INTEGRATING ARCHITECTURAL AND ENERGY VIEWPOINT FOR A MULTI OBJECTIVE OPTIMIZATION DURING EARLY DESIGN STAGE

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ABSTRACT

In recent years, applying optimization techniques towards the design of energy efficient buildings has become very useful. These techniques are particularly effective if they are used during architectural design stage, because early decisions have more profound effect on the final energy performance of buildings compared with later decisions. In this research, an optimization is performed on a hypothetical detached house to determine minimum energy performance with optimum cost level. The purpose is to demonstrate the use of simulation based optimization for an early design stage case study. An emphasis is placed on choosing design variables with a perspective of both architectural and engineering viewpoint. Particularly architectural design variable like geometry are inflexible to change later in the design process. The results suggest lowering the U-value for the external wall and window from their values mentioned in Finnish Building code D3. A 2-floor design is energy and cost optimal compared to 1-floor design. Space heating demand is the dominant energy component affected by the choice of design variables. Although the results are rather obvious, the power of simulation based optimization during the early design stage is shown. This investigation solves the problem of relevant data scarcity during early design phase and guides the decision making in an optimal manner.

1. INTRODUCTION

1.1 Importance of energy efficiency and optimization at early design stage

The building energy consumption accounts 40% of the primary energy demand in the EU Union [EU Commission, 2011]. In order to improve the energy efficiency in buildings, the EU member states agreed that by 2020 all new buildings would be nearly zero energy building (nZEB) [EPBD, 2010]. To achieve this goal, the early design phase plays a crucial role as it is characterized by a dominating influence on the design and the cost. As a consequence, guiding the early design for energy efficiency is of utmost importance, where decisions have highest impact on energy performance and costs [Hygh et al., 2012] [Attia et al., 2012]. A study by [UNEP, 2003] shows that early design stage of building offers the highest possibilities to influence the life cycle performance and costs. As the design process advances, changing design options is difficult and time consuming [Balcomb et al., 2000]. Most of the design decisions (around 20%) are executed during early design stage, which are responsible for 80% of the building operational costs [Bogenstätter, 2000].

Usually, many of early design decisions are contrasting in nature. For instance, solar shading versus natural illumination (i.e, daylighting). Particularly for countries situated at high latitude, an adverse decision during early design phase reduces the design space to achieve high energy performance goals. The designers may decide on a early design concept with less insulation thickness for building envelope to achive low cost and more space, but the potential problem is the rise in heating demand. On the other hand, a thicker insulation for building envelope increases the cost with lower heating demand. Hence, these decisions are based on different conflicting criteria such as energy demand, life cycle cost etc. If the initial considerations are not optimal, then it will have a detrimental effect on final energy perfomance and life cycle cost of buildings. This kind of early design decisions can be aided by performing a multi objective optimization.

1.2. Relevant optimization studies

Building energy optimization is a process of identifying optimal design from a vast number of design alternatives confirming the energy performance requirements. Many of building studies, e.g [Hasan et al., 2008] [Hamdy et al., 2013] [Kurnitski et al. 2011] [Hamdy et al, 2011] investigated on cost optimality, minimum energy performance and minimum CO_2 emission issues. For instance, [Hasan et al., 2008] utilized simulation based optimization approach to minimize the life-cycle cost of a detached house in Finland. The study by [Hamdy et al., 2013] minimized primary energy and life cycle cost of a detached house using multi-stage simulation based optimization. Again [Hamdy et al., 2011] aims to design low emission and cost effective dwellings. The optimization study by [Stavrakakis et al., 2012], aims for optimized window design for thermal comfort in naturally ventilated buildings. Exclusively for building service systems, there are optimization studies to maximize the performance of ventilation system [Zhou and Haghighat, 2009], onsite renewable energy (hybrid PV thermal collector) [Vera et al. 2014], HVAC heat exchanger [Kumar et al., 2008]. The above studies evaluated limited number of design variables from architectural viewpoint. For example, geometry, orientation, window area are the parameters of architectural interest, and possess an impact on energy performance were not included. Again, these parameters are rather inflexible to change later in the design process. Usually the early designers (or architects) make energy decisions based on personal experience or perform qualitative analysis. According to [Reichard and Papamichael, 2005], the energy consumption values are rarely calculated in early stage, despite rules of thumb for energy efficiency values are often used to aid the design decision. Thereby, indicates the need of including optimization as early design practice in order to ensure optimal decision making. The architectural parameters with a measurable effect on energy efficiency are considered as decision variables of optimization. . Therefore, in this optimization study, an architect's interest is well ensured by choosing design variables from both architectural and engineering importance.

2. METHODOLOGY

In Finland, residential buildings comprise 85% of the building stock. Within residential buildings, 89% of the building stock and 55% of the building area is represented by detached houses [Statistics Finland, 2010]. Therefore, a detached house concept in Helsinki (60°N, 25°E) is selected for this study.

2.1. Simulation and optimization software

The target building was modeled in IDA ICE whole building simulation software, developed by KTH and Institute of Applied Mathematics [Sahlin, 1996]. IDA-ICE has been validated by EN 13791 [Kropf and Zweifel, 2001] [EN ISO 1379, 2004]. The study conducted on the empirical validation of models of five simulation tools, including IDA-ICE, concludes that the agreement between measured and simulated data was good [Travesi et al., 2001]. The IDA-ICE software allows the modeling of multi-zone buildings, HVAC systems, internal loads, outdoor climate etc., and provides dynamic simulation of heat and air flow with a variable time-step. It is a suitable tool for the simulation of energy consumption, thermal comfort, and daylighting in buildings.

MOBO (**M**ulti-**O**bjective **B**uilding **O**ptimization) developed by [Palonen et al., 2013] is a generic freeware with graphical user interface (GUI) optimization program. To optimize the energy performance of building, it imports the building simulation model. Nyugen et al., 2014 reviewed MOBO as one of the mostly used 18 optimization program found in building performance optimization literature. Moreover, Palonen et al, 2013 in his study reviewed several available optimization tools to highlight the useful features of MOBO.

MOBO includes the GUI to write the values of the design variables of optimization. Additionally it includes the GUI to write cost data, delimiters of energy demand (to copy the data from IDA ICE output file) and objective functions. To perform the optimization, MOBO imports the building simulation model in IDA ICE. The working scheme of this simulation based optimization is shown in Figure 1.

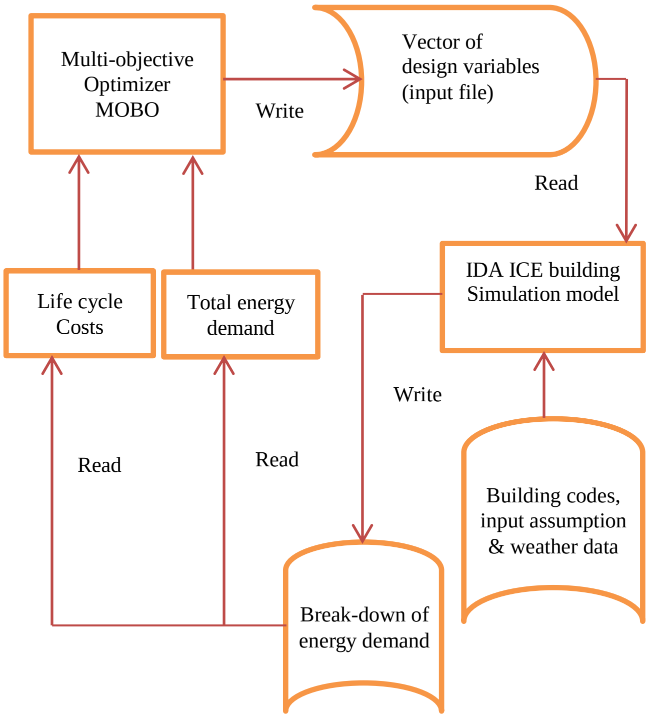

Figure 1: Working scheme of simulation based optimization

2.2. General design of building

The method aims to perform simulation based optimization of a building in early design stage when data availability is limited. In order to deal with this problem, a simplified hypothetical detached house of 160 m^2 is considered for this study. It is important to note that the floor area is kept constant, although the building geometry is changed in the optimization. The internal height of the model is considered as 2.7 m. The building is located in Helsinki (60°N, 25°E). The total window area is 10% of the floor area, equally distributed on opposite facades.

The energy performance level of the building envelope and systems has been designed according to Finnish Building code D3 2012 [Ministry of Environment, 2012]. The building is ventilated by a centralized constant air volume (CAV) mechanical supply and exhaust ventilation system with heat recovery control. The temperature efficiency of the heat recovery system is 70%. For AHU, the supply air set-point temperature is 18°C. The hourly profile of lighting, electrical appliances, occupants, etc., is based on statistical information gathered trough questionnaires and hourly measured consumption of 1630 Finnish houses over a year [Safdarin et al, 2014]. The demand profile for domestic hot water is based on measurements from 15 district-heated houses in Helsinki [Koivuniemi, 2005]. The building envelope has an airtightness (n_{50}) of 2 1/h, where n_{50} is the number of air changes per hour equivalent to an air-leakage rate, with a 50 Pa pressure difference between the indoors and outdoors [Ministry of Environment, 2012]. The simulation uses the Finnish test-reference-year weather file (TRY2012) for Helsinki [Kalamees et al., 2012]. The set-point temperature is 21°C for heating and 27°C for cooling.

2.3. Defining design variables

The design variables of this optimization are chosen from the perspective of both architectural and engineering viewpoint. In total, eight design variables are proposed to improve the energy performance of the proposed building. The details of the design variables are listed in Table 1. The architectural design variables are selected with a view of improving the energy performance. Other architectural variables related to form, function and aesthetic value of the buildings were not considered, as primary focus of this paper is on energy efficiency.

Table 1: Specification of design variables

Sl. no.		Design variable	Values	No of options
1	Architectural design variables	Building geometry	Option 1: 1-floor (20x8 m^2), Option 2: 1-floor (16x10 m^2), Option 3: 1-floor (12.65x12.65 m^2), Option 4: 2-floor (10x8 + 10x8 m^2).	4
2		Storey height	2.7, 3.0, 3.5	3
3		Orientation	Option 1: N-S, Option 2: E-W oriented windows.	2
4		Window area	10%,15%, 20% of floor area	3
5	Engineering design variables	Insulation thickness of external wall	500, 330, 170 mm. From U-value 0.07 to 0.16 W/m^{2}K.	3
6		Insulation thickness of roof	550, 425, 300 mm. From U-value 0.06 to 0.10 W/m^{2}K	3
7		Insulation thickness of floor	450, 350, 200 mm. From U-value 0.08 to 0.18 W/m^{2}K.	3
8		Window type	U-value: 1.0, 0.8, 0.6 W/m^{2}K	3

The thicknesses of insulation for external wall, roof and floor are selected to cover the U-value compliance of Finnish building code D3 [Ministry of Environment, 2012] to the U-value level that realizes passive house [RIL, 2009]. The optimizer engine MOBO uses the building model created in IDA ICE to perform simulation based optimization. In this case, Brute-Force algorithm is employed to solve the combinations of design variables. Brute-Force algorithm simulates all possible combinations of design variables.

2.4. Defining objective functions

The objective of this study is to define low energy and cost efficient design solutions for early designers. This leads to a multi-objective optimization problem with two objective functions;

$$\text{Min } \{f_1(\bar{x}), f_2(\bar{x})\}, \ \bar{x} = [x_1, x_2, \ldots, x_8] \qquad (1)$$

where $\bar{x}$ is the combination of design variables, f_1 is the energy demand (ED) of a house and f_2 is the life cycle cost (LCC). The energy demand includes space heating, ventilation, domestic hot water (DHW), cooling, lighting and appliances consumption. Life cycle cost (LCC) is widely used to access the economic viability of building projects. It is the sum of the present value of investment, operation, maintenance and replacement costs:

$$LCC = IC + OC + MC + RC \qquad (2)$$

where IC is investment cost of the building structural material and considered design variables. In this case, the structural frame material is made of reinforced concrete (RC) concept as in [Takano et al., 2015]. The investment costs are presented in Table 1 [Haahtela, 2013] [Hamdy et al., 2011] [Isover Oy]. OC is operational energy cost, RC is replacement cost of window and roof. For replaced elements, no maintenance cost (MC) is considered. It is to be noted that orientation is assumed to have no investment cost implication in this optimization problem.

The analysis period in this calculation is 30 years. All the costs taken from a source are updated based on the inflation rate from [Statistics Finland, Building cost indices]. A 3% real interest rate is used in the cost calculation [European Union, 2012]. The average energy prices and its escalation rates which are used in the calculation are shown in Table 3 [Statistics Finland, Energy prices].

Table 2: Investment cost details [Haahtela, 2013] [Hamdy et al., 2011] [Isover Oy]

Description	Price
IC of external wall	214 €/m^2 (structure) + 65 €/m^3 (insulation)
IC of roof	119 €/m^2 (structure) + 37 €/m^3 (insulation)
IC of floor	78 €/m^2 (structure) + 114 €/m^3 (insulation)
Window (U-value = 1,0.8,0.6)	252, 290, 350 €/m^2

Table 3: Energy prices and escalation rate [Statistics Finland, Energy prices]

Energy carrier	Price (c/kWh)	Escalation rate (%)
Electricity	12.08	2.74
District heat	8.20	1.78

2.5. Limitation

Firstly, the present study possess limitation in terms of the selected building typology as only detached house with an energy performance level of Finnish building code. However, it is an usual assumption in optimization studies to consider a particular house type with an energy performnace corresponding to national building codes. For instance, [Hamdy et al., 2013] assumed a detached house with energy performance level of Finnish building code in his optimization study. Outside Finland, the optimiztion study by [Ferrara et al., 2014] also considered a particular high performance single family detached house in France.

Secondly, the present study considers a particular location (i,e, Helsinki) for the house. Sometimes, optimization studies consider different locations with a view of performing sensitivity analysis. But within the scope of the present paper, this aspect has not been considered as it requires a detail exploration of the building energy codes and cost details pertaining to the new location (country). Primarily, the present results are limited to detached house in cold climate region. However, the proposed optimization approach is flexible and can aid decision making to other design cases, provided that the corresponding building simulation model and local cost data are available. Sometimes only changing the climate data might be a possibility of sensitivitry analysis. But in this study, it will lead to trivial set of results. For example, by changing the location to a warmer climate, the heating demand will decrease along with a rise in cooling demand.

3. RESULTS & DISCUSSION

3.1. Non-dominated optimal combinations of design variables

In order to achieve energy efficient and cost optimal building designs, the energy demand of the house and LCC of the design variables are minimized. Figure 2 shows the relationship between energy demand and LCC for all combinations of design variables. The pareto front or the combination of non-dominated optimal solutions as an outcome of this exhaustive search is indicated by red dots in Figure 2. In total there are 24 non-dominated solutions representing the pareto front. The values of the design variables for those non-dominated solutions are shown later in Figure 3-7.

In first step, the total combinations (1 x 3 x 2 x 3 x 3 x 3 x 3 x 3 = 1458) for a 2-floor house were explored using Brute-Force algorithm. The results of those evaluations are indicated by blue dots in Figure 3. The best solutions for the 2-floor house result in a storey height of 2.7 m. This is because, a 2.7 m storey height indicates minimum external wall area and hence the heat losses reduce. This holds true even for 1-floor house. Therefore, in 1 –floor house evaluations the storey height is considered as 2.7 m only. Finally, the total combinations (3 x 3 x 2 x 3 x 3 x 3 x 3 = 1458) for a 1-floor is evaluated using Brute-Force algorithm as indicated by green dots.

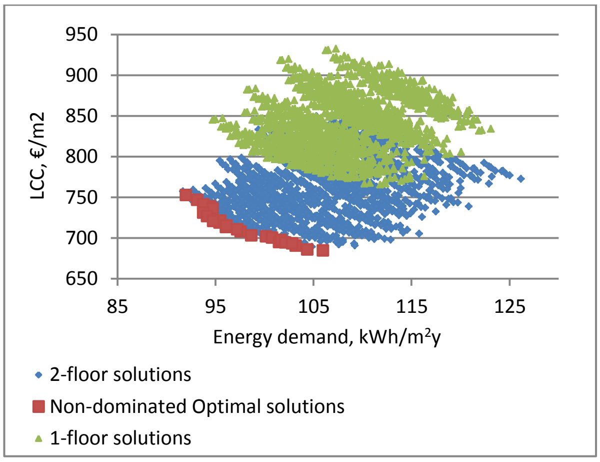

Figure 2: Energy demand versus life cycle cost for different combinations of design variables

In general, the 1-floor house evaluations show higher LCC values. 1-floor design possesses higher envelope area which requires more structural and insulation material thereby increasing the investment costs. The energy performance level of best solutions for 1-floor house ranges between 111.8 to 94.7

kWh/m²y, whereas the best solutions for 2-floor design ranges between 105.9 to 92 kWh/m²y. It seems that both the design types possess close energy performance level, but 1-floor solutions are more expensive. Therefore, the best solutions of 2-floor evaluation can be concluded as non-dominated optimal solutions of the whole evaluation including both 1-floor and 2-floor construction concept. In other words, with equal heated area a 2-floor construction is optimal in terms of energy performance and cost as compared with 1-floor construction. Let's assume a design situation where 1- floor construction is the requirement of client. In that case, a square shaped geometry (12.65 x 12.65) is beneficial from both energy and cost side. As all the best solutions of 1-floor house are indicated by square shaped geometry.

Across the non-dominated solutions, the selection of window orientation is always N-S. The values of other design variables for the non-dominated solutions are shown in Figure 3-7. For external wall, nearly 66% of the non-dominated solutions are indicating a U-value of ≤ 0.1 W/m2K. Whereas the current Finnish building code D3 recommends a U-value of 0.16 W/m²K. For roof, the behavior is evenly distributed across three U-values. For floor, 62% of the non-dominated solutions indicate a U-value of 0.18 W/m²K. The reason for this is the expensive floor insulation material. For window type, half of the non-dominated solutions show a U-value of 0.6 W/m²K. A lower U-value window is capable to reduce the space heating demand particularly for the selected case study building in higher latitude. For window area, 91% of the non-dominated solutions indicate an area of 16 m² (i.e, 10% of floor area). Only 2 optimal solutions indicate a window area of 24 m² (i.e, 15% of the floor area). This can be explained by the decrease in lighting demand for last 2 non-dominated solutions as shown in Figure 8. This is due to greater availability of daylighting as a result increased window area. Finally it can be concluded that a lower U-value for external wall and window compared with Finnish building code D3 standard would be beneficial in order to achieve optimal energy performance for the case study house.

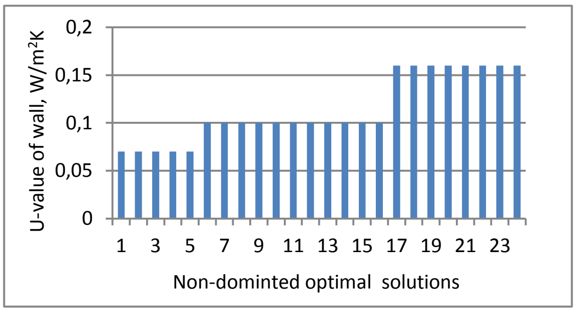

Figure 3: External wall U-value of the non-dominated optimal solutions

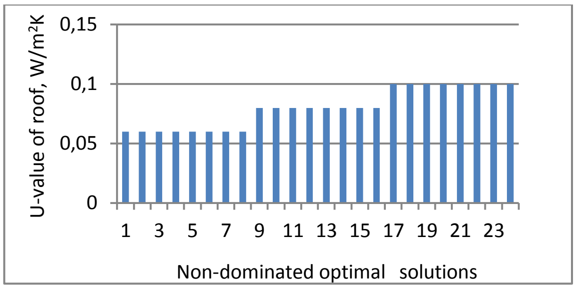

Figure 4: Roof U-value of the non-dominated optimal solutions

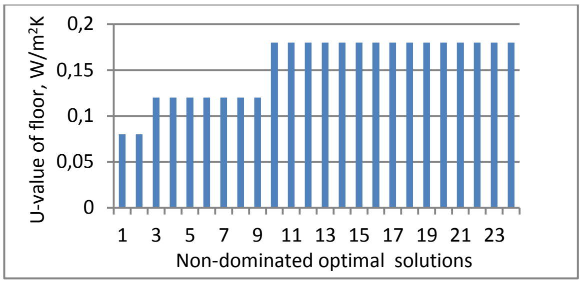

Figure 5: Floor U-value of the non-dominated optimal solutions

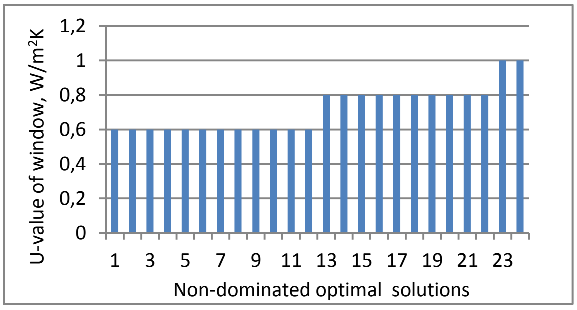

Figure 6: Window U-value of the non-dominated optimal solutions

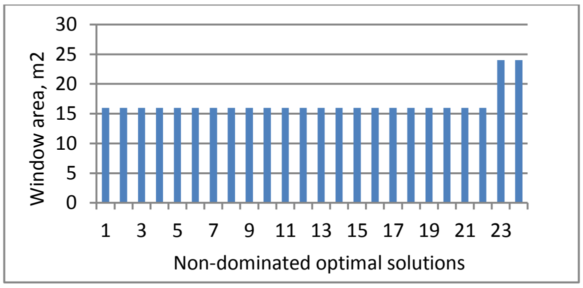

Figure 7: Window area of the non-dominated optimal solutions

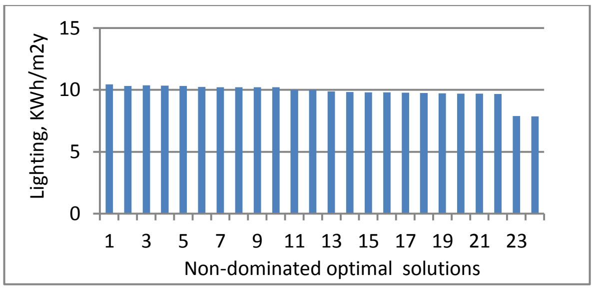

Figure 8: Lighting demand of the non-dominated optimal solutions

Here the indoor conditions of the non-dominated optimal solutions are analysed. The adopted evaluation criterion for the indoor condition is based on overheating degree hours (ODH). In the simulation, the set point temperature for cooling is 27°C. According to Finnish building code D3, the annual ODH limit is 150 degree-hours. This means the annual limit of the operative temperature duration above 27°C is 150 hours. Figure 9 shows the ODH values of the non-dominated optimal solutions. Although some degree-hours of overheating is recorded, but on the other hand it is worth mentioning that during these overheating hours the indoor operative temperature does not show any peak rise. It varies between 27 to 28°C only for the ODH values shown in Figure 9.
From solutions 1 to 22, the ODH values decreases, whenever there is an increase in U-value (i.e, thinner insulation) for any components of building envelope. For example, at solution number 6 there is a rise in U-value of external wall. Correspondingly, there is a drop noticed in the ODH value at solution number 6. Thinner insulation allows more heat flow from indoor to outdoor thereby reducing the indoor operative temperature. Interestingly, there is a rise in ODH for last 2 non-dominated solutions due to increase in window area from 16 m^2 to 24 m^2 with same U-value. Larger window area allows the possibility of more solar gain during the summer and causes overheating. In general, the first 2 non-dominated solutions exceeding the ODH limit of 150 degree-hour. These two solutions possess the thickest insulation for all components of building envelope and thereby the ODH criterion is not fulfilled.

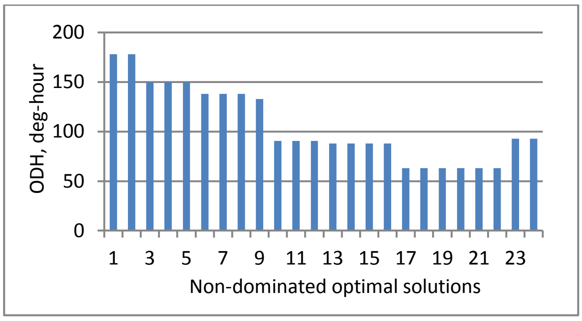

Figure 9: ODH of the non-dominated optimal solutions

3.2 Energy breakdown of optimal solutions

The energy breakdown of 3 representative optimal solution is shown in Figure 10. Additionally, 3 representative best solutions for 1-floor house is shown in Figure 11. The best energy efficient solution is corresponding to the extreme left red dot and worst energy efficient solution is the extreme right red dot in Figure 2. The energy breakdown at the middle is corresponding to a point situated nearly mid-way in the red dot curve.

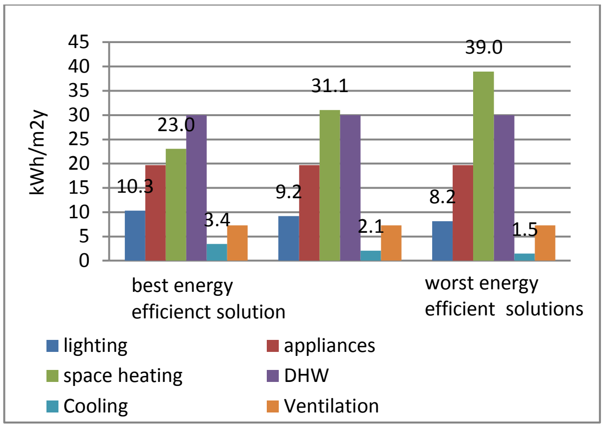

Figure 10: Energy breakdown of 3 representative non-dominated optimal solution (2-floor)

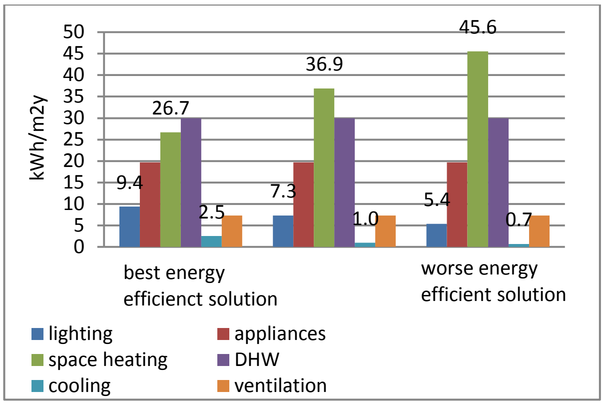

Figure 11: Energy breakdown of 3 representative best solutions for 1-floor house

Space heating is the dominant energy component which is affected by the choice of design variables across the optimal solution space. This is definitely the effect of cold climate. However there were variations noticed for lighting and cooling demand. As expected the rest of the energy components are constant. Only the space heating demand is higher for 1-floor house as compared with optimal solution. This can be explained by higher envelope area which leads to higher heat loss for a 1-floor construction. All non-dominated optimal solutions are 2-floor design which possess less envelop area compared with 1-floor design.

On the other hand, the cooling demand behaves in an opposite way. The optimal 2-floor construction shows higher cooling demand than 1-floor construction. One reason is the thermal mass of heavy concrete in 1-floor house. The intermediate floor in a 2-floor house is made of light construction material. In 1-floor house there doesn’t exist any intermediate floor, the whole floor is made of heavy reinforced concrete. In summer, heat is stored in thermal mass and hence reducing the peak cooling load. The stored heat is released later when cooling needs are less thereby maintaining thermal comfort level.

4. CONCLUSION

This paper proposes the utilization of optimization technique during early design phase of buildings. As architects are the main decision makers during this stage. So, a mixed approach of selecting design variables from both architectural and engineering interest is followed. An optimization is performed with the selected design variables to achieve energy and cost optimal solutions for a building operational life cycle of 30 years. A brief summary of the findings are indicated below.

- With equal heated area, a 2-floor construction is energy and cost optimal compared with a 1-floor construction.
- A square shaped geometry is optimal for 1-floor house construction.
- The optimal solution space is represented by 24 solution points.
- There is a requirement to improve the U-value of external wall and window as mentioned in Finnish building code D3 in order to achieve energy and cost optimal designs.
- The present U-value of roof and floor mentioned in D3 is satisfactory.
- A window area of 10% of floor area is optimal in this application.
- Space heating demand is lower in 2-floor construction house whereas the cooling demand is lower for 1-floor construction house.
- The indoor condition is evaluated by calculation overheating degree-hours.
- Lighting demand is decreasing slightly due to higher window area.

The results of this study show that an optimization is able to solve the problem of relevant data scarcity at early design stage. It guides the decision making in an optimal manner instead of rules of thumb. Although the results are rather obvious, the main purpose of this computational exercise is to demonstrate the power of simulation based optimization during early design phase.

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