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A parametric tool for the assessment of operational energy use, embodied energy and embodied material emissions in building

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Abstract

Current European legislation calls for the abatement of greenhouse gas (GHG) emissions through better building design and technological solutions, in order to reduce operational energy use, embodied energy and embodied material emissions originating from buildings. Presently, environmental performance assessment tools for buildings fall short of documenting all of these parameters. Comparative life cycle assessment (LCA) may be used to obtain a clear overview of mass and energy flows in a building. However, construction professional consider LCA calculations as complex and time consuming. Therefore, this paper outlines a methodology for the development of a dynamic parametric analysis tool (PAT) for the comprehensive assessment of operational energy use, embodied energy and embodied material emissions during the production and operation phases of a building. A simple, conceptual building case study is presented to demonstrate the potential use of this parametric analysis tool. The results show that the PAT developed in this study can be used to define optimal solutions of building envelopes for the different parameters of the analysis. In conclusion, this study facilitates the first steps of development and testing for a PAT that evaluate optimised solutions that minimise operational energy use, embodied CO_{2eq} emissions and embodied energy. The tool, which is not meant to give precise results, given its limitations in the calculation method, can be used for performing a comparative pre-assessment of various design solutions. This body of work highlights considerable scope of work for the further development of this tool.

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Keywords: Building; Operational energy; embodied energy; embodied CO_{2eq} emissions; parametric analysis tool

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1. Introduction

The building sector is responsible for a significant proportion of global energy consumption, which gives rise to greenhouse gas (GHG) emissions and the depletion of energy resources [1, 2]. Current European legislation calls for the abatement of GHG emissions through better building design and technological solutions [3]. Emerging trends towards energy efficient buildings, such as passive house, zero emission and energy-positive buildings, address the target of reducing operational energy and emissions in buildings [4-10]. These targets are typically reached by implementing energy efficiency measures, such as installing effective insulation materials and better performing windows, reducing infiltration losses, recovering heat loss from ventilation systems, and through using renewable energy resources, in order to meet the remaining energy demand [11, 12].

However, as buildings become more energy efficient, the relative proportion of embodied energy and associated carbon emissions arising during the building lifecycle increases [13-16]. Many studies analysed operational energy use and emissions arising from the operational stage of a building, whilst fewer studies examined embodied energy or embodied material emissions arising from building materials in a building [17-22].

Life cycle assessment (LCA) is a widely recognised and accepted method for the assessment of burdens and impacts throughout the lifecycle of a building. LCA evaluates all resource inputs, including energy, materials and water, in order to calculate the environmental impacts of a building at either the material, product or whole building level. Within the construction industry, the life cycle inventory (LCI) phase is considered the largest obstacle, due to the time-consuming process of data collection. There are many existing LCI databases available (e.g. University of Bath's Inventory of Carbon and Energy (ICE) [23] and the Swiss Ecoinvent database [24]), however many of these databases rely on generic data and require a platform for LCA calculations. Often these calculations are carried out in process-based LCA tools such as Simapro or Gabi [25, 26], which are not designed specifically for buildings. The Ökobaudat is an LCI database that consists of a mixture of generic data and environmental product declarations (EPDs) [27], which have the advantage of taking into account regional production variations [28]. There have been many developments within the building sector to simplify LCA calculations, and the IEA Annex 31 developed an assessment tool classification system, which is divided into five parts: 1) Energy modelling software, 2) Environmental LCA tools for buildings, 3) Environmental assessment frameworks and rating systems, 4) Environmental guidelines for design and management of buildings and 5) environmental product declarations [29]. Many energy modelling tools (e.g. SIMIEN, IDA-ICE, EnergyPlus [30]), environmental assessment tools for buildings (e.g. ATHENA Environmental Impact Estimator, Building Environmental Assessment Tool (BEAT), EcoEffect [31]) and environmental product declarations (EPDs) from different EPD program operators (EPD Norge, the International EPD system, IBU) stem from this classification [32].

In addition, there are a number of parametric analysis tools (PAT) available for a range of parameters such as optimal structure, optimal daylighting or optimal comfort. Parametric analysis is a useful since it facilitates for the dynamic testing of multiple scenarios simultaneously. However, few PATs combine and assess the environmental impacts arising from both operational energy and material use in buildings. Previous studies evaluated existing sustainable building assessment tools, [31, 33-35] and found that they cover a wide range of building types and different aspects of a building's life cycle. Some previous PAT studies focused on the parametric design in tall buildings [36], optimised daylighting in a Grasshopper based PAT [37], the performance of a PAT in energy efficiency measures [38], the performance of building envelopes in residential buildings [39].

The objective of this study is to build upon the existing body of knowledge outlined above, by combining three types of tools identified by the IEA Annex 31 classification system; namely, energy modelling, environmental LCA tools for buildings, and EPDs; into one interactive parametric analysis tool. This parametric analysis tool differs from the other existing tools, as it combines three assessment tools into one holistic tool for buildings. Therefore, this paper investigates ways of simplifying the data collection process for users through the implementation of an environmental parametric analysis tool. The tool is designed to help architect, engineer and constructor (AEC) professionals identify which design options lead to lower operational energy use, embodied energy and embodied CO2eq emissions. For that reason, we developed a PAT in MS Excel with a simple and intuitive user interface.

This paper presents a tool specifically developed to perform a parametric analysis of wall and window components in a building, in order to evaluate optimised solutions that minimise operational energy use, embodied CO2eq emissions and embodied energy. A residential zero emission building (ZEB) concept model, developed by the Norwegian ZEB Research Centre [40, 41] was used as a base case for testing the tool. Previous investigations [40] shown insulation as one of the dominant sources of embodied emissions, and space heating as responsible for the largest energy demand. This body of work performs a parametric analysis of insulation thickness, window size and type in order to select the options with the lowest embodied emissions and energy demand arising from wall and window components in the ZEB single-family house (SFH) concept building. For each alternative, operational energy, embodied energy and embodied CO2eq emissions are calculated.

2. Methodology

An MS Excel-based parametric analysis tool has been developed and tested for a residential ZEB single-family house concept building. More specifically, the wall and window components are analysed in order to evaluate optimised solutions that minimise operational energy use, embodied energy and embodied CO_{2eq} emissions. The parametric analysis tool follows the lifecycle approach according to EN 15978. This methodology is based on the principles of LCA as outlined in ISO 14040 and ISO 14044.

The methodology section of this paper is divided into three parts. The first part outlines the methodology for energy modelling, which includes the calculation of operational energy use (according to ISO 13790), and emissions arising from the building operational energy use (module B6 of EN 15978). The second part outlines the LCA methodology used for the calculation of embodied energy and embodied CO_{2eq} emissions arising from the production of building materials (modules A1 – A3 of EN 15978). For simplicity, the building elements and components included in this tool are structured according to NS 3451 –Table of Building Elements nomenclature. This second part also describes how EPDs have been collected and used in the LCI database as part of the tool. The third part outlines the parameters used for analysis in this study. The parameters to be investigated are window types, fenestration areas and insulation thickness.

2.1. Energy modelling methodology

This part of the tool is dedicated to the calculation of operational energy use on the whole building level, and was built according to ISO 13790. The standard indicates two methods for calculating building heat balance: a monthly and an hourly calculation. The monthly calculation method was chosen, since the scope of the PAT is to give users a simplified pre-assessment of the building's annual heating and cooling demand. The building energy balance is calculated in the tool by considering:

- The transmission heat transfer between conditioned space and the external environment (which includes heat transmission between the building envelope and outdoor air and ground).
- The ventilation heat transfer between conditioned space and the external environment (which includes both natural and mechanical ventilation).
- Internal heat gains (which includes gains from users, appliances and lighting).
- Solar heat gains (which includes direct and diffuse solar radiation through windows).

Annual building energy use is calculated for heating and cooling, as well as electricity use for lighting, appliances, and ventilation. The internal heat gains from people are calculated according to the ISO 7243. The electricity use from lighting is calculated by dividing the required lux level by the luminous efficacy of the chosen luminaire (incandescent, halogen, metal halide, fluorescent, compact fluorescent, and LED), and by multiplying this result with the distance between the working surface and the luminaire. Required lux level are to be chosen by the user, and are given in ISO 12464-1:2011. The luminous efficacy (in lm/W) is retrieved from commercial catalogues and producers of luminaries and light bulbs. Different control systems for the luminaries (manual switch, dimmer, and presence detection) are provided in the tool according to EN 15193:2007. Electricity consumption of appliances is retrieved from catalogues for electronic products and white goods. All energy used for lighting and by appliances is assumed to be transferred into the conditioned environment as internal heat gains. Heat transfer due to natural ventilation and infiltration is calculated for either single-side or cross ventilation strategies [42] according to EN 15242:2007. A schedule of the hours and days for natural ventilation is included in the tool. The heat transfer due to mechanical ventilation is calculated according to EN 15251:2007. A reduction factor for heat transfer due to air heat recovery is included in the calculations, as well as electricity use for fan operation, according to EN 13779:2007.

Solar gain is included by calculating the direct and diffuse solar radiation falling on window glass. The diffuse horizontal radiation and the direct normal radiation [Wh/m^2] are extracted from IWEC weather files for the Oslo climate [43]. The direct solar radiation falling onto the window glass surface area is calculated from the direct normal radiation according to [44] and [45] for a range of orientations and tilt angles. Different shading options (i.e. curtain, venetian blind) are available to the user. The shading is assumed to be operative once the global radiation hitting the glass surface is above 175 Wh/m^2. The transmission heat transfer between the conditioned space and the ground is calculated according to ISO 13370:2007 for slab-on-ground floors. The u-value and g-value of different glazing systems (i.e. single, double, triple and quadruple) are retrieved from catalogues from window manufacturers. The heat transfer for different windows frames (i.e. wood, plastic and metal) is calculated according to ISO 10077-1. Operational energy use for heating and cooling is calculated by assuming a simplified heat pump with an annual coefficient of performance (COP) scenario. The heating and cooling season is calculated through degree days, which are retrieved from the relevant weather file [43] The operational energy use emissions (kgCO$_{2eq}$) are calculated by multiplying operational energy use (kWh/m^2/yr) with electricity-to-emission conversion factors. These are sourced from [46]. The calculation of the building energy use, used in the current version of the tool, does not include the gain utilization factor for heating and cooling. Moreover, the following aspects relevant for the calculation of the building lifecycle energy use are not implemented in the tool in its current version:

- The electricity production from photovoltaic panels and their embodied energy and emissions.
- The embodied energy and emissions of appliances.
- The embodied energy and emissions of luminaires.
- The embodied energy and emissions of the heating and cooling systems (heat pump).

The control variables for the parametric analysis are limited to the insulation type and thickness in the walls, the window type in the walls, and the glazing area for each of the different wall orientations. A future version of the tool will have the above-described limitations removed.

2.2. Life cycle assessment methodology

Detailed material inventory information regarding building parts, components and materials is structured in the parametric analysis tool according to NS 3451 nomenclature [23]. The following building parts have thus been included: groundwork and foundations, outer walls, inner walls, floor structure, outer roof, stairs and balconies, and technical equipment. The building parts are then divided into building components (e.g. load-bearing outer wall or ground floor), and further divided into building materials (e.g. gypsum board or insulation) which can then be selected by the user from a drop-down menu.

The LCA system boundary is currently limited to cradle-to-gate, which includes the initial production stages (modules A1-A3) according to EN 15978 [22]. Two impact categories are so far included; namely global warming potential (GWP) and cumulative energy demand (CED). The embodied material emissions are measured in terms of GWP (kgCO$_{2eq}$/m^2/yr), and are calculated according to the IPCC GWP 100-year method [47]. The embodied energy of materials is measured in terms of CED or primary energy consumption (MJ/m^2/yr), and quantifies all renewable and non-renewable primary energy resources used [48]. A functional unit of 'per m^2 of heated floor area per year of building lifetime' is used for both the embodied energy and embodied CO$_{2eq}$ emission calculations.

Embodied energy and emission background data was collected from environmental product declarations. These EPDs were collected from the following program operators: EPD-Norge in Norway, IBU in Germany and the International EPD System in Sweden, all of which are compliant with EN 15804 [14] and are considered representative of construction products in Europe. When product specific data was lacking, generic data from the LCI database Ecoinvent v.3.1 [24] has been sourced. Generic data was required for a number of technical installations, such as ventilation, heating and electrical equipment. Unfortunately, the current version of the tool does not include an embodied energy factor for the underfloor heating, solar thermal collectors or hot water tank. All of this background data has been gathered into one material library, and is utilised for embodied energy and embodied CO$_{2eq}$ emission calculations. Some of the datasets have been modified to provide a range of product thicknesses common in the construction market, for example with insulation or timber. For ease of use, only the materials applicable to that application area in the building are available in the drop-down menu for that part of the building. For example, only gypsum boards suitable for internal use are made available in the inner wall section of the tool. Limiting material options in this way may reduce the level of user error. Similarly, the tool is designed so that the user does not have to subtract window areas from total wall areas. Finally, the following input data is required from the user to evaluate embodied energy and embodied CO_{2eq} emissions of a building:

- Heated floor area (m^2), heated building volume (m^3), floor to ceiling height (m) and building lifetime (years).
- For outer wall, inner wall, roof, stair and balcony, and floor components: total area (m^2), type and thickness of material, and weight (kg) of structural materials. In addition, the size (m^2) and type of window and door openings in the outer wall, inner wall and roof are required.
- For groundwork and foundations: total volume (m^3) of construction, and type of materials used.
- For technical equipment: type and quantity of equipment used.

2.3. Parameters

In this study, a series of parametric analyses are performed in order to identify optimised solutions that minimise operational energy use, embodied energy and embodied CO_{2eq} emissions. These parameters are not in themselves a methodology, but are necessary to test the other two methodologies within a parametric analysis. The parameters to be investigated are window types (with different U-values, g-values, and embodied energy), fenestration areas (with different areas for South and North facades), and insulation thickness ranging from 50 to 350mm. An overview of these options are provided in Table 1. In all, seven options are provided for insulation thickness, four options for window type, seven options for north window area and seven options for south window area. The combination of all these options generates 1372 iterations within the parametric assessment tool. The operational energy use, embodied CO_{2eq} emissions and embodied energy are calculated by combining all variations of the above mentioned parameters. A shortcoming of this parametric analysis is that the building energy use for cooling is not included in calculations. This is because this was not calculated in the original operational energy use calculations for the ZEB SFH concept study. The base case is representative of the ZEB SFH concept study, and consists of 350mm insulation (option 7), triple glazing (3-ply) window with 0.71W/m^2k and g-value 0.55 (option 1), 12m^2 north window area (option 2) and 18m^2 south window area (option 3). The ZEB SFH was originally designed by researchers to have low operational energy use and embodied material emissions. In contrast, the parametric analysis tool finds the optimal combination of parameters in relation to either operational energy use, embodied CO_{2eq} emissions or embodied energy.

Table 1. Parametric variations

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
Insulation	50mm	100mm	150mm	200mm	250mm	300mm	350mm*
Window type	3-ply* 0.71 W/m2k g-value 0.55	2-ply 2.6 W/m2k g-value 0.78	3-ply 0.50 W/m2k g-value 0.50	2-ply 1.30 W/m2k g-value 0.62	-	-	-
North window area	10 m2	12 m2*	15 m2	20 m2	25 m2	30 m2	35 m2
South window area	10 m2	15 m2	18 m2*	20 m2	25 m2	30 m2	35 m2

*Base case scenario

3. Case study

The case study presented in this paper is based on a zero emission concept building described in Houlihan Wiberg et al. [20]. Originally, the calculation of the operational energy use was carried out in SIMIEN, and the calculation of the embodied emission was carried out in a tool specifically developed by the ZEB Research Centre. At first, these assessment tools were selected so that the concept building could be harmonised with other Norwegian pilot studies from the ZEB Research Centre. Consequently, the building material quantities of the ZEB SFH were imported from a building information model (BIM) via MS Excel. Embodied energy calculations have previously not been performed. All previous data inputs are to be transferred into the parametric analysis tool for a holistic review of the operational energy use, embodied energy and embodied CO_{2eq} emission calculations.

The concept building is a timber framed two-story single-family house. The building was originally assumed to be located in Oslo. The concept building consists of a well-insulated building envelope, combined with solar façade-mounted thermal collectors and an air-to-water heat pump. A roof-mounted and grid-connected photovoltaic (PV) system is implemented to generate enough electricity to offset the operational energy emissions. The heat pump is combined with solar thermal collectors (STC) through a hot water tank to provide both domestic hot water (DHW) and space heating. This means that the only form of delivered energy to the building is electricity. The building has a balanced mechanical ventilation system, equipped with a heat recovery unit (85% efficiency). A functional unit of 'per m^2 of heated floor area per year of building lifetime' is used for embodied energy and embodied CO_{2eq} emission calculations, whereby the concept building has a heated floor area of $160m^2$ and a building lifetime of 60 years. A specification of the materials used in the ZEB SFH as well as the data sources used are shown in Table 2.

Table 2. Material inventory

Building Parts	Unit	Building materials
Groundwork and Foundations	m3	The material quantities for the foundations are integrated into the slab-on-ground material quantities, located under 'Floor Structure.'
Outer Wall	kg	Structural timber
	m2	13mm plasterboard, vapour barrier, 350mm rockwool insulation, wind barrier, 22mm timber cladding, window
Inner Wall	m2	13mm plasterboard, 100mm glass wool insulation, door
Floor Structure	m2	Slab-on-ground: 300mm EPS insulation, radon membrane, 100mm floor screed, damp proof membrane, 21mm timber flooring
	kg	First floor: Structural timber
	m2	13mm plasterboard, 300mm glass wool insulation, 23 x 48mm battens at 600c/c, vapour barrier, MDF, 21mm timber flooring
Roof	kg	Structural timber
	m2	13mm plasterboard, OSB, 400mm EPS insulation, vapour barrier, bitumen roof waterproofing system
Stairs and Balcony	m2	Not assessed, as the material take-off was not included in the original BIM.
Technical Equipment	pc	Ventilation system, heat pump, hot water tank
	m2	PV, STC

4. Results

Table 3 shows the optimal solutions for building operational energy use, embodied CO_{2eq} emissions and embodied energy in terms of minimum values. The optimal solutions vary depending on the parameter of evaluation (i.e. operational energy use, embodied CO_{2eq} emissions or embodied energy). For example, we see that the optimal solution for operational energy use consists of a triple glazed window with a u-value of 0.5 W/m^2k, 350mm of insulation, and $35m^2$ of glazing on both the north and south facades. The optimal solution for embodied CO_{2eq} emissions consists of a triple glazed window with a u-value 0.5 W/m^2k, 350mm of insulation, $12m^2$ of glazing on the north facade and $20m^2$ glazing on the south facade. In contrast, the optimal solution for embodied energy consists of a double glazed window with a u-value 2.6 W/m^2k, 50mm of insulation and $10m^2$ of glazing on both the north and south facades. For the embodied energy optimised result, we experience 64.4$MJ/m^2/yr$, 8.2 $kgCO_{2eq}/m^2/yr$ and 50.2 $kWh/m^2/yr$, whilst in the operational energy use optimised result, we experience 72.8 $MJ/m^2/yr$, 7.1 $kgCO_{2eq}/m^2/yr$ and 38.9 $kWh/m^2/yr$.

Figures 1 and 2 show the results for all of the iterations simulated in Test 2, for embodied CO_{2eq} emissions and operational energy use respectively. Both of these figures show all 1372 iterations of the 25 parameters. Figure 1 includes notations for understanding and reading the bar charts, whereby each data result corresponds to a specific south window area, each group of seven data results (enlarged) corresponds to a specific north window area, each group of 49 data results corresponds to a specific insulation thickness and each quarter of the results correspond to a window type. Figure 2 shows the operational energy use results for each of the 1372 iterations, but also shows the proportion of energy use in terms of heating, ventilation, lighting and appliances. As previously mentioned, cooling is not included in the analysis of this particular case study.

Table 3. Results from the parametric analysis tool

	Operational energy use (kWh/m2/yr)	Heating demand (kWh/m2/yr)	Embodied CO2eq emissions (kgCO2eq/m2/yr)	Embodied energy (MJ/m2/yr)	Optimal Solution
Test 1	40.6	15.5	7.7	74.5	Base case: 3-ply, 0.71 W/m2k, g-value 0.55, 350mm, 12m2 north, 18m2 south
Test 2 (parameters)	38.9	13.8	7.1	72.8	Lowest operational energy use: 3-ply, 0.50 W/m2k, g-value 0.50, 350mm, 35m2 north, 35m2 south
	39.6	14.5	7.0	68.4	Lowest embodied CO2eq emissions: 3-ply, 0.50 W/m2k, g-value 0.50, 350mm, 12m2 north, 20m2 south
	50.2	25.1	8.2	64.4	Lowest embodied energy: 2-ply, 2.6 W/m2k, g-value 0.78, 50mm, 10m2 north, 10m2 south

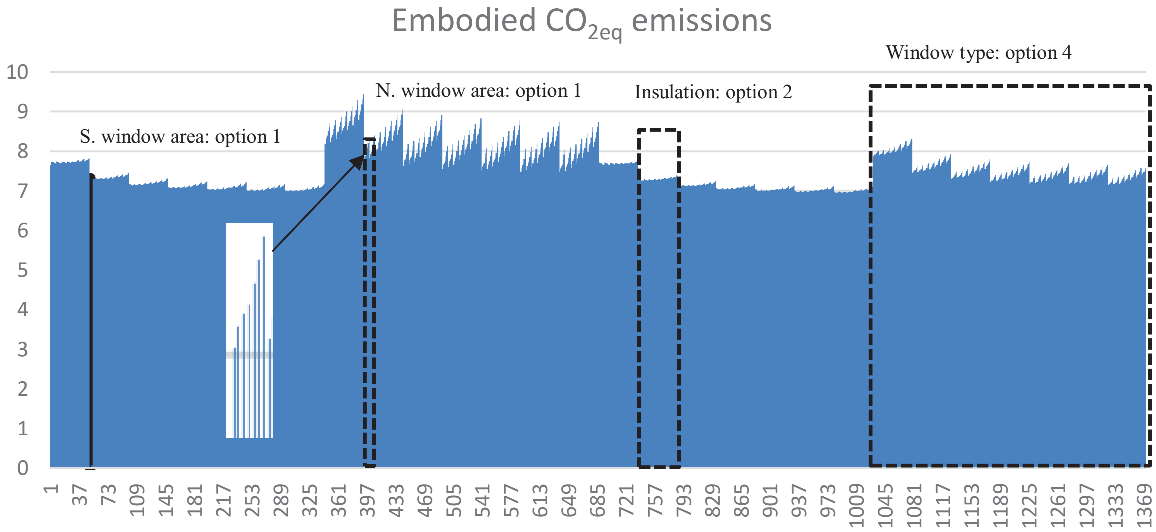

Fig. 1. Bar chart of embodied CO2eq emission results for all iterations in the parametric analysis tool.

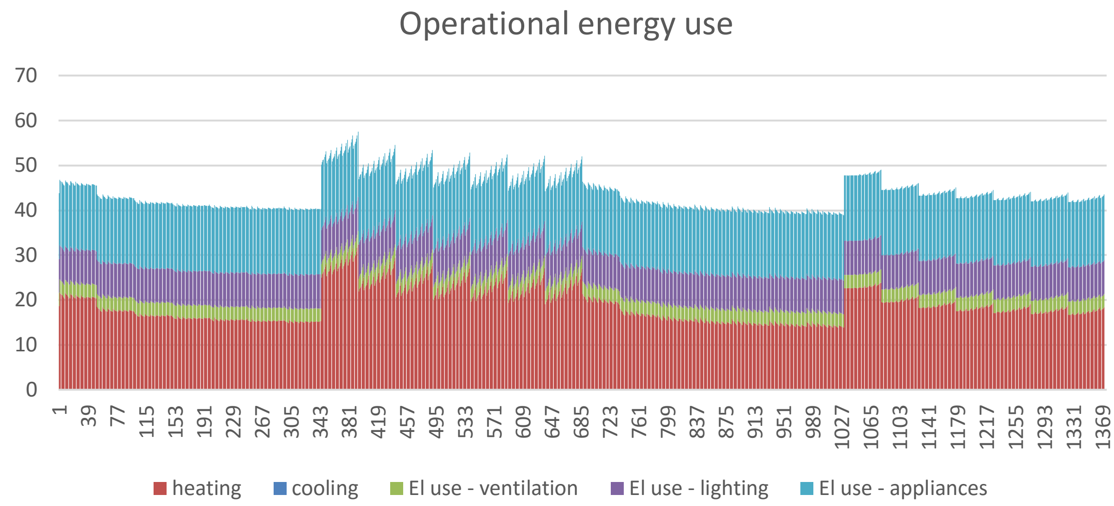

Fig. 2. Bar chart of operational energy use for all iterations in the parametric analysis tool.

5. Discussion

This research set out with the ambitious goal of combining three types of assessment tools into one parametric analysis tool for buildings. The literature review demonstrated that there are many tools available for energy modelling, environmental LCA for buildings, or for the assessment of individual building products through EPDs. However, very few of these tools combine all of these aspects into one holistic parametric analysis tool for buildings.

The results from Table 3 show the optimised solutions for operational energy use, embodied CO_{2eq} emissions and embodied energy. The optimised solution for embodied CO_{2eq} emissions is the closest to the base case, supplying only 6m^2 extra glazing to the south facade. The optimised solution for operational energy use has almost the same parameters as the base case, apart from the glazing area parameters, which experience a maximum of 35m^2 of glazing to both north and south facades. A total window area of 70m^2 may lead to excessive overheating and thus require mechanical cooling. The operational energy use calculations did not include the cooling demand as it was not considered in the original calculations for the ZEB SFH concept study. The optimised solution for embodied energy varied the most from the base case. Although low embodied energy was achieved, this parametric variation resulted in high operational energy use, from the implementation of double-glazed windows instead of triple-glazed windows, and 50mm insulation instead of 350mm. This shows that the parametric analysis tool can lead to different conclusions, depending on the environmental measure being applied and that this may have an impact on the way buildings are designed. Figures 1 and 2, show that insulation thickness has more of a significant role (larger height variation in the graphs) when a lesser performing window type is selected. Similarly, when a better performing window is selected, the insulation thickness is of lesser significance (smaller height variation in the graphs). The two figures also show that the results for operational energy use and embodied CO_{2eq} emissions are similar, and to some degree correlate.

The results from this study, comprise the first generation of testing for this specific parametric analysis tool, and highlights some areas for further work. Firstly, the scope of operational energy use calculations covers wall components only, and does not assess the sensitivity of technical equipment or other building components. Secondly, the scope of the LCA is preliminarily limited to the product phase (modules A1 – A3). This may be extended to include the whole lifecycle of the building, and be used to develop different future scenarios. Thirdly, the emission data available for window types and specific technical systems is limited. Future work may involve collecting product specific data, in the form of EPDs, for the building materials and components that were lacking. This may be achieved by expanding the scope of the LCI database to include more program operators.

The parametric analysis tool demonstrates the potential of parametric analysis, in finding optimal building envelope solutions in terms of operational energy, embodied CO_{2eq} emissions and embodied energy. In the future, the parametric analysis tool may be used for setting energy performance goals and benchmarks, optimising renewable energy and passive systems, integrating architectural features, minimising changes during construction and integrating building systems. The tool, however, is at this stage, not meant to give precise results, given its limitations in the calculation method, but may be used for performing a comparative pre-assessment of various design solutions. Further work on the parametric tool may include opening up for different types of parametric assessments, such as for climate, electricity emission factor or building type. Furthermore, the tool is tested using a single case study. In future work, the tool may be tested and compared with other case studies.

6. Conclusion

This body of work has demonstrated that numerous individual assessment tools (e.g. energy modelling, LCA of buildings, EPDs) with different functions, can be combined through a parametric assessment tool in order to evaluate the environmental performance of a building. This was demonstrated through the application of one SFH concept study, with a number of parameters that measured window type, insulation thickness and area of glazing on the north and south facades. More specifically, the results show that the parametric analysis tool developed in this study can be used to select the options with the lowest operational energy use, embodied CO_{2eq} emissions and embodied energy arising from wall and window components in the ZEB SFH concept building compared to the original design. This shows that the parametric analysis tool can lead to different design conclusions, depending on the environmental measure being applied, and that this may have an impact on the way buildings are designed.

In conclusion, this study facilitates the first steps of development and testing for a parametric analysis tool that optimizes operational energy use, embodied CO_{2eq} emissions, and embodied energy use, through the testing of the tool with a conceptual building model. The tool, which is not meant to give precise results, given its limitations in the calculation method, can be used for performing a comparative pre-assessment of various design solutions.

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