Visual tool to integrate LCA and LCC in the early design stage of housing

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Abstract. Over their whole life cycle, buildings are responsible for high environmental impacts and require critical financial resources. Decisions in the early design phase have a significant impact on both. This study aims to develop a visual decision support tool for architects in order to integrate an environmental and economic life cycle approach for dwellings. To evaluate the environmental impacts of the building design, the tool uses the Belgian LCA method, ‘Environmental Profile of Building Elements’. This method translates 17 environmental indicators in environmental costs by considering the cost to avoid, reduce or compensate the effects to a level that is bearable. The tool allows to combine these life-cycle environmental costs (LCEC) with Life Cycle financial Cost (LCFC). To estimate the operational energy use of the building, the “dynamic Equivalent Heating Degree Day (dEHDD)” method is used. This method allows for fast and relatively accurate heating energy estimations in the early phase, based on a limited number of input data. The tool visualises the results in a graphical way which can be easily understood by architects. Even more, visualisation is seen as a powerful communication tool to share information and ideas with all stakeholders.

1. Introduction
As the built environment has been well-known as a crucial contributor to climate change [1,2], the 2010 European Directive on the Energy Performance of Buildings Directive (EPBD) requires EU Member States to improve the energy efficiency of new buildings to achieve the target of nearly Zero Energy Buildings (nZEBs) by 2020 [3]. In the same line, in November 2015, 174 countries signed an agreement to plan a drastic reduction in greenhouse gas (GHG) emission at the UN Conference on Climate Change in Paris. Design decisions in the early design stage significantly determine a building’s life-cycle environmental and economic impacts [4,5]. However, due to the complexity of life-cycle cost (LCC) and life-cycle assessment (LCA) and the time constraints to consider those aspects in the early design phase, including those aspects, has remained a challenge especially for small scale project like dwellings [6]. As architects play a crucial role to reach the target, they must be better equipped to estimate influences of their decision on the impacts. In the constant feedback loop of designedly thinking, architects use mainly visual tools [7,8]. This paper proposes a visual design support tool for architects to design a sustainable dwelling based on LCA and LCC approaches. This paper is structured into five sections. The framework of the research is described in section 2. The calculation method is presented in section 3. The data visualisation in the tool is demonstrated in section 4. Results and discussion are described in section 5. Finally, conclusions are provided in section 6.
2. Framework for the approach

2.1. Goal

The objective of this study is to develop an approach to integrate life-cycle environmental and economic performance assessment in the early design stage to support architects when making their design decisions for a sustainable dwelling. The major hurdles for architects to integrate LCA and LCC in the early design stage are: time constraints, complexity of input and integration of dataset/results of the simulation. To overcome these difficulties, this study includes the following features:

- User-friendly input (no additional time and effort for input)
- Quick calculation method for estimating the heating energy in winter
- Graphical representation of results

In this study, the environmental impacts are monetised into a life-cycle environmental cost (LCEC). This monetisation enables to compare LCA and LCC in the same unit and to aggregate into a single figure. In addition, monetisation allows environmental taxation which is high on the EU political agenda [9] and has many advantages as highlighted by the organisation for economic co-operation and development (OECD) such as environmental effectiveness, economic efficiency, the ability to raise public revenue, transparency and addressing a wide range of issues [10]. As buildings have an effect on a wide range of issues such as energy, carbon, transport, waste, air and water pollution and resource through the life-cycle, LCEC can be used for the preparation of building life-cycle environmental taxes. The life-cycle total cost (LCTC) is defined as the sum of LCEC and life-cycle financial cost (LCFC). Both LCEC and LCFC can be divided into initial costs and in-use including the end of life costs (use+EOL) (Fig.1).

![Four leaves clover diagram of LCTC](image)

Figure 1: Four leaves clover diagram of LCTC

2.2. Workflow of the proposed approach

Figure 2 presents the hypothesis regarding the workflow of the design process considered in this research. The proposed tool, which is an Excel spreadsheet, consists of several input sheets, developed for each sub-stage: Brief-Form0, Form1 and Form2. Input parameters are classified into three categories: (1) geometry, (2) technical choices and (3) user behaviour. In the more advanced design stages, more detailed input parameters are required for each category. The user-friendly input and the calculation for estimating the heating energy in the tool are explained more details in [11]. Based on the input of these three categories, the tool provides a fast calculation of LCFC and LCEC. LCEC is based on ‘Environmental Profile of Building Elements (MMG)’. Inputs of technical choice use a database of elements and materials from MMG. The database was extended with financial costs. The outputs are translated into two graphical representations: Sankey diagrams and parallel coordinate plots.
3. Calculation method

3.1. Life-cycle financial costing (LCFC)

LCFC is based on the following formula [12]:

$$\text{LCFC} = IF + SPV(PF_0) + SPV(EOLF_0)$$

(1)

With:
- IF: initial financial cost (€)
- SPV(PF₀): the sum of the present values of periodic financial cost (€)
- SPV(EOLF₀): the sum of the present values of the EOL costs (€)

The present value of future costs is calculated as follows [12]:

$$PV[C_t] = C_0 \left( \frac{1+g}{1+d/1+i} \right)^t$$

(2)

With:
- PV[Cₜ]: present values of a cost (€)
- C₀: cost for a year of reference (€)
- g: nominal growth rate
- d: nominal discount rate
- i: inflation rate
- t: year of the cost (year)

In this study, the total financial cost is the sum of a construction cost, present values of future costs such as maintenance costs, heating costs, electricity cost for appliances and lighting and the EOL financial cost. A more detailed description can be found in [12].
3.2. Dynamic Equivalent Heating Degree Day (dEHDD) method to estimate operational heating energy

Figure 3: Representation of dEHDD for the temperate climate in Belgium and two different occupant behaviour profiles

The proposed tool uses a refinement of the Equivalent Heating Degree Days (EHDD) method to predict operational heating energy [13]. The Heating Degree Days (HDD) method predicts the yearly required energy for heating based on the number of days with a difference between the daily average outdoor and indoor temperature.

The EHDD takes into account the free solar and internal heat gains in a static way by a fixed reduction of the HDD [14]. In the dEHDD method, this reduction is calculated month by month for a better approximation of the solar gains and internal gains by occupant and appliances. The outdoor temperature ($T_e$) is obtained via linear regression of monthly temperature during autumn, winter and spring from Test Reference Years weather data (TRYs) [15]. The approach can be represented in a graphical way (Fig.3) with horizontally the number of days of the heating season and vertically the temperature. The number of dEHDDs is represented by the blue area in Fig.3. A more detailed description can be found in [13].

3.3. Life-cycle assessment (LCA) method: Environmental Profile of Building Elements (MMG)

In this study, the MMG method (the Belgian LCA method for buildings and elements developed for the Public Waste Agency of Flanders) is used to assess the life cycle environmental impacts and to monetise the environmental loads [16]. Seven environmental indicators “CEN” [17] in line with the European standard and ten additional environmental indicators “CEN+” from Belgian legislation [18] are taken into account. The method is described in more detail in [16]. This method monetises life cycle impacts as the cost to avoid, reduce and compensate environmental damage to a bearable level for the earth. The monetisation method in the MMG is described in [19].

4. Data visualisation in the tool

4.1. Sankey Diagram

Sankey Diagrams (SDs), initially developed by Riall Sankey to analyse the thermal efficiency of steam engines in 1898, are widely used to visualise quantitative flows in many fields of application. The width of the arrows is proportional to the size of flows. In this study, SDs are used to visualise the financial component of design decisions regarding elements. In the centre of Figure 4, the total cost for the different elements and costs for heating and electricity use by appliances and lighting are represented. The left flow (“flow (1)” in fig 4) visualises the relationship between elements and the sum total of LCFC and LCEC. The right flow (“flow (2)” in fig 4) visualises the relationship between elements and total initial cost and the cost during the use phase including the end of life (use+EOL). Several tools are available for SDs visualisation. “Sankey Diagram Generator v.1.2” [20] is used in this paper. Results of environmental cost are automatically collected from the MMG database to the proposed tool and the proposed tool automatically translates the dataset of LCFC and LCEC into a JavaScript code to visualise...
via the “Sankey Diagram Generator v.1.2”. Figure 4 and 5 show a representation of two design options. The useful feature for SDs is the possibility to visualise selected flows, e.g. in Fig.5 the inputs from the different elements of cost in “use+EOL phase”. SDs give architects insight into the impact of each design and help to evolve to a sustainable building.

Figure 4: Representation of SDs for a design option (above) and diagram of flows (below)

Figure 5: Representation for a design option and highlighting of “use+EOL phase” in SDs
4.2. Parallel coordinate plot for visualisation of design space

Parallel coordinates are one of the most general techniques for representation and exploration of multidimensional problems. Parallel coordinate plots (PCPs) represent input and output parameters on parallel axes and all input and output values of one case are connected via lines. Hence, PCPs enable to represent an $n$-dimensional problem in a plane and allow to represent how a whole range of input parameters affect several outputs [21]. Several tools are available for visualisation via PCPs. For this paper “Xdat version 2.2” is used [22]. As highlighted by Siitola et al. [23], advantages of PCPs for architects in the early design phase are, firstly, an overview of the design space is easily grasped because PCPs itself is an overview. It enables architects via colouring and a selecting mechanism to understand the impacts of each parameter on the result quickly and to observe the relationship between parameters. Secondly, rearrangement operations such as changing the order of coordinate-lines, inverting the axis direction and so on, often give additional insights into the data set. Thirdly, architects can highlight the set of connections to facilitate comparisons between selected and non-selected lines. Fourthly, it is possible to display exact values per axis. It helps architects to discover design alternatives between certain limits, such as targets of LCTC and LCEC, investment cost, and so on. Figure 6 shows two design options (same total floor area but more or less compact buildings based on width, depth and number of floors) filtered so that only one value is considered for the ventilation rate, internal heat gains by people and appliances. The elaborated tool can automatically create a design space with user-defined parametric ranges and steps of each parameter. Figure 7 visualises the representation of a whole design space, applying different colours for each compactness and highlights design options of the smallest and the largest LCTC via a thick black line. It illustrates that the important feature of PCPs is its power to translate numerical data set into a visual representation and the ability to provide both an overview and detailed numeric values.
5. Discussion

This paper presents a tool to assess the life-cycle environmental and economic aspects for architects in an early design stage in order to support the design of sustainable dwellings. The tool proposed in this paper:

- Requires no additional effort to obtain LCFCs and LCECs of each design proposal than what architects already consider, such as orientation, location, geometry, materials, and so on. The proposed tool requires primary inputs categorised into (1) geometry, (2) technical choices and (3) user behaviour for energy estimation. A more detailed input can be provided along the design process if more detailed calculations are desired, typically evolving in level of detail from brief, sketch design and preliminary design.

- Enables fast and accurate estimations of the heating energy and electricity for appliances and lighting of each design option. This energy is translated into LCEC and LCFC. This quick estimation method enables architects to understand how their design decisions influence the environment and finance in a step by step process. As important design decisions are taken early in the design phase, this tool hence allows to assess the influence of these decisions at a crucial moment.

- Provides easily understandable output via monetisation of LCEC. Both environmental and economic impacts expressed in a single unit (€) and aggregated into a single figure enables to compare both easily.

- Demonstrates two types of visualisation of results: “Sankey Diagrams” (SDs) and “parallel coordinate plots” (PCPs) because architects often hesitate to deal with numerical datasets. SDs visualise the impacts of changing design parameters on LCEC and LCFC during a step by step design approach (bottom-up approach). PCPs generate an overview of the design space (top-down approach). However, since in the Sankey diagram the vertical scale is often adapted so that the sum of all costs of considered elements covers the whole screen vertically, the absolute differences between the design variants are not represented graphically but can only be read as a numerical value. To overcome this disadvantage, the tool allows to generate a design space by defining for each parameter a minimum value, a maximum value and a number of steps in between. This design space is visualised via parallel coordinates plots (PCPs). This plot can visualise the different costs on different axes. Analysing the effect of different design decisions becomes very graphical and allows an interactive iteration. Therefore, the combined use of these
two visualisation techniques enables architects to find better design solutions for sustainable buildings from an early design stage on. Even more, visualisation is a powerful communication tool for architects to share information and ideas with other architects, engineers, stakeholders and clients.

- Enables to use different climatic conditions with any Test Reference Years (TRYs) (also predicted future TRYs) for estimation of heating energy demands via dEHDD.

6. Conclusion

The advantages of the proposed approach are: (1) user-friendly limited inputs for the life-cycle financial cost (LCFC) and no extra effort to estimate in addition the life-cycle environmental cost (LCEC), (2) fast analysis of the importance of heating via LCEC and LCFC and (3) easy comprehensive visualisation. Via the tool, it is not a huge challenge anymore to integrate extra aspects (life-cycle environmental and economic) in the design processes as it does not require extra time and effort and it is easily interpretable via different graphical representations. This research is a starting point to assist architects in making decisions for sustainable nearly Zero Energy Buildings (nZEBs) from the sketch design stage onwards. Concerning further research, the usability test will be carried out by students and a workshop for architects will be organised to obtain feedback from practitioners. Furthermore, the tool will be extended to evaluate summer comfort/discomfort to avoid the need for active cooling.

References

[1] T. Boermans, A. Hermelink, S. Schimschar, J. Grözinger, M. Offermann, Principles for nearly zero-energy buildings - Paving the way for effective implementation of policy requirements, BPIE - Build. Perform. Inst. Eur. (2011).

[2] UNEP SBCI, Buildings and Climate Change: Summary for Decision Makers, (2009).

[3] EPBD recast, DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Union. (2010) 13–25.

[4] I. Kovacic, V. Zoller, Building life cycle optimization tools for early design phases, Energy. 92 (2015) 409–419. doi:10.1016/j.energy.2015.03.027.

[5] SETAC-Europe, Life-cycle Assessment in Building and Construction: A State-of-the-art Report, 2003, SETAC, 2003.

[6] T. Jusselme, E. Rey, M. Andersen, An integrative approach for embodied energy: Towards an LCA-based data-driven design method, Renew. Sustain. Energy Rev. 88 (2018) 123–132. doi:10.1016/j.rser.2018.02.036.

[7] J. Anderson, Architectural design, Lausanne AVA, 2011.

[8] C. Gänshirt, Tools for ideas: an introduction to architectural design, Basel Birkhäuser, 2007.

[9] S. Speck, S. Paleari, Environmental taxation and EU environmental policies, European Environment Agency, Copenhagen, Denmark, 2016. https://www.eea.europa.eu/publications/environmental-taxation-and-eu-environmental-policies (accessed March 5, 2019).

[10] OECD, Environmental Taxation A Guide for Policy Makers, (2011). https://www.oecd.org/env/tools-evaluation/48164926.pdf.

[11] A. Miyamoto, D. Trigaux, T. Nguyen Van, K. Allacker, F. De Troyer, From a Simple Tool for Energy Efficient Design in the Early Design Phase to Dynamic Simulations in a Later Design Stage, in: vdf Hochschulverlag AG, Zurich, 2016. doi:10.3218-3774-6.

[12] K. Allacker, Sustainable building. The development of an evaluation method, KU Leuven, Leuven, n.d.

[13] A. Miyamoto, T. Nguyen Van, D. Trigaux, K. Allacker, F. De Troyer, Visualisation tool to estimate the effect of design parameters on the heating energy demand in the early design phases, in: Ass. Building Green Futures, Bologna, 2015: p. 287. doi:10.13140/RG.2.1.1515.2085.
[14] Diensten voor de programmatie van het wetenschapsbeleid, Ontwerp en thermische uitrusting van gebouwen - deel 2, Brussels, 1984.

[15] Carlo Joyce Correna Roberto Lamberts, Test Reference Years weather data, (2005). https://energyplus.net/weather (accessed January 20, 2019).

[16] K. Allacker, W. Debaeker, L. Delem, L. De Nocker, F. De Troyer, A. Janssen, K. Peeters, J. Van Dessel, R. Servaes, E. Rossi, M. Deproost, S. Bronchart, Environmental profile of building elements. Update 2017, OVAM, Mechelen, 2018. http://www.vlaanderen.be/nl/publicaties/detail/environmental-profile-of-building-elements-update-2017 (accessed March 4, 2019).

[17] CEN, ed., EN 15804:2012+A1:2013 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2013.

[18] NBN, ed., NBN/DTD B 08-001 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products - National supplement to NBN EN 15804+A1, 2014.

[19] L. De Nocker, W. Debacker, Annex. Monetisation of the MMG method. Update 2017, OVAM, Mechelen, 2018. http://www.vlaanderen.be/en/publications/detail/anex-monetisation-of-the-mmg-method-update-2017 (accessed March 4, 2019).

[20] The Sankey Diagram Generator, Acquire Procure. Serv. (2016). http://sankey-diagram-generator.acquireprocure.com (accessed March 12, 2019).

[21] A. Inselberg, B. Dimsdale, Parallel coordinates: a tool for visualizing multi-dimensional geometry, in: Proc. First IEEE Conf. Vis. 1990 Vis. 90, 1990: pp. 361–378. doi:10.1109/VISUAL.1990.146402.

[22] Xdat version 2.2, 2015. http://www.xdat.org/.

[23] H. Siirtola, K.-J. Räihä, Interacting with parallel coordinates, Interact. Comput. 18 (2006) 1278–1309. doi:10.1016/j.intcom.2006.03.006.