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# FROM A SIMPLE TOOL FOR ENERGY EFFICIENT DESIGN IN THE EARLY DESIGN PHASE TO DYNAMIC SIMULATIONS IN A LATER DESIGN STAGE

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**Abstract**

In the past decade, many tools have been developed to support design decisions related to energy efficient buildings. However, these energy simulation tools are complex and require too detailed input data to be appropriate for use in the sketch design stage. Architects and designers hence often take energy related design decisions based on their own experiences or intuition. This paper proposes a simple tool to estimate the energy consumption in the sketch design stage which can, in a later design stage, be linked to a dynamic simulation tool. Furthermore, this study proposes the use of visualisation methods by architects to improve the integration of energy simulations in the sketch design stage. The proposed simple energy estimation tool is based on the "dynamic Equivalent Heating Degree Day Method (dynamic EHDD)". Relevant sketch design parameters identified are thermal compactness, insulation level, effective use of direct and indirect solar gains, internal gains including occupant presence and activities, and ventilation strategies. In order to develop in-depth simulations, the tool is linked to the dynamic energy simulation software "EnergyPlus" to be used during the detailed design stage. The tool is developed for the Belgian context, but the approach is also valid for other contexts.

**Keywords:** design supporting tool; design process; dynamic EHDD; user behaviour; solar gains; internal heat gains; energy simulation

## 1 INTRODUCTION

The 2010 Energy Performance of Buildings Directive (EPBD) requires EU member states to improve energy efficiency in new buildings for achieving the target of Nearly Zero Energy Buildings (NZEBs) by 2020 [1]. In order to reach this target, architects should integrate energy efficiency in their design process from the early design phase on, especially in small scale projects with a lack of engineers' support due to financial and time constraints.

The use of Building Performance Simulation (BPS) tools during the design process is effective to support decisions for energy efficient buildings. However, most existing BPS tools are not suitable in the early design phase [2]. Tools which generate rough energy estimations in the sketch design stage and which are later on linked to more accurate calculations in the detailed design stage, are required to stimulate the exchange of ideas and solutions between clients, architects and engineers [3][4]. In addition, the performance of buildings depends not only on architectural design solutions but also deeply on user behaviour [5]. The well-known gap between predicted and actual performance in energy efficient buildings is partially caused by the lack of consideration for user patterns during the design process [6]. It is therefore essential to consider the influence of both architectural design decisions and user behaviour on the energy performance, from an early design phase onward. This paper proposes a decision support tool including these two perspectives. Section 2 presents the methodology related to the dynamic Equivalent Heating Degree Days (dynamic EHDD) and solar gain calculation. The use of the tool during the different design stages is described in section 3. Section 4 focuses on the tool structure. Conclusions are formulated in the final section.

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## 2 METHOD

### 2.1 Dynamic Equivalent Heating Degree Day (dynamic EHDD) method

The dynamic EHDD is a refinement of the Equivalent Heating Degree Day method (EHDD), which is a simplified calculation method for predicting the heating energy demand in buildings, taking into account the internal and solar "free" heat gains [4].

Compared to the existing EHDD method [7], the dynamic EHDD includes more accurate calculations of internal gains from occupants and appliances and solar gain calculations based on semi-dynamic simulations [8]. The number of EHDD is estimated for each month of the heating season based on two temperature curves (Fig.1): the temperature of no more heating ($T_{NH}$) and the temperature without heating ($T_{WH}$). The first temperature line ($T_{NH}$) is defined as the indoor temperature above which no heating is required, as the internal gains will be sufficient to compensate the heat losses. $T_{NH}$ is calculated, considering the impact of the temperature set point ($\Delta T_{set}$) and internal gains from appliances ($\Delta T_{app}$) and occupants ($\Delta T_{per}$). The second temperature line ($T_{WH}$) is the increased indoor temperature, resulting from solar gains ($\Delta T_{sun}$), when the building is not heated and not occupied. The line of the outdoor temperature ($T_e$) is obtained via linear regression of monthly temperature reported in the Test Reference Year [9]. In Fig.1 the number of dynamic EHDDs is represented by the blue area.

The dynamic EHDD method is fast and accurate enough to predict the heating demand. Moreover, this method is particularly appropriate for the early design phase because of the limited number of required input data. A more detailed description of the dynamic EHDD can be found in [4].

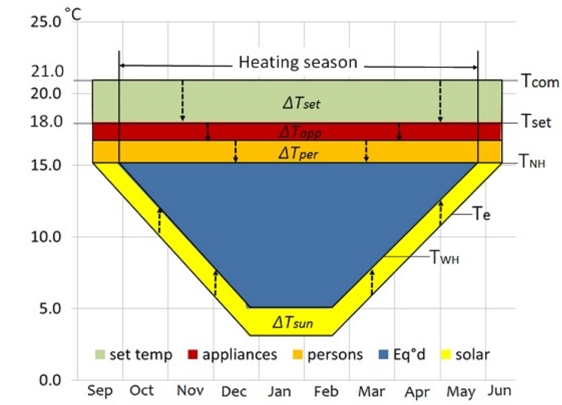


*Fig. 1: Representation of dynamic EHDD for the temperate climate in Belgium.*

### 2.2 Solar gain calculation

In the proposed tool, solar gains are calculated based on the semi-dynamic method defined in the Flemish Energy Performance of Buildings (EPB) regulation [10]. In this method solar gains are calculated as the sum of the direct, diffuse and reflected solar gains. The impact of shading patterns is approximated by defining a set of obstructions and overhang angles for each window [11]. In the proposed tool, as the obstructions in the surrounding environment are defined as cylinder obstructions, those vertical angles are calculated based on the average of the horizontal obstructions in a range of 90° around the centre of each window. More details concerning the EPB method for solar gain calculations can be found in [11].

## 3 DESIGN PROCESS

Based on the RIBA Plan of Work 2013 [12], the early design process can be divided into three stages (Fig.2): (1) Preparation and Brief, (2) Concept Design and (3) Developed Design. In this research, the early design stages are further subdivided into three sub-stages: (a) Pre-Design stage, (b) Sketch design stage and (c) Preliminary design stage. In the proposed tool, specific input sheets are developed for each sub-stage: Brief-Form0, Form1 and Form2. Input parameters are classified into three categories: geometry, technical choices and user behaviour. In the more advanced design stages, more detailed input parameters are required in each category. The following subsections describe the different sub-stages of the early design process.

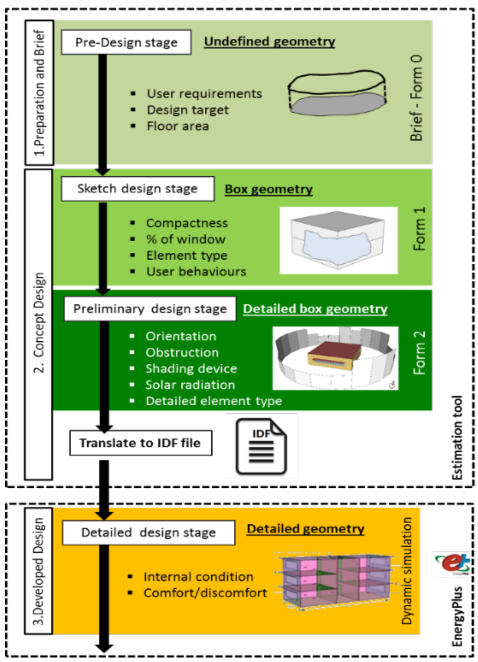


*Fig. 2: Design process and design stages.*

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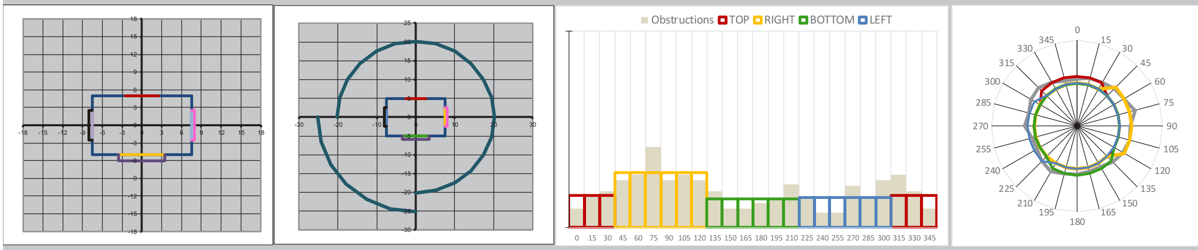
**Form2: Geometry+Technology**




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Building typology | | single unit | type | detached | | single unit,detached | |
| facade | | 15.0 | | floor area | 150.0 | External surface 450 | Total sureface 450 |
| depth | | 10.0 | | Volume | 450.0 | Compactness (V/S) 1.00 | |
| storey height | | 3.0 | | façade total | 150.0 | E rad TOP 83.2 | Total (W) 464.4 |
| number of floors | | 1.0 | | façade wall | 117.0 | RIGHT 90.9 W | |
| buiing height | | 3.0 | | façade window | 33.0 | BOTTOM 157.4 W | 3.10 W/m2fl |
| Building north | >=-180 | 0 ° | <=180 | %window | 22% | LEFT 132.8 W | |

Climate: EPW_Brussels | TRY_Brussels | TRY_Oostende | TRY_St.Hubert

| | | | | Ratio | invst/elem | HW(trm)/m²el | Price/m²vl | HW(t+v)/m²vl | Totale invest | Tot HW (t+v) | R tot | Um |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (13) floor on ground | | EPS 04 cm | | 1.000 | 199.7 | 30.1 | 199.7 | 30.1 | 29,959.5 | 4,519.4 | 1.5 | 0.69 |
| (23) storey floor | | | | 0.000 | 220.0 | | 0.0 | | 0.0 | | | |
| (21)+ TOP full facade | 180.0 ° | rockwool 14 cm | | 0.250 | 269.9 | 30.4 | 67.5 | 7.6 | 10,120.2 | 1,139.1 | 4.3 | 0.23 |
| (31) TOP window with U (g+f) | 17% | | 3.33 | 0.050 | 400.0 | 302.8 | 20.0 | 15.1 | 3,000.0 | 2,270.9 | 0.30 | 3.33 |
| (41) TOP Overhang (m) | 0 | No solar shading | | | | | | | | | | |
| (21)+ RIGHT full facade | -90.0 ° | rockwool 14 cm | | 0.150 | 269.9 | 30.4 | 40.5 | 4.6 | 6,072.1 | 683.5 | 4.3 | 0.23 |
| (31) RIGHT window with U (g+f) | 25% | | 2.85 | 0.050 | 400.0 | 259.1 | 20.0 | 13.0 | 3,000.0 | 1,943.6 | 0.35 | 2.85 |
| (41) RIGHT Overhang | 0.5 | Fixed | | | | | | | | | | |
| (21)+ BOTTOM full facade | 0.0 ° | rockwool 14 cm | | 0.230 | 269.9 | 30.4 | 62.1 | 7.0 | 9,310.6 | 1,048.0 | 4.3 | 0.23 |
| (31) BOTTOM window with U (g+f) | 23% | | 2.84 | 0.070 | 400.0 | 258.4 | 28.0 | 18.1 | 4,200.0 | 2,713.0 | 0.35 | 2.84 |
| (41) BOTTOM Overhang | 1 | Fixed | | | | | | | | | | |
| (21)+ LEFT full facade | 90.0 ° | rockwool 14 cm | | 0.150 | 269.9 | 30.4 | 40.5 | 4.6 | 6,072.1 | 683.5 | 4.3 | 0.23 |
| (31) LEFT window with U (g+f) | 25% | | 2.85 | 0.050 | 400.0 | 259.1 | 20.0 | 13.0 | 3,000.0 | 1,943.6 | 0.35 | 2.85 |
| (41) LEFT Overhang | 0.5 | Fixed | | | | | | | | | | |
| (27) roof | 0.0 ° | EPS 10 cm | | 1.000 | 174.8 | 42.9 | 174.8 | 42.9 | 26,223.1 | 6,435.0 | 3.1 | 0.33 |
| Other element | | sum (21)+ | | 0.780 | | | 700 | 33.5 | 5,029.2 | 5,029.2 | | |
| Total construction price | | sum (31) | | 0.220 | | | 1373.1 | 189.4 | 205,957.7 | 28,408.8 | 234,366.4 | |
| Totale price / m² gross per area | | | | | | | | | 1,373.1 | 189.4 | 1,562.4 | |
| Um= | | | 0.46 | | kref= | 1.00 | | K-Peil= | 46 | | | |

Geom+User_2 into Dashboard

*Fig. 3: Input parameters and graphical representation of obstructions in Form2.*

| Economic factors | | | | | | % tot.cost | index |
|---|---|---|---|---|---|---|---|
| Construction cost | 1200 | €/m² | Construction cost | 1,200 | €/m² | 57.5% | 100% |
| Maintenance % | 1.5% | | PV Maintenance cost | 829 | €/m² | 39.7% | 69% |
| Time horizon | 120 | years | PV Heating costs | 57 | €/m² | 2.7% | 5% |
| Interest rate | 4.0% | | Total costs | 2,086 | €/m² | 100.0% | 174% |
| General inflation | 2.0% | SPV fi | 46.0 | 0,024*eq°d*(prijs/nuttige kWh)*sHWf= | | | 73.69 |
| growth rate energy | 3.0% | SPV fe | 70.7 | 0,00816*eq°d*(prijs/nuttige kWh)*sHWf= | | | 25.05 |
| Price gasoil (€/liter) | 0.8 | €/l incl VAT | 10.13 kWh/l | 0.093 €/kWh | | | |

| input parameters | | | | | | | | | | output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geometry | | | T set | Transm. | Ventilation | Persons | appliances | Solar gains | η system | Degree days | Transmission | Ventilation | Energy load | costs |
| total floor area (m²) | height (m) | compactness (Vol./Envelop)(m) | Tset (°C) | U-value (W/m²K) | ventilation (1/h) | people (W/m²fl) | appliance (W/m²fl) | solar gain (W/m²fl) | η system (%) | degree day | transmission loss | ventilation loss | energy load | cost €/ (year m²fl) |
| | | 3 | 21 | 2 | 2 | 3 | 6 | 5 | 95% | 4000 | kWh/(year * m² floor) | | | |
| 150 | 3.0 | 1.00 | 15.0 | 0.21 | 0.14 | 2.02 | 2.14 | 1.33 | 85% | 467 | 7 | 2 | 9 | 0.81 |
| 150 | 3.0 | 1.00 | 15.0 | 0.21 | 0.14 | 2.02 | 2.14 | 1.33 | 85% | 467 | 7 | 2 | 9 | 0.81 |
| 150 | 3.0 | 1.00 | 15.0 | 0.21 | 0.14 | 2.02 | 2.14 | 1.49 | 85% | 439 | 7 | 2 | 8 | 0.76 |
| 150 | 3.0 | 1.00 | 15.0 | 0.21 | 0.14 | 2.02 | 2.14 | 1.48 | 85% | 441 | 7 | 2 | 8 | 0.77 |
| 150 | 3.0 | 1.00 | 15.0 | 0.21 | 0.14 | 2.02 | 2.14 | 1.48 | 85% | 445 | 7 | 2 | 8 | 0.78 |
| 150 | 3.0 | 1.00 | 15.0 | 0.30 | 0.14 | 2.02 | 2.14 | 1.40 | 85% | 744 | 16 | 3 | 19 | 1.74 |
| 150 | 3.0 | 1.00 | 15.0 | 0.30 | 0.14 | 2.02 | 2.14 | 1.40 | 85% | 744 | 16 | 3 | 19 | 1.74 |
| 150 | 3.0 | 1.00 | 15.0 | 0.32 | 0.14 | 2.02 | 2.14 | 1.40 | 85% | 792 | 18 | 3 | 21 | 1.95 |
| 150 | 3.0 | 1.00 | 15.0 | 0.32 | 0.14 | 2.02 | 1.86 | 1.40 | 85% | 838 | 19 | 3 | 22 | 2.07 |
| 150 | 3.0 | 1.20 | 14.7 | 0.27 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 679 | 11 | 5 | 16 | 1.46 |
| 150 | 3.0 | 1.20 | 14.7 | 0.27 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 679 | 11 | 5 | 16 | 1.46 |
| 150 | 3.0 | 1.20 | 14.7 | 0.28 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 702 | 12 | 5 | 17 | 1.55 |
| 150 | 3.0 | 1.00 | 14.7 | 0.28 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 816 | 16 | 6 | 22 | 2.05 |
| 150 | 3.0 | 1.15 | 14.7 | 0.28 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 729 | 13 | 5 | 18 | 1.65 |
| 150 | 3.0 | 1.10 | 16.0 | 0.35 | 0.28 | 2.50 | 1.30 | 1.40 | 85% | 1,155 | 26 | 8 | 34 | 3.20 |
| | | 0.5 | 13 | 0.15 | 0.05 | 0.5 | 0.3 | 0.1 | 50% | 200 | | | | |

*Fig. 4: All design combinations in the “Dashboard”.*

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Area 150 m2
People 4 persons

| | Refrigerating appliances | | | Washing machine | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fridge | Freezer | Combination | washing process | spin dry process | tumble dryer | energy by evaporation | Dishwasher | Cooking hobs | Light | Electoronic | Household equipment | auxiliary Power | **Total** | |
| Installation | installed | installed | not installed | installed | installed | installed | | installed | installed | | | | | | |
| Location | heated area | heated area | heated area | heated area | heated area | heated area | in heated area | heated area | heated area | heated area | | | | | |
| Type | - | - | - | - | - | Vented | Vented | - | - | Traditional | | | | | |
| Class | A+ | A+ | A++ | A | D | B | | A++ | - | - | | | | | |
| kwh/cycle | | | | 0.96 | 1.0184 | 2.77 | 3.13 | 0.9 | 0.25 | - | | 50 | 2.16 | | |
| spin speed (rpm) | - | - | - | - | 1000 to 1100 rpm | - | | - | - | - | | | | | |
| residual moisture per rmd | - | - | - | - | 60% | - | | - | - | - | | | | | |
| correction for energy consumpti | - | - | - | - | 0.875 | - | | - | - | - | | | | | |
| kwh/cycle(corrected) | - | - | - | - | 0.8911 | - | | - | - | - | | | | | |
| kg | - | - | - | 5 | 5 | 5 | | - | - | - | | | | | |
| W | | | | | | | | | | 50 | 80 | | | | |
| number of light | | | | | | | | | | 5 | | | | | |
| % of CFLs | | | | | | | | | | 80% | | | | | |
| hour/person/day | | | | | | | | | | 3 | | | 24 | | |
| cycle(hours for cooking)/person/week | - | - | - | 1 | 1 | 1 | 1 | 4 | 7 | - | | | 7 | | |
| h/person/year | - | - | - | 52.14 | 52.14 | 52.14 | 52.14 | 208.57 | 365.00 | 1095 | 550 | | 8760 | | |
| kwh/year | 130.00 | 346.00 | 0.00 | 200.23 | 111.51 | 576.76 | 652.83 | 750.86 | 365.00 | 1095.00 | 176.00 | 200.00 | 788.40 | **3575.36** | **kwh/year** |
| % heat gain | 100% | 100% | 100% | 30% | 30% | 80% | -100% | 30% | 50% | 100% | 100% | 100% | 50% | | |
| internal gain (W) | 14.84 | 39.50 | 0.00 | 6.86 | 3.82 | 52.67 | -74.52 | 25.71 | 20.83 | 125.00 | 20.09 | 22.83 | 45.00 | **234.80** | **W** |
| | | | | | | | | | | | | | | **1.57** | **W/m2** |
| % energy consumption | 4% | 10% | 0% | 6% | 3% | 16% | | 21% | 10% | 31% | 5% | 6% | 22% | | |
| % internal gain | 6% | 17% | 0% | 3% | 2% | 22% | -32% | 11% | 9% | 53% | 9% | 10% | 19% | | |

*Fig. 5: The input and output parameters in the "Appliances" support sheet.*

### 3.1 Pre-design stage: Brief-Form0

The pre-design stage is an important stage for all stakeholders as it includes the definition of the design target and the setting of global technical aspirations [13]. This stage is implemented in the input sheet "Brief-Form0". This sheet includes the several architectural and economic factors. Input parameters related to the geometry include the floor area, floor height and a global estimation of the building compactness. For the technical choices a global thermal insulation level and a ventilation strategy are considered. Concerning the user behaviour, a daily average set point temperature over 24 hours and all spaces is defined. For the definition of the design target, without carrying out detailed calculations, and detailed knowledges, references are included in Brief-Form0.

### 3.2 Sketch design stage: Form1

In the sketch design stage, important decisions are made influencing the scheme of the project and future decisions. Important parameters are the building geometry and layout. In Form1, the building layout is defined as a box geometry with a global window ratio. The building compactness is calculated based on the box geometry. Concerning the technical choices, standard element types are selected based on the database of building elements from the MMG research project ("Environmental profile of building elements) [14]. Input parameters include the insulation material and thickness and window materials. Based on the selected insulation characteristics and global window ratio, the average building U value can be calculated. Regarding the user behaviour, more detailed temperature set points are defined and internal gains by appliances and occupants are estimated.

### 3.3 Preliminary design stage: Form2

More detailed design decisions are made in the preliminary design stage preparing the later phase [13]. Concerning the building geometry, the impact on solar gains of shading devices and obstructions from the environment is calculated. For the technical choices specific insulation materials are selected for each element of the building envelope. Per orientation, the glazing type and frame type are selected for each window (Fig.3). Regarding the user behaviour, detailed internal heat gains are calculated (Fig.5).

### 3.4 Translation to an Input Definition File (IDF) for dynamic energy simulations

A macro is developed to translate the input parameters from the estimation tool to an Input Definition File (IDF file) that can be used for dynamic energy simulations with the software EnergyPlus [15]. This macro provides a link between the design language of the architects, used in the estimation tool and the numeric language of the engineers, used in an IDF-file [16]. This approach reduces the gap between the architects and engineers and between the early and later design phases.

## 4 TOOL DESCRIPTION

### 4.1 "Dashboard" to navigate in the design space

A simple spreadsheet interface, called the "Dashboard", is implemented to define different design options. For each design option, the annual heating energy demand is calculated as the sum of the heat losses by transmission and ventilation, based on the dynamic EHDD [4]. As during the early design phase the possibility to compare alternatives is more important than an absolute value [17], all design options that are defined in different design stages (Form 0, 1 and 2) are

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reported in the core line of the "Dashboard" (Fig.4). Below that line the design history remains visible and is also visualized in a graph, using parallel coordinates (Fig.6). The graph can speed up the analysis of the design space and improve the integration of energy simulations in the early design phase. In this graph, all input variables leading to one output result are connected via a line. The exploration of the "design space" is hence investigated in the "Dashboard". Supporting sheets are used to generate input (via macros) for the "Dashboard". Different colours explain the origin of the values from different design stages: light green is from Brief-Form0, green is from Form1 and dark green is from Form2. For each input parameter, average values (in white) and minimum and maximum values (in grey) are defined as a starting case for the Belgian context.

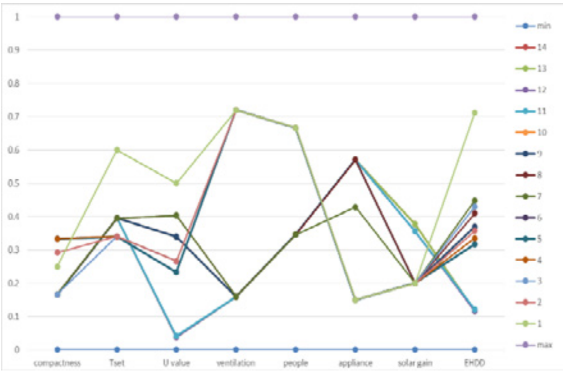


*Fig. 6: Graphical representation of all design combinations, using parallel coordinates.*

### 4.2 User behaviour

As the energy consumption is strongly related to the user behaviour, considering user requirements from the early design phase can effectively increase the energy efficiency in buildings.

Parameters related to the user behaviour are divided into four categories: (1) Temperature setpoint (2) Human activity (3) Usage of appliances (4) Ventilation strategy.

Firstly, the temperature setpoint ($T_{set}$) is calculated based on the heating setpoint schedule over 24 hours and over all the building zones in the building. In the $T_{set}$ sheet, setting the schedule of $T_{set}$ and ratio of the heating zone provides an average daily $T_{set}$. Weekly and seasonally $T_{set}$ are calculated based on a daily $T_{set}$.

Secondly, internal heat gains resulting from human activities are estimated. Due to the metabolic activity, human bodies lose heat into the surrounding environment. Based on the metabolic rates for different states of activity, defined in ASHRAE Fundamentals [18] and using an activity schedule over 24 hours, the average internal gains from occupants can be calculated.

Thirdly, electrical energy used by appliances in a household is partly released as heat. The internal heat gains from appliances are based on power data from technical specifications. The heat output rate is calculated based on the calculation method defined in the Passive House Planning Package (PHPP) [19]. Input parameters are the location in the building, the equipment class according to the EU energy label and the user pattern (Fig.5). Furthermore, this step introduces architects and occupants to the impact of varying the equipment type and the user pattern on energy consumptions by appliances. Fourthly, the ventilation strategy is based on the Belgian standard "Ventilation facilities in residential buildings" (NBN D 50-001) [20]. An input parameter is the efficiency of the ventilation system.

### 4.3 Obstructions

The use of passive solar gains in buildings is a critical issue in cold and moderate climates. Optimizing solar gains from the early design phase is an effective way to improve the energy efficiency in buildings. In this research, obstructions in the surrounding environment are modelled as cylinder obstructions composed of segments with different height in order to model any environmental conditions. The cylinder is divided into 24 parts (15°) and angles are defined based on the obstruction distance and height for different orientations (Fig.3).

## 5 CONCLUSIONS

In this paper a design tool is developed to support architects making decisions for energy efficient buildings and to link their decisions in the early design phase to those in the later detailed design phase. The strength of this tool is its capacity to generate fast and comparative energy estimations during different design stages, including the consideration of occupant behaviour. Consequently, the proposed tool facilitates the architect's work in designing energy efficient buildings and improves the communication with other stakeholders during the design process. Moreover, this research can be applied to other contexts by using other climatic data as input for the dynamic EHDD method.

Concerning further research, the validation and usability of the design tool will be tested based on case studies. The tool is developed in cooperation with some architecture tutors and students. The usability test will be carried out by students. A workshop for architects will be organised to obtain feedback from practitioners. Furthermore the tool will be extended to evaluate summer comfort/discomfort.

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