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Optimization of insulation levels from an environmental perspective: impact of HVAC controls and Personal Comfort Systems

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Abstract. Today, strict insulation requirements apply. Nevertheless, the inverse correlation of thermal conductivity with insulation thickness leads to decreasing energy savings with increasing insulation packages. Therefore, a balance between potential energy savings and environmental impact due to additional materials using Life Cycle Assessment (LCA) needs to be strived for. This balance is sought for a case study called ‘The Mobble’ i.e. a flexible, modular, and circular building system developed by a student team from Ghent University. Through an iterative design process supported by LCA, comfort and dynamic energy simulations efforts are made to design an energy-efficient and low impact module with an agreeable indoor environment. First, material choices are made based on LCA and the material impact of a 5-module home is calculated. Second, energy calculations are executed in Modelica/Dymola. For this, three possible energy reductions are explored: insulating the building, altering the working regime of the HVAC system and lowering the setpoint temperature while maintaining comfort by using personal comfort systems (PCS). The results support PCS as a possible energy conservation measure and indicate that reducing operational energy does not shift the environmental burden to the additional materials’ production. However, these environmental saving effects decrease as the operational share decreases.

1. Introduction
The European building sector is responsible, among other factors, for no less than 40% of all greenhouse gas emissions, 50% of all raw material extractions and 50% of all energy use [1]. These numbers undeniably indicate the need for action. Despite the fact that many studies have highlighted an urgent need to shift the focus from this ‘use phase’ to the full life cycle of the building i.e. production, construction, use phase and end-of-life phase [2-3], the main focus today is still solely on energy reduction in the ‘use phase’ of the building [4]. In addition, some studies set a limit to the insulation degree [5-6]. Although the optimal insulation degree in these studies differs according to the boundary conditions (e.g. insulation material, HVAC system, service life, chosen impact indicators, climate, …), this limit clearly indicates the need to search for a balance between material impact and operational energy for a building design. In contrast, an extensive literature review by Mirabelle et al. [2] concludes that operational energy is still the decisive factor with an impact of up to 89% for existing buildings. However, a shift is detected for new low-energy dwellings for which all phases but the use phase can result in an impact of 68%, which in turn argues for an analysis of the entire life cycle and indicates the importance of system efficiency on the balance between material impact and operational energy.
Therefore, this paper focuses on three possible energy reductions (i.e. insulating the building, altering the working regime of the HVAC system and lowering the setpoint temperature while maintaining comfort by using PCS) to optimize the insulation levels from an environmental perspective and to examine the robustness of building design with far-reaching energy savings.

2. Building concept ‘The Mobble’

The Mobble – Modular Building Block – is a module facilitating a flexible, modular and circular building system. The module consists of 2 wooden structural frames (5 layers of plywood) with 3 columns each and 10 prefabricated sandwich panels with plywood and mineral wool to form the floor and roof. The module’s dimensions (2.4m wide, 6m long, 3.1m high) simplify transporting multiple modules which can be placed on-site next to each other on a steel foundation to form a dwelling. The number of modules needed for the dwelling depends on the homeowner’s present wishes and can increase/decrease over time. On a large scale, people’s opposing needs (e.g. family with children leaving the house and couple with a baby on the way) can complement each other, allowing material use to be more efficient due to this modularity. Around these modules, prefabricated sandwich panels and window elements are mechanically fastened to form the façade resulting in a wind- and watertight dwelling in only one day. The mechanical fasteners together with sophisticated sizing of the modules and panels allow all these elements to be dismantled and reused without damage and therefore be interchangeable.

3. Methodology

The new building concept ‘The Mobble’ is a result of an iterative design process by using life cycle assessments, comfort and dynamic energy simulations. The total environmental impact consists of material impact and operational energy.

First, the environmental impact of various materials is calculated using Life Cycle Assessment (LCA). This calculation is executed in the life cycle software SimaPro 9 with the Swiss ecoinvent [7] database version 3.6. As impact assessment method, ReCiPe 2016 (H/A) is chosen [8]. This method translates the impact on 17 different categories into a single score with as unit environmental points [Pt]. In this research, the impact of producing the construction materials and the energy use during the building’s lifetime of 60 years is included in a so called, cradle-to-use approach. This entails that the dwelling’s decommissioning and accompanying waste is not considered. This approach aligns with the Mobble concept in which all elements are undamaged interchangeable. However, every 15 years finishing layers (e.g. wood varnish) are renewed and every 30 years secondary elements (e.g. wall panels and glazing) are replaced. To determine the preferable material, the functional unit is chosen so that the energy use in all situations is equal and therefore negligible. Based on this first analysis, the composition of the module and material impact of a dwelling formed by five modules is determined.

Second, energy calculations are executed in Dymola/Modelica using the IDEAS-library. The dwelling is heated and cooled by the use of an air-to-air heat pump of Daikin (indoor and outdoor unit respectively FDXM50F9 – 3MXM52M). In the model, two HVAC systems are implemented: a constant and a demand based system. The constant HVAC system ensures that the setpoint temperature is
maintained at all times, whereas for the demand based system, the heating/cooling is shut down during the occupant’s absence allowing the temperature to drop. The simulated energy use is converted to primary energy use by using a primary energy factor (PEF) of 2.5 according to the 2012/27/EU [9]. To conduct an optimization exercise, the dynamic energy simulations and postprocessing of the data are automated using python 3.7. According to the first principle of ‘Trias Energetica’, the environmental impact of a dwelling is lowered by reducing the dwelling’s energy demand. To obtain a lowered energy demand, three approaches are explored: (1) insulating the dwelling, (2) altering the working regime (constant to demand-based) and (3) using personal comfort systems (PCS) e.g. heated chair, heated clothing during winter, and fans and cooled clothing during summer. By using PCS, the setpoint temperature of the HVAC system can be lowered resulting in a possible energy reduction. However, it is crucial that the occupants’ comfort levels are maintained. Comfort is defined by ASHRAE as ‘the condition of mind that expresses satisfaction with the thermal environment’ and is therefore a very personal experience. Hence, the importance of conducting the study on various user profiles i.e. single working male (P1), male continuously present (P2), couple continuously present (P3) and family with school-going child (P4). These user profiles were drawn based on the daily activities of average Belgian families [10]. Depending on the activities of the occupants they have a different metabolic rate, which is important for the amount of heat that needs to be added or subtracted to provide the occupant with comfort, e.g. occupant doing the dishes has a metabolic rate of 1.6 and as a result feels too warm faster than too cold. To verify the comfort levels, human thermal sensation and thermoregulation under transient and asymmetric environmental conditions are simulated in the Human Thermal Module software from Thermo Analytics. The second analysis results in 4563 building design variations with corresponding energy use for a 5-module dwelling with insulation thickness ranging from 10 to 50 cm.

Both the material impact and operational energy from the two analyses are added to calculate the total environmental impact. This balancing of both environmental burdens ultimately provides insight in whether there is an optimal insulation thickness and the environmental saving related to the use of PCS.

4. Results and discussion

4.1. LCA study

4.1.1. Material level. In order to make decisions at the material level in an environmentally conscious way, various equivalent materials are compared with each other. The materials are equivalent by considering an equal functional unit in the life cycle assessment i.e. 1m² of insulation material with a heat resistance value of 4 m²K/W (R-value) for a building lifespan of 60 years. If an insulation material has a lower lifespan [16] than 60 years, replacements are included. Table 1 shows an example of a comparison of insulation materials. The amount of material included for each insulation material for 1m² of wall with a lifespan of 60 years is shown in table 1 and is calculated on the basis of an equal heat resistance value of 4 m²K/W (R-value).

| Insulation material | Thermal conductivity [W/mK] | Lifespan [years] | Thickness [m] | Density [kg/m³] | Total mass [kg] | Environmental impact [Pt] |
|---------------------|-----------------------------|------------------|--------------|----------------|---------------|--------------------------|
| Cellulose           | 0.040                       | 30               | 0.16         | 50             | 16            | 0.54                     |
| EPS                 | 0.038                       | 75               | 0.15         | 30             | 4.5           | 0.62                     |
| Foam glass          | 0.040                       | 100              | 0.16         | 110            | 17.6          | 1.46                     |
| Glass wool          | 0.040                       | 75               | 0.16         | 40             | 6.4           | 0.89                     |
| PUR                 | 0.027                       | 75               | 0.11         | 32.5           | 3.6           | 0.99                     |
| XPS                 | 0.033                       | 75               | 0.13         | 37.5           | 4.9           | 1.31                     |
| Stone wool          | 0.040                       | 75               | 0.16         | 40             | 6.4           | 0.43                     |

Stone wool has the lowest environmental impact amongst the insulation materials listed in table 1, as opposed to foam glass with the heaviest environmental burden. The sandwich panels are therefore
insulated with stone wool. If the sandwich panels would be insulated with PU insulation, roughly half as much panels would cause an equal impact as the stone wool insulated sandwich panels.

4.1.2. Building level. As a case study one configuration of the explained building system ‘The Mobble’ is adopted for which the floorplan is shown in figure 1(b). This case study consists of 50 prefabricated floor and roof panels, 10 wooden frames with 3 columns each, 20 prefabricated wall panels and a glazed façade. The environmental impact of each material is calculated using the ReCiPe 2016 (H/A) impact method [8] in SimaPro 9 with ecoinvent database 3.6 [7] and is shown in table 2. Even so, the relative share of each material in the building component is determined highlighting the large contribution of plywood.

| Building component          | Environmental impact | Unit  | Relative share [%] |
|-----------------------------|-----------------------|-------|--------------------|
| Sandwich panel (wall, floor, roof) |                       |       |                    |
| - Interior varnish          | 0.137                 | Pt/kg | 1%                 |
| - Plywood (interior)        | 32.377                | Pt/m³ | 37%                |
| - Stone wool                | 0.069                 | Pt/kg | 13%                |
| - Rafters                   | 11.203                | Pt/m³ | 6%                 |
| - Plywood (exterior)        | 38.269                | Pt/m³ | 41%                |
| - Exterior varnish          | 0.137                 | Pt/kg | 2%                 |
| Wooden frame                |                       |       |                    |
| - Plywood                   | 32.377                | Pt/m³ | 94%                |
| - Glue                      | 0.102                 | Pt/kg | 4%                 |
| - Screws                    | 0.391                 | Pt/kg | 2%                 |
| Windows                     |                       |       |                    |
| - Triple glazing            | 2.994                 | Pt/m² | 43%                |
| - Frame                     | 35.427                | Pt/m² | 57%                |

The material impact as shown in figure 2 linearly increases with increasing insulation thickness of the wall, floor and roof panels. Insulating the sandwich panels with 50 cm stone wool (U-value of 0.08 W/m²K) instead of 10 cm (U-value of 0.35 W/m²K) adds 39% of material impact. This increased environmental impact attributed to the production of the initial construction materials and later replacements (e.g., finishing layers such as varnish have a lifespan of 15 years) results in a larger share of the material impact with increasing insulation thickness.

![Figure 2](image)

**Figure 2.** Environmental impact of the materials used for ‘The Mobble’ as illustrated in figure 1(b) for insulation thicknesses ranging from 10 to 50 cm. A subdivision of the impact is made for each insulation thickness containing the impact for the wooden structural frame, window with triple glazing and sandwich panels for wall, roof and floor.

4.2. Energy simulations

4.2.1. HVAC setpoint temperature 20°C (heating)/26°C (cooling). The energy use of the air-to-air heat pump is simulated in Modelica/Dymola for a constant and a demand based HVAC system and then converted to primary energy use by using a primary energy factor of 2.5 which is according to the Directive 2012/27/EU [9] for four user profiles as explained in section 3. By increasing the insulation
thickness from 10 cm to 50 cm, an energy reduction of 59% can be obtained for ‘single working male’ with a constant HVAC system. The energy reductions for P2, P3, P4 with a constant HVAC system are 60%. By altering the working regime of the HVAC system from constant to demand based, energy reductions range between 14-17% and 12-14% for user profile 1 and 4 and 10-50 cm of insulation respectively: high insulation degrees ensure uniform indoor temperatures resulting in higher energy savings by altering the working regime.

Figure 3. Primary energy use for the four user profiles (i.e. P1: single working male, P2: male continuously present, P3: couple continuously present, P4: family with school-going child), two HVAC working regimes (constant and demand based) and insulation thickness ranging from 10 to 50 cm.

4.2.2. Lowering of HVAC setpoint temperature and PCS for thermal comfort. Previous energy simulations are done with a setpoint temperature of 20°C for heating season and 26°C for cooling season. Before lowering the setpoint temperature, more insight in the occupant’s comfort is needed. This parameter is seen as non-negotiable. In literature, various comfort theories can be found [11-12]. In short, the comfort theory of Fanger [11] presumes thermal neutrality. However, the concept of a thermal neutral state being the most pleasant state to be in, has been contradicted by many researchers [13]. In contrast, Zhang [12] presupposes a direct link between thermal sensation and skin temperature which is substantiated by several studies [14-15]. The overall comfort of the occupant is best approximated by the mean of the maximum and two least comfortable thermal sensation votes. By lowering the operative indoor temperature, body parts could experience discomfort, e.g. cold feet.

Therefore it is important to target the right body parts with the personal comfort systems and those differ for winter and summer [13]. In winter, the overall comfort is mostly influenced by hands, feet and head. In summer, only the head has a large impact on the overall comfort. As personal comfort devices, a heated chair, heated clothing during winter, and fans and cooled clothing during summer are chosen. Those devices will supply or extract heat to provide the occupants in their comfort as listed in table 3.

Table 3. Heat output in respectively winter and summer in W.

| PCS          | Metabolic rate [-] | Set point temperatures HVAC (heating) | PCS          | Set point temperatures HVAC (cooling) |
|--------------|--------------------|--------------------------------------|--------------|---------------------------------------|
|              | 16°C               | 17°C                                 | 18°C         | 19°C                                  | 20°C                                 | 26°C     | 28°C     | 30°C     | 32°C     |
| Heated chair |                    | 0                                     | 0            | 0                                     | 0                                     | 0         | 0         | 10        | 20        |
| 1.0          | X                  | 60                                   | 45           | 30                                    | 0                                     | Fans      | 0         | 0         | 15        | 25        |
| 1.2          | 85                 | 50                                   | 22           | 5                                     | 0                                     | 0         | 0         | 15        | 25        |
| 1.6          | 0                  | 0                                    | 0            | 0                                     | 0                                     | 0         | 20        | 30        | 40        | X         |
| Heated clothing | 1.0               | 60                                   | 48           | 12                                    | 6                                     | 0         | Cooled Clothing     | 0        | 0         | 0         | 18        | X         |
| 1.2          | 36                 | 8                                    | 4            | 0                                     | 0                                     | 0         | 0         | 18        | 24        | X         |
| 1.6          | 0                  | 0                                    | 0            | 0                                     | 0                                     | 0         | 18        | 24        | X         | X         |
| X: comfort cannot be provided at this setpoint temperature with this personal comfort system |

The use of PCS is only interesting if energy is saved on a yearly basis. Figure 4 demonstrates that there is indeed a saving potential by using PCS in comparison with a constant heating/cooling at respectively 20°C and 26°C for all user profiles and all considered PCS (winter: heated chair and heated clothing; summer: fans and cooled clothing). The heated chair and clothing are used in the temperature range of 16-19°C, while the fans and cooled clothing are used in the temperature range of 26-32°C. Figure
4 demonstrates the total annual saving for (a) heated chair and fans and (b) heated clothing and fans. The following results for potential energy saving by using a personal comfort system are limited by the ability of providing comfort as listed in table 3. For example, the energy saving by using a heated chair ranges from 8 to 26% for P1. With 26% the potential energy saving by lowering the operative temperature to 17°C and not 16°C because the heated chair is unable to provide comfort to an occupant with metabolic rate of 1.0 at 16°C (table 3). In the same manner, the use of fans generate an energy saving between 9 to 16%. If the occupant tolerates discomfort at 32°C while walking around (metabolic rate of 1.6), the corresponding saving can be up to 21%. Heated and cooled clothing generate energy savings of 10-39% and 9% for the same user profile. For the other user profiles, the saving percentages slightly differ based on the following two principles: (1) the longer occupants are at home, the longer the heating/cooling device is used (2) the more occupants are at home, the more heating/cooling devices are used. Both principles result in higher energy use of the device(s) and consequently lower energy saving potential as shown in figure 4.

![Figure 4](image_url)

**Figure 4.** Total annual energy saving (a) heated chair and fans (b) heated and cooled clothing (dashed line: comfort is not provided) for a case study ‘the Mobble’ with 30 cm of insulation for wall, floor and roof panels with a constantly working HVAC system.

4.3. *Trade-off between material impact and operational energy*

Since it is crucial to know if by reducing the energy demand in the operational phase, the environmental burden is not shifted to the production of additional materials, a trade-off needs to be made between material impact and operational energy. The material impact was calculated in section 4.1. For the operational energy, the final energy use of section 4.2 needs to be multiplied by the environmental impact of the production of low voltage electricity with a Belgian energy-mix which is 0.008 Pt/kWh according to ReCiPe 2016 (H/A) [8].

The optimal insulation thicknesses range between 22cm and 28cm and are reported in figure 5. For example by lowering the HVAC setpoint temperature for user profile 1 with a constant HVAC working regime from 20°C to 17°C, the optimal insulation thickness decreases from 28 cm to 24 cm. In addition, there are also examples in which the energy savings do not reflect in a smaller insulation thickness, although the environmental impact decreases (vertical shift in total environmental impact). For example, the optimal insulation thickness for ‘single working male’ with HVAC setpoint temperature of 19°C combined with the use of a heated chair is 26 cm for both a constant and a demand based HVAC working regime, although the total environmental impact is lowered with 16% by changing this working regime.
Figure 5. Optimal insulation thicknesses for four user profiles, temperatures ranging from 20°C to 17°C and two HVAC working regimes i.e. constant and demand based).

Figure 6 shows a minimum value, which represents the optimal insulation thickness. For higher insulation levels, the decrease in operational energy use is superseded by the environmental impact of the insulation materials. To conclude, the lowest environmental impact is reached by implementing a demand based HVAC working regime with a setpoint temperature of 17°C, whereas the highest environmental burden is caused by a constant working regime with a setpoint temperature of 20°C (Figure 6) illustrating the importance of operational energy. However, the higher the insulation degree and thus the higher the share of material impact, the lower the impact of energy saving on the total environmental impact e.g. changing the working regime (constant to demand based) while lowering the setpoint temperature (20°C to 17°C) using a heated chair for thermal comfort results in decreasing environmental saving from 19% to 8% for an insulation thickness of 10cm and 50 cm respectively.

5. Conclusion
The decreasing energy savings with increasing insulation thicknesses as a consequence of the inverse correlation of thermal conductivity with insulation thickness leads to a need for a balance between material impact and operational energy from an environmental perspective. Therefore, this paper explores three possible ways to save energy: (1) insulating the dwelling with thicknesses between 10 and 50 cm, (2) changing the operating regime of the HVAC system from constant to demand-driven, (3) lowering the set point temperature while ensuring thermal comfort with personal comfort systems.

The results show that there is indeed an optimal insulation thickness from which the energy saving is superseded by the additional insulation materials needed. However, it is important to note that the environmental impact of the PCS itself has not been considered, nor has the impact of the HVAC installation, but the latter is the same in all cases except for the working regime. Besides, these optimal insulation thicknesses are hardly affected by the energy savings ensuring a negligible effect of occupant behaviour from an environmental perspective, which allows for unambiguous requirements at the building level. Next, HVAC system efficiency has a limited effect on the optimal insulation thickness allowing simplifications in the modelling of the operational energy in LCA. By comparing the lowest and highest environmental impact, the importance of the operational energy is emphasized: the former
uses a demand based HVAC working regime with a setpoint temperature of 17°C, while the latter constantly maintains 20°C. Nonetheless, the higher the insulation degree, the lower the impact of primary energy saving on the total environmental impact.

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