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A tool for the parametric assessment of operational energy use and embodied GHG emissions in a single-family house concept study

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Abstract. Present day European legislation focuses upon the reduction of greenhouse gas (GHG) emissions in buildings through better design and technological solutions, with a view to reduce operational energy use and embodied GHG emissions. Currently, environmental performance assessment tools for buildings lack in assessing these parameters over the entire lifecycle of a building. Life cycle assessment (LCA) is a well-established methodology that gives a clear insight into the potential environmental impacts during the service life of a building. However, architect, engineer and constructor (AEC) professionals consider LCA as complex and time consuming. This paper builds upon a methodology for the development of a parametric analysis tool (PAT), which comprehensively assesses operational energy use and embodied GHG emissions during the lifecycle of a building. In this phase of the PAT's development, the complexity of the tool has been increased by expanding the number of parameters from four (i.e. insulation thickness, window types, North façade glazing area and South façade glazing area) to seven (i.e. climatic zones, solar shading and electricity emission factors). This has increased the amount of parametric permutations from 1,372 to 12,348. The PAT has been applied to a conceptual two-storey single-family house, developed by the Norwegian ZEB Research Centre, which is assumed to be in either Oslo (Norway) or Lecce (Italy). The results show that the choice of insulation thickness influences total energy use less than the selection of shading types or glazing areas. The results also show the parametric selection with the least amount of operational energy use (34kWh/m^2/yr) in the Lecce climate consists of triple-glazed windows (0.5W/m^{2}k), 10m^2 of glazing on the north façade, 20m^2 of glazing on the south facade. The results show the parametric selection with the lowest total GHG emissions in the Oslo climate (7.8kgCO_{2eq}/m^2/yr) consists of triple glazing (0.5W/m^{2}k), 10m^2 of glazing on the north facade and 20m^2 glazing on the south facade. This is because a lower electricity emission factor (132gCO_{2eq}/kWh for Norway and 290gCO_{2eq}/kWh for Italy) was used for converting operational energy use to GHG emissions, even though the Oslo climate has a higher heating demand compared to Lecce. In conclusion, this paper shows how complex design options can be evaluated in a holistic way through PAT to ascertain the best selection of design criteria for low GHG emissions and low operational energy use.

1. Introduction

Present day European legislation focuses upon the reduction of greenhouse gas (GHG) emissions in buildings through better design and technological solutions [1]. Existing approaches for the reduction of operational energy and emissions in buildings include passive house, zero emission, energy-plus buildings and zero emission neighbourhoods [2-13]. These approaches are generally achieved by implementing energy efficiency measures such as, using effective insulation and better performing windows, reducing infiltration losses, recovering heat loss from ventilation systems and using renewable energy resources [14, 15]. Regardless, as buildings achieve lower operational energy demand, the relative proportion of embodied material emissions increases [16-19].

Life cycle assessment (LCA) is a well-established methodology used for the systematic assessment of environmental burdens during the lifecycle of a building and can be used to assess the environmental performance of buildings [20-24]. LCA appraises all resource inputs, in order to calculate the environmental impacts of a building at either the material, product or whole building level [25].

Currently, there are numerous environmental building assessment tools (e.g. BREEAM, LEED), energy modelling tools (e.g. SIMIEN, IDA-ICE, EnergyPlus [26]) and parametric analysis tools (PATs) (e.g. Grasshopper, Daysim) available for a range of building parameters such as optimal structure, daylighting or comfort. Previous studies have shown environmental building assessment tools [27-30] cover a wide range of building typologies and emphasise various phases of a building's lifecycle. Previous studies that assess both embodied GHG emissions and operational energy use in Norwegian buildings include a study on lessons learnt from embodied GHG emission calculations in ZEBs [31], a study on strategies for reducing embodied impacts from buildings [32], a study on analysing methodological choices in embodied energy and GHG emission calculations from buildings [33], and a study that investigates if a net life cycle balance for energy and materials is achievable in a single family ZEB in Norway [34]. However, none of this research includes PATs. One literature review of parametric LCA models and algorithms used in the building and construction industry highlighted that few previous studies have focused on parametric design [35]. Previous international PAT studies have appraised complex structural systems in tall buildings, [36] optimised daylighting for occupants in a Grasshopper based PAT, [37] and assessed energy efficiency measures [38]. Another study documented an MS Excel-based PAT, which assessed the performance of building envelopes in residential buildings across climatic regions in India. However, this tool did not assess embodied emissions of building envelopes against operational energy [39]. To the author's knowledge there is only one previous study that has used parametric design to minimise the embodied GHG emissions in a ZEB [40], and only one other study that assesses ventilated timber wall constructions using parametric LCA [41]. One advantage of PATs is that they facilitate for the dynamic comparison of various scenarios simultaneously, in order to ascertain the best design alternative within a modest timeframe and at a relatively low cost. A disadvantage of market-available PATs is that they are difficult for inexperienced users to operate [36].

The objective of this paper is to continue the previous body of work explored by the authors in [42]. This work parametrically assessed insulation thickness, and window area for wall and window components in buildings and facilitated for the first steps of development and testing of a PAT that optimises operational energy use, embodied GHG emissions and embodied energy use. This paper takes the parametric tool a step further by expanding the scope of the PAT to include climate, electricity emission factors and solar shading. The tool uses the Norwegian ZEB Research Centre's single-family house (SFH) concept building as a case study, and assesses wall and window components in a building, to reduce operational energy use and embodied GHG emissions [43, 44].

This paper starts by outlining the methodology, parameters and case study used. This is followed by a discussion of the results, concerning the impacts parameters have on operational energy use and embodied GHG emissions. Finally, the conclusion surmises the work and results so far, and outlines scope for further research. It should be acknowledged that the development of this PAT is part of an ongoing process, and the results from this paper contribute to its further development.

2. Methodology

An MS Excel-based PAT was previously developed and tested for the ZEB SFH concept building [42]. In the previous version of the PAT, seven insulation thicknesses (50-350mm), four window types (3-ply 0.71 W/m^2K g-value 0.55, 2-ply 2.6W/m^2K g-value 0.78, 3-ply 0.50 W/m^2K g-value 0.5, 2-ply 1.30 W/m^2K g-value 0.62), seven North façade glazing areas [10-35m^2] and seven south façade glazing areas

(10-35m^2) were tested. This generated 1,372 parametric permutations. Further details about the original methodology and parameters can be found in [42].

This study builds upon that research and methodology in MS Excel, and facilitates for the testing of additional parameters, namely two different climates (Oslo, Norway and Lecce, Italy), two electricity emission factors (132gCO_{2eq}/kWh and 290gCO_{2eq}/kWh) and three solar shading options (none, curtains and venetian blinds). In this version of the PAT, some of the original parameters have been adjusted according to lessons learnt. Firstly, there are now six insulation thickness parameters ranging from 100 to 350mm. Secondly, the North and South glazing area parameters have been reduced to 10, 15 and 20m^2. Lastly, the four window types have been adjusted to three window types (2 ply 2.8W/m^{2}K g-value 0.78, 2-ply 1.0W/m^{2}K g-value 0.63, 3-ply 0.50 W/m^{2}K g-value 0.50). These changes have been made to portray more realistic building scenarios and reflect available market products. In this study, the updated array of parameters increases the PAT's complexity and generates up to 12,348 permutations. An overview of the parameters considered in this study are shown in Table 1. In this study, the parametric assessment has been carried out in two stages. The first stage generates operational energy use results for all parametric variations listed in Table 1, whilst the second stage takes a selection of parametric variations and calculates embodied GHG emissions from operational energy use and material use (Table 2). Next is a description of the operational energy use calculations, embodied GHG emission calculations and case study.

Table 1. First selection of parametric variations used in the operational energy use analysis.

Parameter	Option A	Option B	Option C	Option D	Option E	Option F
Insulation	100mm	150mm	200mm	250mm	300mm	350mm
Window type	2-ply 2.8 W/m^{2}k g-value 0.78	2-ply 1.0 W/m^{2}k g-value 0.63	3-ply 0.50 W/m^{2}k g-value 0.50	-	-	-
North window area	10m^2	15m^2	20m^2	-	-	-
South window area	10m^2	15m^2	20m^2	-	-	-
Solar shading type	No shading	Curtain 0.5 global radiation	Venetian blind 0.08 global radiation	-	-	-
Climate	Oslo	Lecce	-	-	-	-
Electricity mix	Norwegian	European	-	-	-	-

Table 2. Second selection of parametric variations used in the emissions analysis.

	Window type	Insulation thickness (mm)	Shading strategy	Electricity to emission factors (gCO_{2eq}/kWh)	Climate
Option 1a	Double glazed [a]	100	No shading	132	Oslo
Option 1b	Double glazed [a]	100	No shading	290	Oslo
Option 1c	Double glazed [a]	100	No shading	290	Lecce
Option 2a	Double glazed [a]	350	Venetian blinds	132	Oslo
Option 2b	Double glazed [a]	350	Venetian blinds	290	Oslo
Option 2c	Double glazed [a]	350	Venetian blinds	290	Lecce
Option 3a	Triple glazed [b]	100	No shading	132	Oslo

Option 3b	Triple glazed [b]	100	No shading	290	Oslo
Option 3c	Triple glazed [b]	100	No shading	290	Lecce
Option 4a	Triple glazed [b]	350	Venetian blinds	132	Oslo
Option 4b	Triple glazed [b]	350	Venetian blinds	290	Oslo
Option 4c	Triple glazed [b]	350	Venetian blinds	290	Lecce

[a] U-value 2.8 W/m^{2}k, g-value 0.78, 10m^2 glazed area in N façade, 20m^2 glazed area in S façade.
[b] U-value 0.50 W/m^{2}k, g-value 0.50, 10m^2 glazed area in N façade, 20m^2 glazed area in S façade.

2.1. Operational energy use
Operational energy use has been calculated for the whole building, on a monthly basis, and includes heating and cooling lighting appliances, ventilation internal heat gains from people and solar heat gain. More details on the calculation of operational energy use can be found in [42].

2.2. Embodied GHG emissions
Embodied GHG emissions have been calculated for the whole building according to EN 15978 and NS 3720 [22, 23] and includes emissions from the production phase and operational energy use. Calculations are structured according to NS 3451 [45] and includes groundwork and foundations, outer and inner walls, floors, roof, stairs and technical equipment. A functional unit of 'per m^2 of heated floor area per year of building lifetime' has been used whereby the heated floor area is 160m^2 and the building lifetime is 60 years. Emissions are calculated according to [46] and are measured in terms of GWP (kgCO$_{2eq}$/m^2/yr) and use material emission factors from [24, 47, 48]. Operational energy use emissions are calculated by multiplying operational energy use (kWh/m^2/yr) with either a Norwegian electricity-to-emission factor of 132gCO$_{2eq}$/kWh or an average European factor of 290gCO$_{2eq}$/kWh [49, 50], depending on the geographical location of the case study. More information on the calculation of embodied GHG emissions can be found in [42].

2.3. Case study
The ZEB SFH concept building has been used as a case study. The building is a two-storey, zero emission single-family house. It is characterised by a well-insulated building envelope, solar thermal collectors, grid-connected photovoltaics, air-to-water heat pump, balanced mechanical ventilation system with heat recovery. All data inputs have been transferred into the PAT for assessment. More information on the case study can be found in [42, 43, 44].

3. Results and Discussion
Figures 1 and 2 show the results for operational energy use in Oslo and Lecce respectively. Both figures simulate 486 iterations each for the parameters listed in Table 1. In Figures 1 and 2, area 1 refers to the parametric results for the three shading options and the three glazing areas to the North and South facades; area 2 refers to the same combination of parameters as in Area 1 and includes the parametric results for the six insulation thicknesses; whilst area 3 includes the three window types, which are identified by areas 3a, 3b and 3c respectively.

By comparing Figures 1 and 2, we observe that the choice of insulation thickness influences total energy use less than the selection of shading type or glazing area. For insulation thickness, the difference in total energy use is approximately 3kWh/m^2/yr. Variations in glazing area leads to a difference in total energy use of approximately 15kWh/m^2/yr. By using a highly insulated window (Option C in Table 1, which corresponds to Area 3c), it is observed that operational energy use decreases. Figure 1 shows in Area 1a (100mm insulation) and Area 1f (350mm insulation) that moving the building into a warmer climate results in a smaller impact from insulation thickness on operational energy use. The glazing areas and type of solar shading is predominant in determining the level of operational energy use.

Table 3 shows the operational energy use, embodied material emission and total emission results for the parametric variations shown in Table 2. For example, Option 4c has the lowest operational energy use of 34kWh/m²/yr) in the Lecce climate and consists of triple-glazed windows (0.5W/m²k), 10m² of glazing on the north façade, 20m² of glazing on the south façade; whereby there is no heating demand and little cooling demand because of effective solar shading, and a well-insulated building envelope. In contrast, Option 4a has the lowest total emissions of 7.8kgCO_{2eq}/m²/yr in the Oslo climate and consists of triple glazing (0.5W/m2k), 10m² of glazing on the north facade and 20 m² glazing on the south façade. This is because a lower electricity emission factor (132gCO_{2eq}/kWh) has been used for converting operational energy use to emissions, even though the Oslo climate has a higher heating demand than Lecce. This shows that total emissions are largely sensitive to the electricity emission factor used.

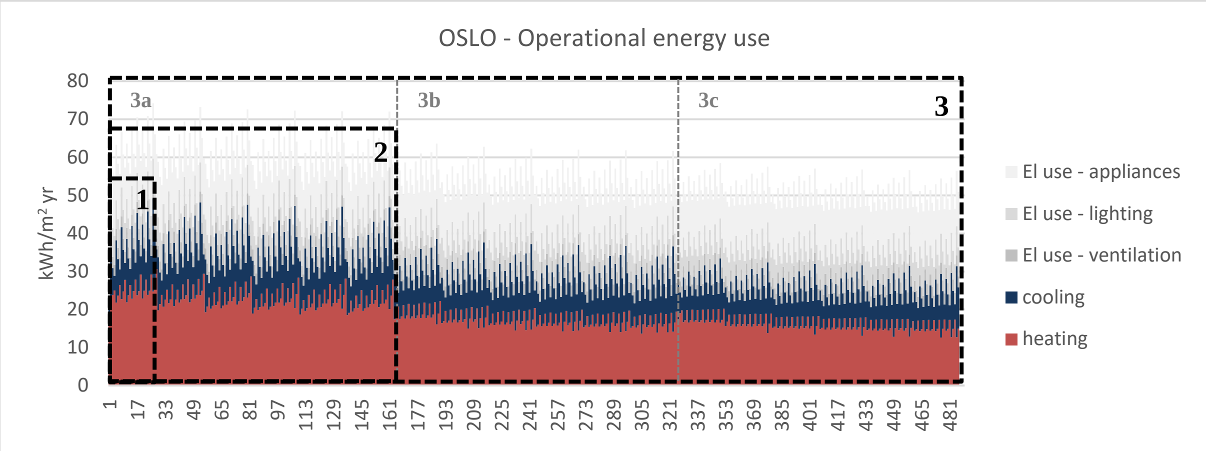

Figure 1. Operational energy use for all parametric iterations, calculated for the Oslo climate.

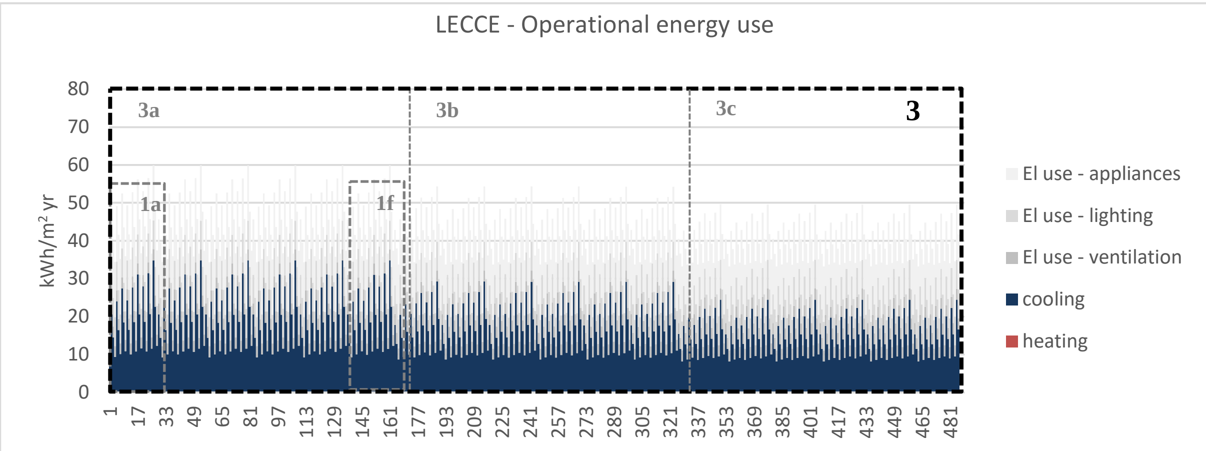

Figure 2. Operational energy use for all parametric iterations, calculated for the Lecce climate.

Table 3. Operational energy use and the embodied material emission results from the parametric analysis.

	Heating demand (kWh/m²/yr)	Cooling demand (kWh/m²/yr)	Total operational energy use (kWh/m²/yr)	Operational energy use emissions (kgCO_{2eq}/m²/yr)	Embodied material emissions (kgCO_{2eq}/m²/yr)	Total emissions (kgCO_{2eq}/m²/yr)
Option 1a	25	19	69	9.1	1.6	10.6
Option 1b	25	19	69	19.9	1.6	21.5
Option 1c	0	27	53	15.2	1.6	16.8
Option 2a	25	4	55	7.2	1.7	8.9

Option 2b	25	4	55	15.8	1.7	17.5
Option 2c	0	11	36	10.4	1.7	12.1
Option 3a	18	13	57	7.5	1.6	9.1
Option 3b	18	13	57	16.5	1.6	18.1
Option 3c	0	20	45	13.0	1.6	14.6
Option 4a	17	4	46	6.1	1.7	7.8
Option 4b	17	4	46	13.4	1.7	15.1
Option 4c	0	9	34	9.9	1.7	11.6

This study has generated 12,348 parametric permutations, a 10-fold increase on the previous study. It demonstrates that PAT is a powerful tool which can handle an increasing level of complexity. This study has emphasised the enormity of analysing and evaluating all possible permutations and has therefore selected 12 variants (Table 3) for discussion. Future work may investigate the introduction of algorithms to provide either analytical or decision support, for example through multicriteria decision-making. Further development may also include expanding the tool to the neighbourhood level, whereby the leap from building to neighbourhood increases the number of parameters and variables exponentially. In the future, this PAT could be used for setting energy and emission performance goals and benchmarks, optimising renewable energy and passive systems, evaluating building envelope schemes, integrating architectural features and integrating building systems.

4. Conclusion

This study has demonstrated that parametric analysis can be a useful tool for AEC professionals when assessing operational energy use and embodied GHG emissions in buildings. The results show that the choice of insulation thickness influences total energy use less than the selection of shading types or glazing areas. The results show the parametric combination with the least amount of operational energy use (34kWh/m^2/yr) and lowest total emissions (7.8kgCO_{2eq}/m^2/yr) do not have the same parameters. This is because a lower electricity emission factor (132gCO_{2eq}/kWh) was used for converting operational energy use to emissions, even though the Oslo climate has a higher heating demand compared to Lecce. The results show that the parametric results are sensitive to climate and electricity emission factor. In conclusion, this paper shows how complex design options can be evaluated in a holistic way through PAT to ascertain the best selection of design criteria for low operational energy use and GHG emissions.

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