IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Environmental and economic optimisation of buildings for different climates

To cite this article: B Kiss *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 032033

IOP Conf. Series: Earth and Environmental Science **588** (2020) 032033 doi:10.1088/1755-1315/588/3/032033

Environmental and economic optimisation of buildings for different climates

B Kiss[1], J D Silvestre[2], J F A Madeira[3,4], R A Santos[2] and Zs Szalay[1]

[1] Budapest University of Technology and Economics, Department of Construction Materials and Technologies, Budapest, Hungary
[2] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal
[3] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal
[4] ISEL/IPL, Rua Conselheiro Emidio Navarro, 1, 1959-007 Lisboa, Portugal

szalay.zsuzsa@epito.bme.hu

Abstract. Introduction: Life Cycle Assessment (LCA) is a scientific method for evaluating the environmental impact of products. Standards provide a general framework for conducting an LCA study and calculation rules specifically for buildings. A challenge is to design energy-efficient buildings that have a low environmental impact, reasonable costs, and provide high thermal comfort, as these are usually conflicting aspects. Efficient mathematical optimisation algorithms can be applied to such engineering problems. **Methodology:** In this paper, a multi-objective optimisation technique, the Direct MultiSearch method, is described and its applicability is tested on a multi-story residential building's case study for two locations, Portugal and Hungary. The objectives are to minimise the life cycle environmental impacts and costs. **Results and conclusions:** The results indicate that optimum solutions are found at a higher cost but lower Global Warming Potential for Portugal than for Hungary. Optimum solutions have walls with a thermal transmittance of about 0.23 and 0.15 W/m^2K for Portugal and Hungary, respectively. Multi-objective optimisation algorithms can be successfully applied to find solutions with low environmental impact and eco-efficient thermal envelope.

1. Introduction

Life Cycle Assessment (LCA) is a scientific methodology for evaluating the potential environmental impact of products and services, with many applications to buildings. With this method, it is possible to compare alternatives or find the environmental hotspots over the life cycle of a building. As the operational energy need is greatly reduced in low-energy buildings due to legislation and economic considerations, the relative contribution of the embodied impacts of materials increases [1]. This makes it even more important to consider the full life cycle.

A challenge in building design is to find those alternatives that have a low environmental impact, low energy use, at reasonable costs, and providing high thermal comfort. It is not easy to fulfil these conflicting criteria at the same time; for example, the reduction of the operational energy need will increase construction's costs and embodied environmental impact. This task is even more demanding as the number of alternatives is very large: a building may be realised using different shapes, materials, and technical building systems. Architects usually consider only a small fraction of the many options. Even if an energy expert is involved in the design, usually only a few combinations are evaluated. What we are dealing with is, in fact, a mathematical optimisation problem that can be solved through various methods. However, due to the high number of possible solutions and the complex calculation models behind them, classical analytical optimisation methods suitable for finding maxima or minima of continuous and differentiable functions are generally not applicable. Evolutionary optimisation algorithms, which can find a range of quasi-optimal solutions, have been applied successfully to such problems, for example in [2-7].

This research has two main goals. The first goal is to test the applicability of multi-objective optimisation techniques, in this case, a Direct MultiSearch optimisation algorithm for designing sustainable and energy-efficient buildings. The second one is to test how regional differences influence the range of optimum solutions. For this purpose, two locations for the case study are compared: Portugal and Hungary.

2. Methodology

In this research, a modular computing framework developed earlier is applied (Figure 1) [8]. This framework combines existing tools and new modules for automatic building optimisation.

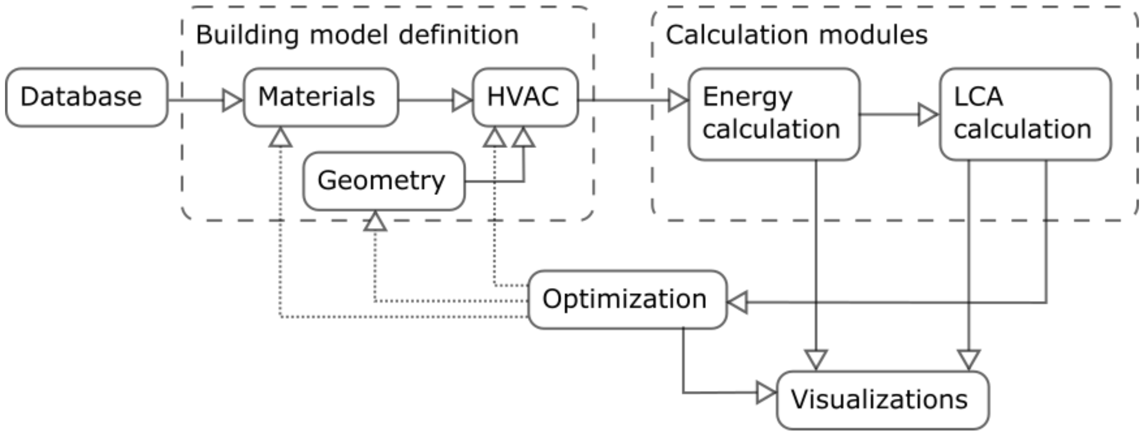

Figure 1. Modular structure of the tool.

The first module defines the building model in 3D, where the designer can input the geometry of the building. In the current framework, we apply the parametric design tools such as Rhinoceros3D and Grasshopper, which enable users to describe the shape of the building with mathematical formula instead of static drawings. This makes it possible to consider the shape of the building also as a design variable that the optimisation algorithm can change automatically. The building model module is linked to a database that includes the properties of materials (physical, environmental and cost). The calculation modules include the energy calculation, the environmental module, and the cost module. Energy calculations can be performed with simple steady-state methods (own code developed in Python) or with dynamic building simulation (Energy Plus). The environmental assessment module (own code in Python) sums up the environmental impacts for each life cycle stage considering the material quantities and the operational energy use. Replacement of building components is also calculated based on the expected service life and the end-of-life considering the most probable scenario for reuse/recycling/disposal. The optimisation module changes the variable inputs with an optimisation algorithm to find the optimal solutions. Finally, results are presented with different visualization techniques (own code) for assisting the decision making. The variables in the optimisation may include the geometry of the building, the ratio of windows on the facades, the type and thickness of building materials, or the service systems. Different objectives may be selected, e.g. to minimise the global warming potential or the acidification potential over the whole life cycle.

The modularity makes it possible to test different calculation methods in each module, for example, to connect different optimisation algorithms.

2.1. Multi-objective optimisation

A constrained non-linear multi-objective optimisation can be formulated mathematically, according to Miettinen [9], as the following:

$$\begin{aligned} &Min\; F(\mathbf{x}) \equiv \left(f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_m(\mathbf{x}) \right)^T \\ &s.t. \quad \mathbf{x} \in \Omega \subseteq IR^n \end{aligned}$$

In which are considered m objective functions $f_j : \Omega \subseteq IR^n \rightarrow IR \cup \{\infty\},\ j = 1, \ldots, m$ to minimise. It is important to notice that maximising f_j is mathematically equivalent to minimising $-f_j$. The feasible region is represented by the non-empty set $\Omega \subseteq IR^n$. Furthermore, in the presence of $m\,(\geq 2)$ objective functions, the minimiser of one function is not compulsorily the minimiser of another. In such a situation, a point that can be considered the optimum for all objectives cannot be obtained [10]. In this situation, Miettinen [9] states that the set of points that is obtained through this is defined as the Pareto optimal or non-dominated set. Additionally, given two points $\mathbf{x}_1, \mathbf{x}_2 \in \Omega$, $\mathbf{x}_1$ is said to dominate $\mathbf{x}_2$ in the Pareto sense, if and only if $\mathbf{x}_1$ is strictly better than $\mathbf{x}_2$ in at least one of the objectives and point $\mathbf{x}_1$ is not worse than $\mathbf{x}_2$ in any of the objectives. Finally, a set of points in Ω is non-dominated when no point in the set is dominated by another one in the set.

Direct MultiSearch optimisation algorithm. Direct MultiSearch (DMS) [10] is a derivative free solver for multiobjective optimisation problems that does not aggregate any components of the objective function. It generalises all direct-search methods of the directional type from single to multi-objective optimisation. A list of feasible non-dominated points (from which the new iterates or poll centers are chosen) is maintained by DMS. The search step is considered to be optional and, whenever it is used, it aims at improving numerical performance. However, DMS tries to capture the whole Pareto front from the polling procedure itself. At each iteration, the new feasible evaluated points are added to the list and the dominated ones are removed. Successful iterations correspond to changes in the iterate list, meaning that a new feasible non-dominated point has been found. Otherwise, the iteration is classified as unsuccessful. In this method, the constraints are handled using the extreme barrier function, which can be represented, according to [10], as the following:

$$F_\Omega(\mathbf{x}) = \begin{cases} F(\mathbf{x}) & if\ \mathbf{x} \in \Omega \\ (+\infty, \ldots, +\infty)^T & otherwise \end{cases}$$

When a point is deemed as infeasible, the components of the objective function F are not evaluated, with the values of F_Ω being set to $+\infty$. This is what allows to deal with black-box type of constraints, where only a yes or no answer is provided. For further details regarding DMS, refer to Custodio et al. [10].

This method has already been used to solve the problem of minimum weight and maximum damping of a viscoelastic sandwich plate by Madeira et al. [11] and by Araujo et al. [12] using a finite element model for the analysis of sandwich laminated panels with viscoelastic core. Additionally, it has been successfully used by Correia et al. [13] to maximise the performance and minimise the weight of functionally graded material (FGM) plate structures while Luis et al. [14] successfully optimised the design of a viscoelastic laminated composite panel with active piezoelectric patches.

2.2 Description of the case study building

The optimisation techniques are tested on a case study building. The building is a four-story multi-family apartment building with a floor area of 140 m^2 per story. Two locations are tested: Budapest in Hungary and Lisbon in Portugal. The building elements and building service systems have been selected so that they represent typical construction systems and are applicable in both countries. The building has clay brick walls with external insulation, reinforced concrete slabs, slab-on-ground with insulation and a flat roof with insulation and waterproofing. For space heating, a gas boiler is applied with an efficiency of 0.9 and for cooling a heat pump with a seasonal efficiency of 2.8.

The optimisation has two objective functions: 1) to minimise the life cycle environmental impact of the building, expressed in terms of Global Warming Potential (GWP100a, CML 2001) and 2) to minimise the life cycle cost of the building over a time period of 50 years. The variables include the window-to-wall ratio on each façade, the type of glazing, the type of window frame, the thickness and type of insulation on the wall and roof, and the thickness of the insulation in the floor to the ground (Table 1). In the LCA and LCC assessments, only the varying elements were considered, as the other elements can be described with a constant environmental impact not influencing the minimum points.

Table 1: Variables in the optimisation.

Variable	Range / discrete values	Unit
Window-to-wall ratio N Window-to-wall ratio W Window-to-wall ratio S Window-to-wall ratio E	0.0 - 0.8	-
Glazing type N Glazing type W Glazing type S Glazing type E	double / triple glazed	-
Window frame type	PVC / wooden	-
Wall insulation thickness Roof insulation thickness Floor insulation thickness	0.01 - 0.30	m
Wall insulation type Roof insulation type	*expanded polysytrene (EPS) / polyurethane (PUR) / insulation cork board (ICB)*	-
Floor insulation type	*expanded polysytrene (EPS)*	-

2.3 Energy calculation method

The initial model was set up in DesignBuilder, which applies the EnergyPlus simulation engine, a widely used validated dynamic energy calculation tool. The settings of the models for the two locations were harmonised as far as possible, but the local climate was assumed.

The climate Hungary can be classified as a warm summer continental climate (Dfb), while the Portuguese climate is Temperate Mediterranean with dry summers, being warm (Csb) in the North of the country and hot (Csa) in the South (Köppen-Geiger climate classification). Specifically, Lisbon has a heating season of 5.3 months with 1071 heating degree-days (HDD; base 18 ºC), 10.8 ºC mean outdoor temperature of the coldest month, and 150 kWh/(m^2.month) of mean monthly solar energy received on a south-facing vertical surface. The cooling season, having a four-month duration, as considered by the Portuguese energy codes, has a mean outdoor temperature of 21.7 ºC and 840 kW/m^2 of accumulated solar energy received horizontally [15]. In Budapest, the heating season is 6 months with 2696 heating degree-days (HDD; base 18 ºC), -0.1 ºC mean outdoor temperature in the coldest month, and 70 kWh/(m^2.month) mean monthly solar energy received on a south-facing vertical surface. The cooling season is three months long with a mean outdoor temperature of 21.2 ºC.

The building was modelled as a residential building with four heated and one unheated (staircase) zone on each floor. An occupancy density of 25 m^2/person was assumed and a power density of 5 W/m^2. Heating and cooling setpoints were considered as 20 ºC and 26 ºC, respectively. A winter air change rate of 0.5 ach was assumed [15] [16]. In the summer, an increased ventilation rate of 5 ach was assumed whenever the internal temperature exceeded 23 ºC and the indoor temperature was at least 2 °C higher than the outdoor temperature.

2.4 LCA database

Due to the limited number of Environmental Product Declarations (EPD) available in the country, the Hungarian LCA data used in this study is based on ecoinvent v3.5 (Cut-Off System Model). The ecoinvent data have been contextualised to acknowledge national differences by adopting the Hungarian electricity and natural gas datasets for materials primarily produced in Hungary.

The inventory of the LCA data of the production of each construction material for the Portuguese case study resulted from site-specific studies completed by the authors in Portuguese plants ([17], [18], [19], [20], [21]) and from EPD from producers of the same country [22]. The corresponding LCA results were calculated using SimaPro software and an environmental impact assessment method with a mid-point approach—CML 2001 baseline method.

Transport distances from the factory to the construction site were considered based on average Hungarian conditions and specific manufacturing plants for Portugal. 2-5% cutting waste was assumed at the construction site according to Kellenberger and Althaus (2009) [23]. In general, no replacement of the materials was assumed, except for plaster after 30 years and windows after 40 years. For waste treatment, standard country-specific ecoinvent data were considered for both countries.

2.5. Cost database

The costs for the Hungarian materials and components were collected from a national guide based on up-to-date average market prices, including material and installation costs [24].

The costs for the Portuguese case were collected from previous research studies ([17], [25], [26] [19]), construction firms, market surveys and building materials suppliers, and reference national documents [27].

3. Results and discussion

The optimisation process was limited to 1000 function evaluations in DMS. The algorithm finds the solutions closest to the origin of the search space of objectives first and then extends the collection of Pareto-optimal solutions into both directions (cost-optimal or GWP-optimal area). This makes it possible to analyse the "trade-off" area first. The optimisation was successful for both cases, which resulted in 21 and 33 non-dominated solutions for the Portuguese and the Hungarian cases, respectively. In figure 2, the evaluated solutions are plotted on the search space for both cases. The non-dominated solutions are highlighted in red colour.

In general, the Portuguese case resulted in higher life cycle costs and lower GWP compared to the Hungarian case. In Hungary, the winter climate is more severe, which leads to a higher heating energy demand and hence higher environmental impact. However, the unit price of natural gas and electricity is about twice as high in Portugal as in Hungary (natural gas is 0.076 EUR/kWh and 0.0346 EUR/kWh and electricity price is 0.2154 EUR/kWh and 0.112 EUR/kWh in Portugal and Hungary, respectively, including taxes). Labour cost is also approx. 1.5 times higher in Portugal than in Hungary and also some of the material costs are higher. These factors result in a higher life cycle cost.

IOP Conf. Series: Earth and Environmental Science **588** (2020) 032033 doi:10.1088/1755-1315/588/3/032033

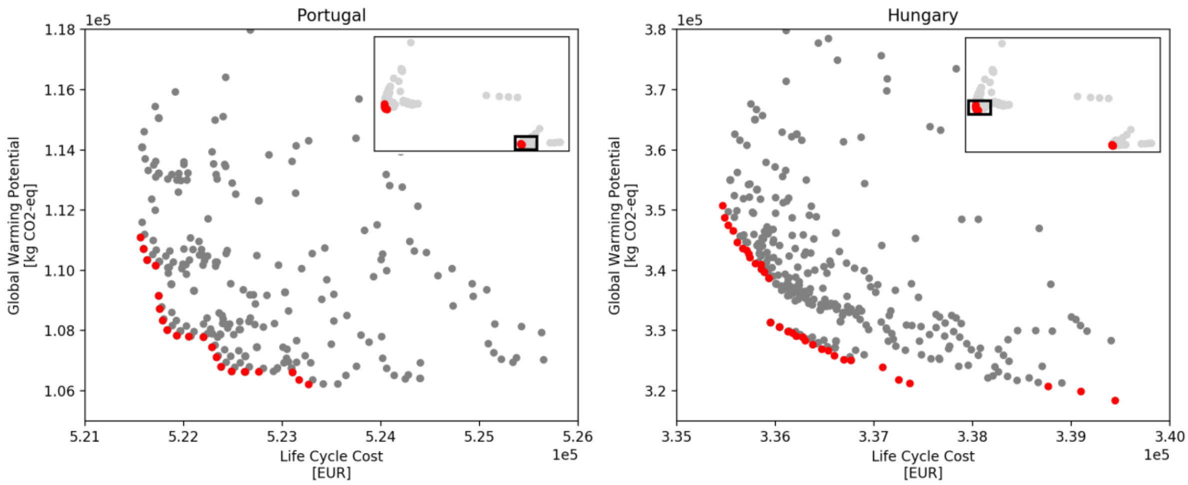

Figure 2. Result of the optimisation for Portugal and Hungary. Evaluated solutions are plotted in grey, non-dominated solutions are highlighted in red colour.

The parameters of the non-dominated solutions are collected in Table 2 for both contexts. Since there is no preferred weight defined between cost and GWP, all solutions can be considered as optimal. The variables are therefore evaluated as the mean (and standard deviation where applicable) of all non-dominated solutions. In the Portuguese context, the optima have lower insulation thickness (11 cm for the wall, 20 cm for the roof and 7 cm in the ground floor) than in the Hungarian context (20 cm on the wall, 22 cm on the roof and 9 cm in the ground floor). In both cases, the standard deviation is low (ca. 1 cm) for the non-dominated solutions. The two sets of optima follow the same preference on insulation material (EPS) and window type (plastic frame and double glazing). On the other hand, the optimal window ratio differs and is higher for the Hungarian context.

Table 2: Parameters of the non-dominated (optimal) solutions for Hungary and Portugal.

	Portugal	**Hungary**
Preferred window-to-wall ratio	0.25	0.37
Preferred glazing type	double	double
Preferred window frame type	plastic	plastic
Wall insulation thickness	11 cm ± 2 cm	20 cm ± 1 cm
Roof insulation thickness	20 cm ± 1 cm	22 cm ± 1 cm
Floor insulation thickness	7 cm ± 2 cm	9 cm ± 2 cm
Preferred insulation type	EPS	EPS

4. Conclusions

The paper described a modular framework for the environmental and economic optimisation of buildings. Direct MultiSearch optimisation was successfully applied to determine the optimum design alternatives for a case study building in a Portuguese and in a Hungarian context. The developed framework can be efficiently applied from an early design stage, which is especially important as the improvement potential is very high at this stage. The optimisation has the potential to be offered as a service to architects or to be furthered developed into a user friendly tool for direct use.

However, cost, energy use, and environmental impact of a building is only some of the aspects of a sustainable building but very important nonetheless. Building design is also influenced by many other architectural constraints, for example, aesthetics, fire safety, legal requirements. Such a tool does not provide a ready-made solution but can assist the complex decision-making process and support the design of sustainable buildings.

Acknowledgement
MooB - Multi-objective life cycle optimisation of sustainable and innovative construction materials and buildings (Project 2018-2.1.15-TÉT-PT-2018-00005) has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary and from FCT, Fundação para a Ciência e Tecnologia, Portugal. The research was also supported by Project FK 128663 implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the FK_18 funding scheme. The financial support of FCT, Fundação para a Ciência e Tecnologia, Portugal, through the PhD scholarship no. PD/BD/135215/2017 of the fourth author in the scope of EcoCoRe Doctoral Programme, to CERIS Research Centre, and to IDMEC, under LAETA project UIDB/50022/2020, is acknowledged. This paper relates to ongoing research within the international project IEA EBC Annex 72.

References
[1] G. A. Blengini and T. Di Carlo, "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings," *Energy Build.*, vol. 42, no. 6, pp. 869–880, 2010.
[2] R. Evins, "A review of computational optimisation methods applied to sustainable building design," *Renew. Sustain. Energy Rev.*, vol. 22, pp. 230–245, Jun. 2013.
[3] G. Verbeeck and H. Hens, "Life cycle inventory of buildings: A calculation method," *Build. Environ.*, vol. 45, no. 4, pp. 1037–1041, 2010.
[4] R. Azari, S. Garshasbi, P. Amini, H. Rashed-Ali, and Y. Mohammadi, "Multi-objective optimisation of building envelope design for life cycle environmental performance," *Energy Build.*, vol. 126, pp. 524–534, 2016.
[5] A. Hollberg and J. Ruth, "LCA in architectural design—a parametric approach," *Int. J. Life Cycle Assess.*, 2016.
[6] G. Lobaccaro, A. H. Wiberg, G. Ceci, M. Manni, N. Lolli, and U. Berardi, "Parametric design to minimize the embodied GHG emissions in a ZEB," *Energy Build.*, vol. 167, pp. 106–123, 2018.
[7] S. Longo, F. Montana, and E. Riva Sanseverino, "A review on optimisation and cost-optimal methodologies in low-energy buildings design and environmental considerations," *Sustain. Cities Soc.*, vol. 45, pp. 87–104, 2019.
[8] B. Kiss and Z. Szalay, "Modular approach to multi-objective environmental optimisation of buildings," *Autom. Constr.*, vol. 111, no. November 2019, p. 103044, 2020.
[9] K. M. Miettinen, *Nonlinear multiobjective optimisation*, 2nd editio. Kluwer Academic Publishers, 1999.
[10] A. . Custódio, J. F. A. Madeira, A. I. F. Vaz, and L. N. Vicente, "Direct Multisearch for Multiobjective Optimisation," *SIAM J. Optim.*, vol. 21, pp. 1109–1140, 2011.
[11] J. Madeira, A. Araujo, C. Soares, C. Soares, and A. Ferreira, "Multiobjective design of viscoelastic laminated composite sandwich panels," *Compos. Part B Eng.*, vol. 77, no. 03, pp. 391–401, 2015.
[12] A. Araujo, C. M. Soares, and C. M. Soares, "Finite element model for hybrid active-passive damping analysis of anisotropic laminated sandwich structures," *J. Sandw. Struct. Mater.*, vol. 12, no. 4, pp. 397–419, 2010.
[13] V. M. F. Correia, J. A. Madeira, A. L. Araujo, and C. M. M. Soares, "Multiobjective optimisation of ceramic-metal functionally graded plates using a higher order model," *Compos. Struct.*, vol. 183, pp. 146–160, 2018.
[14] N. F. Luis, J. Madeira, A. Araujo, and A. Ferreira, "Active vibration attenuation in viscoelastic laminated composite panels using multiobjective optimisation," *Compos. Part B Eng.*, vol. 128, pp. 53–66, 2017.
[15] "REH, Regulation of the Energetic Performance of residential buildings (in Portuguese)," 2013.

[16] H. Government, “TNM 7/2006. (V.24.) Hungarian Government Decree on the energy performance of buildings.” .

[17] R. Gomes, “Life Cycle Assessment ‘From Cradle to Cradle’ of Building Assemblies-Application to Flat Roofs (in Portuguese),” Lisbon University, Lisbon, Portugal, 2019.

[18] R. Gomes, J. D. Silvestre, and J. De Brito, “Environmental Life Cycle Assessment of Thermal Insulation Tiles for Flat Roofs,” *Materials (Basel).*, vol. 12, p. 2595, 2019.

[19] J. D. Silvestre, “Life Cycle Assessment ‘From Cradle to Cradle’ of Building Assemblies-Application to External Walls,” Technical University of Lisbon, 2012.

[20] J. D. Silvestre, A. M. P. Castelo, J. J. B. C. Silva, and J. M. C. L. De Brito, “Retrofitting a Building ’ s Envelope : Sustainability Performance of ETICS with ICB or EPS,” *J. Appl. Sci.*, vol. 9, no. 7, p. 1285, 2019.

[21] J. D. Silvestre, N. Pargana, J. De Brito, M. D. Pinheiro, and V. Durão, “Insulation Cork Boards — Environmental Life Cycle Assessment of an Organic Construction Material,” *Materials (Basel).*, vol. 9, no. 5, p. 394, 2016.

[22] DAPHabitat, “DAPHabitat - National registration system of environmental product declarations for the habitat (in Portuguese),” 2020. [Online]. Available: daphabitat.pt. [Accessed: 02-Jan-2020].

[23] D. Kellenberger and H. J. Althaus, “Relevance of simplifications in LCA of building components,” *Build. Environ.*, vol. 44, pp. 818–825, 2009.

[24] HUNGINVEST, *Construction costs (Építőipari költségbecslési segédlet - in Hungarian)*. Építésügyi Tájékoztatási Központ Kft., 2019.

[25] J. Brito, J. Silvestre, and M. Pinheiro, “Life-cycle impact ‘cradle to cradle’ of building assemblies,” *Proc. ICE - Eng. Sustain.*, vol. 167, pp. 53–63, 2014.

[26] T. MARRANA, J. D. SILVESTRE, J. de BRITO, and R. GOMES, “Life cycle cost analysis of flat roofs of buildings,” *J. Constr. Eng. Manag.*, vol. 143, no. 6, 2017.

[27] A. Manso, M. Fonseca, and L. Espada, *Information about Costs—Productivity Sheets (in Portuguese)*. Laboratório Nacional de Engenharia Civil: Lisbon, Portugal, 2010.