaptable for different study cases and overcomes the limit of pre-defined solutions. The inputs of the CBm are the cost and the thermal features of the chosen materials to operate the refurbishment. The CBm outputs two sets of parameters. First, the per-unit cost of changing thermal mass or Y-value (in $\$/kWh/K$) and thermal resistance or R-value (in $\$/K/kW$) of each element of the existing house (EX). The cost of materials per unit increase in R-value of a wall is the cost per square meter of the material chosen for the refurbishment, multiplied by the surface of the wall, divided by the material's R-value per unit of thickness. The R-value of windows can be increased/decreased by three strategies: adding coatings, replacing part of the window or replacing the whole window. Each strategy has a different cost and leads to different R-changes. The cost of materials per unit increase in Y-value is the cost per cubic meter of the chosen material divided by the product of its density and specific heat. The cost of materials $c_l^{r,-}$ for decreasing the R-value and $c_s^{y,-}$) for decreasing the Y-value of a wall-element are 1/5 the cost for increasing it. The cost of labour is given by the average hourly salary of a builder, times the time required for the specific work.

Second, the minimum and maximum values allowed for the Y-value (kWh/K) and R-value (K/kW) for each element of the house, according to the chosen materials. The CBm takes r_l^{max}, the maximum value of R, of a wall as the R-value of the wall's l-element in EX plus the ratio between the maximum suitable space for the insulation layer in each wall times the wall's surface. The r_l^{max} of a window is modelled as the ratio between the maximum R-value that the window producer can offer and the window's surface. The minimum values of R (r_l^{min}) for each element l in EX is the minimum allowed by building regulations for the given location. Similarly, the CBm takes y_s^{max} (resp. y_s^{min}) as the Y-value of s-element in EX plus (resp. minus) the product of the maximum (resp. minimum) suitable space for the layer in s-element, the density and the specific-heat capacity of the chosen material for refurbishment.

2.2. Level 2: Optimization Framework (OF)

Level 2 is a mixed integer non-linear optimisation problem (MINLP) and takes the output of the previous levels to find the optimal Y- and R-values, the corresponding minimum cost of refurbishing, and the heating/cooling consumption of the refurbished house (RE). We model the house following the EMS model of Salerno et al [7] with some differences. First, the ORD is a MINLP. Second, R and Y values are decisional variables. Third, the objective function (1) differs. It is now constituted by more terms. The first two minimise energy consumption and indoor-temperature fluctuation, respectively. The third term associates costs of materials ($c_l^{r,+}$ and $c_l^{r,-}$) to each change in R-value of a wall-element (dR_l^+ and dR_l^-) and considers the cost of work ($c_l^{work,R}$) if the binary variable X_l is active. The fourth term acts similarly to the third, but for changes in Y-value. The fifth term minimizes the cost of the three windows refurbishment strategies ($\mathcal{WS}$), per each of which it associates the cost of material of coating/part/whole window ($c_{ws}^{material}$) plus the cost of work (c_{ws}^{work}) to the dedicated binary variable (X_{ws}). Each term is multiplied to a weight ($w^{W/T/R/Y/wind}$) that represent the its annualised cost, allowing for the assumed life of the refurbishment.

$$\min \sum_{i\in\mathcal{I}} w^W \sum_{l\in\mathcal{L}} W_{i,l} + \sum_{i\in\mathcal{I}} w^T(dT_i^+ + dT_i^-) + w^R \sum_{l^{wall}\in\mathcal{L}} (c_l^{r,+} dR_l^+ + c_l^{r,-} dR_l^- + X_l c_l^{work,R})$$
$$+ w^Y \sum_{s\in\mathcal{S}} (c_s^{y,+} dY_s^+ + c_s^{y,-} dY_s^- + X_s c_s^{work,Y}) + \sum_{ws\in\mathcal{WS}} w_{ws}^{wind} X_{ws}(c_{ws}^{material} + c_{ws}^{work}) \quad (1)$$

Fourth, we keep the constraints from the EMS model corresponding to "balance", "branch flows", "ACH in ventilation lines", "heat from generators", "energy storage", "storage level of charge" and "temperature limit", and we add constraints 2, 4, 3, 5 and 6 accounting for the changes of refurbishment design. Constraint (7) guarantees thermal comfort inside the room, during day-time. During each time frame $\tilde{i}$, the temperature of the room ($T_{\tilde{i},b^{room}}$) deviates from the set point chosen by the user ($t^{set\ point}$) by the value of $dT^{+}_{\tilde{i},b}$ (positive deviation) or $dT^{-}_{\tilde{i},b}$ (negative deviation). Finally, all the deviation variables are restricted to be non-negative.

$$R_l^{opt} = r_l + (dR_l^+ - dR_l^-)X_l \quad \forall l^{wall} \in \mathcal{L} \tag{2}$$

$$Y_s^{opt} = y_s + (dY_s^+ - dY_s^-)X_s \quad \forall s \in \mathcal{S} \tag{3}$$

$$r_l^{min} \leq R_l^{opt} \leq r_l^{max} \quad \forall l \in \mathcal{L} \tag{4}$$

$$y_s^{min} \leq Y_s^{opt} \leq y_s^{max} \quad \forall s \in \mathcal{S} \tag{5}$$

$$R_l^{opt} = r_l + \sum_{ws \in \mathcal{WS}} (X_{ws}^+ dr_{ws}^+ - X_{ws}^- dr_{ws}^-) \qquad \forall l^{window} \in \mathcal{L} \tag{6}$$

$$T_{\tilde{i},b^{room}} = t^{set\ point} + dT^+_{\tilde{i},b^{room}} - dT^-_{\tilde{i},b^{room}} \qquad \forall \tilde{i} \in \tilde{\mathcal{I}} \tag{7}$$

3. Realistic Study Case with the ORD Model

In this Section we use the ORD model to simulate the refurbishing of an apartment located in Montreal, Canada.

3.1. The Existing House (EX)

We consider as EX the case of a dwelling in a larger building. The dwelling has only one south-oriented façade and the user aims to reduce the overall heating/cooling demand. We assume neighbours on all sides at the same temperature as the dwelling. Heating/cooling demand is satisfied by a heat pump that runs in heating and cooling mode. It is centralized at the building level and operates between the outdoor and indoor temperatures. The owner is willing to refurbish all the walls (internal walls, roof, floor and external façade) and windows. His preference is a indoor temperature set point of 21 $°C$ from 7 AM until 9 PM (day-time). During night-time, the indoor temperature can vary between 16 and 25 $°C$.

The data for EX are as follows, where the R- and Y-values of the walls and ceilings are computed according to the EN ISO 13786. The façade is constituted by 0.015 m of plaster, 0.20 m of concrete, 0.02 m of air, 0.06 m of EPS 030 insulant, and an external 0.02 m layer of natural stone. Its Y-value is 1.08 kWh/K and its external and internal R-values are both equal to 46.45 K/kW. The internal walls are constituted by 0.015 m of plaster, 0.45 m of bricks and a second 0.015 m layer of plaster. The ceilings are constituted by 0.015 m of plaster, 0.20 m of bricks, 0.05 m of concrete, 0.015 m of insulant, 0.05 m of concrete and 0.018 m of linoleum. The Y-values of ceilings and internal walls are 12.73 kWh/K, and their internal and external R-values are 3.53 K/kW. The windows are made of 24 mm clear double glazing glass in a PVC frame. The equivalent R-value is 27.78 K/kW. The living space has a Y-value of 0.69 kWh/K.

The architect carries out R-value refurbishment by adding/removing EPS 030 insulation panels (same of in EX). A panel costs 14.63 $\$/m^2$, is 0.08 m thick, and has a conductance of 0.03 W/m K. The maximum suitable space to increase the thermal insulation of each element is 0.1 m. Thermal mass refurbishment is achieved by adding/removing concrete layers. Concrete costs $\$128.04/m^3$, has a density of 1800 kg/m^3 and specific heat of 0.00028 kWh/kg K. The maximum suitable space to increase the Y-value of each element is 0.08 m. The architect can provide a window more insulated than the EX's one at $682.91 each, and a worse insulated at $341.45. Furthermore, coating is $\$17.07/m^2$ and replacing part of window (ex. frame) is $256.09 each. The better (resp. worse) window increases (resp. decreases)R by a factor of 4, the coating by half and the part-replacing by 80%. Labour costs $\$20.49/hr$ and windows, R- and Y- of walls require 1, 2 and 1 hours of work per m^2 of window/wall, respectively. We assume that the refurbishment lifetime is 20 years for all the materials, except for coating is 8. Electricity costs \$0.34 kWh and penalty for deviating from the indoor target temperature is 1/3 the electricity price. Accordingly, $w^W = 730$, $w^T = 225.50$, $w^{coat} = 2.5$ and $w^R = w^Y = w^{part/whole} = 1$. The optimisation runs for two independent design days for Montreal (average winter external is $-24.07\ °C$, during summer is $+22.06\ °C$). The code is written in Julia language and solved by JuMP package, IpOpt and Juniper solvers. During those days, EX has a heating (resp. cooling) consumption of 27.31 $kWh/2days$ (resp. 1.53 $kWh/2days$), for a total of 28.84 $kWh/2days$.

3.2. The Refurbished House (RE)

The optimal combination of R and Y found by the ORD lowers RE's energy demand by 23% to 22.28 $kWh/2days$ during the two days of design (heating demand of 20.88 $kWh/2days$, cooling of 1.41 $kWh/2days$). RE guarantees thermal comfort: during day-time, the indoor temperature is always equal to the user's target; during winter night-time, it drops to 16 $°C$ and during summer to 19.37 $°C$. The total cost of refurbishing is \$671.96. The main work is done on increasing thermal insulation of walls (\$463.51) and the strategy chosen for windows is adding coating for a total cost of \$170.73. Figure 2 illustrates the refurbishing strategy, where EX's values are shown by black crosses, RE's by red dots, and variable bounds by grey lines. The top graph shows Y-values of each node, while the bottom graph shows R-values for each line representing the insulation of an element. "Int-walls" include internal wall-partitions, ceilings and floors. Increasing R- has a larger impact on consumption, than varying Y-values. In addition to that, an optimal placement of the insulation can maximise the benefit of thermal mass. In this example there is a small advantage in having the all of the façade's insulation on the external side so leaving the thermal mass within the insulation envelope, and this is the solution found by the ORD. Lowering the room's Y is an advantage in winter as it allows the night time room temperature to drop more rapidly, so lowering thermal losses to the exterior. The ORD finds the optimal compromise for the winter and summer conditions.

3.3. Performance Validation: EX vs RE

In this Section, we validate the strategy by comparing the annual consumptions of EX and RE. We now use the Level 2 of the ORD model as an energy simulator, with fixed R and Y values. In the case of EX, they are fixed to the EX's values. Similarly, for the RE, they are fixed to the optimal values found. We run one-year simulations and we use real weather data from 2007 for Montreal. We find that RE's annual energy consumption (1401.07 kWh/year) is 23% lower than EX's (1815.54 kWh/year). The one year simulation confirms the improvements estimated by the optimization. Furthermore, due to its annual heating demand of 14.01 kWh/m^2/year, RE achieves the Passive House Standard ($\leq$ 15 kWh/m^2/year) [8], with an estimated payback of 4.77 years.

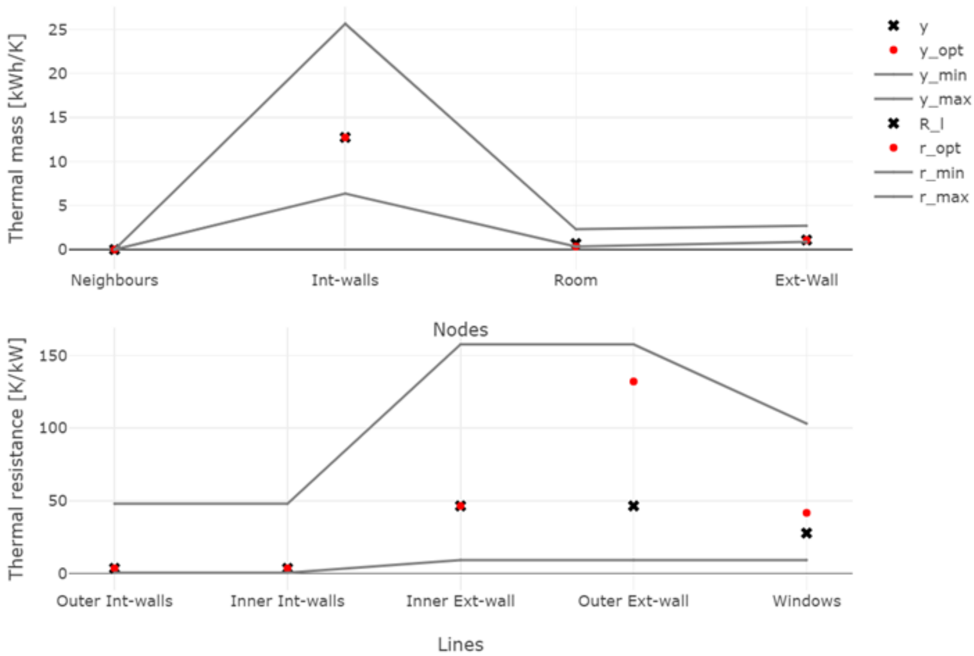

Figure 2: R-value and Y-value comparison

4. Conclusions

We presented and tested the ORD model, which is a novel 2-level MINLP optimization framework to assist architects with building refurbishment and design. We simulated a realistic study case and showed that the renovated house's heating/cooling consumption is 23% lower than that of the existing house. Furthermore, the refurbished house achieves the Passive House Standard with a payback of less than 5 years. For future work, we plan to test the ORD model on real buildings and we suggest two open questions: the possibility of refurbishing the heating/cooling system and the inclusion of sun-shadings.

References

[1] Evins R 2013 *Ren. and Sust. Ene. Rev.* **22**:230–45
[2] Pernodet F, Lahmidi H, Michel P. 2009 *11th Int. IBPSA Conf.* **22**:27-30
[3] Chantrelle F P, Lahmidi H, Keilholz W, El Mankibi M, Michel P. 2011. *Appl. Ene.* **88**(4):1386–94
[4] Jin Q, Overend M. 2012 *Proc. of Build. Sim. and Opt. Conf.* **10**:378–85
[5] Asadi E, Da Silva M G, Antunes C H, Dias L. 2012. *Ene. and Build.* **44**:81–7
[6] Am. Soc. of Heat., Refr. and Air-Cond. Eng. 2009. *ASHRAE Hand. Fund.* Atlanta, GA
[7] Salerno I, Anjos M F, McKinnon K, Gomez-Herrera J A. 2021. *Jour. of Build. and Eng.*
[8] International Passive House Association. https://passivehouse-international.org

Table of contents

Volume 2042

2021

◂ Previous issue Next issue ▸

CISBAT 2021 Carbon-neutral cities - energy efficiency and renewables in the digital era 8-10 September 2021, EPFL Lausanne, Switzerland

Accepted papers received: 23 September 2021

Published online: 18 November 2021

Open all abstracts

Preface

Data mining for the built environment (big data & machine learning)

The open access *Journal of Physics: Conference Series (JPCS)* provides a fast, versatile and cost-effective proceedings publication service.

Latest published conferences

Vol 2102 Go

Conference archive

2021 Go

View forthcoming volumes accepted for publication.

If you would like more detailed information regarding *Journal of Physics: Conference Series* please visit conferenceseries.iop.org, and if you are interested in publishing a proceedings with IOP Conference Series please visit our page for conference organizers.

Conference organizers can use our online form and we will get in touch with a quote and further details.

Most read

Most cited

Latest articles

JOURNAL LINKS

Journal home

Journal Scope

Information for organizers

Information for authors

Contact us

Reprint services from Curran Associates

JOURNAL HISTORY

2004-present Journal of Physics: Conference Series
doi:10.1088/issn.1742-6596
Online ISSN: 1742-6596
Print ISSN: 1742-6588