43 Integrating BIM, Optimization and a Multi-criteria Decision-Making Method in Building Design Process

Elaheh Jalilzadehazhari and Peter Johansson

Abstract

European Energy Performance of Building Directive (EPBD) defined a target as all new constructed buildings within the EU region must be a zero-energy building by the end of 2020. Furthermore, all European countries must ensure the minimum comfort threshold in energy calculations. Reducing energy consumption and improving indoor comfort, including visual and thermal comfort, can contribute to economic benefits. However, the main problem is the exitance of conflicts among visual comfort, thermal comfort, energy consumption and life cycle cost. To solve the abovementioned problem and to fulfil the EPBD's target, this study aims to apply an integration between BIM, optimization and Analytical Hierarchy Process as a multi-criteria decision-making method on an office building in Sweden. Accordingly, 3 types of windows and 5 types of external wall, ground floor and external roof constructions were specified as optimization variables. The combination between the optimization variables generated 375 design alternatives. The performance of all 375 design alternatives were evaluated with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Later, AHP was used to find a trade-off design alternative. The results show that the combination between window type 1, external wall type 5, ground floor type 1 and external roof type 5 is the trade-off design alternative. Furthermore, the results show the integration enables to solve the abovementioned conflicts and to fulfil the EPBD's target.

Keywords

Building information modelling • Optimization • Analytical hierarchy process • Decision making

43.1 Introduction

The Energy Performance of Building Directive (EPBD) has determined a target as all new constructed buildings, within the EU region, must be near zero energy buildings by the end of 2020 [1]. In addition, the subsequent annex to the EPBD demands all European countries to ensure the minimum comfort threshold, defined at the national level, in the calculation of energy consumption [1]. In Sweden, office buildings gain a significant role in decreasing the total energy consumption. Because, office buildings, with a total area of 32.3 million square meter, make up the second greatest share among the non-residential buildings in Sweden [2]. Office buildings were responsible for about 6.25 TWh energy consumption[1] in 2016, which correspond to 32.5% of the total used energy within the non-residential building sector in Sweden [3].

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[1] Total energy consumption comprised the energy need for space heating, cooling, domestic hot water, electricity need for lighting, ventilation and office equipment.

E. Jalilzadehazhari
Linnaeus University, 39182 Växjö, Sweden
e-mail: Elaheh.jalilzadehazhari@lnu.se

P. Johansson (✉)
Jönköping University, 55318 Jönköping, Sweden
e-mail: peter.johansson@ju.se

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According to International Energy Agency [4] decreasing the energy consumption contributes to a gradually reduction in greenhouse gas emissions and provides a steading increase in economic growth.

In addition to energy consumption, indoor environment in office buildings have also a substantial role in presenting economic benefits [5, 6]. Because, improving indoor environment, especially visual and thermal comfort, contributes to a higher level of productivity and enhanced health [7, 8], which can provide further economic benefits in the lifecycle of office buildings [5, 6]. Therefore, building professionals are expected to concurrently reduce energy consumption and cost also improve visual and thermal comfort. Accomplishing this task requires a constructive communication between building professionals, including architects, energy experts and engineers from different specialties [9, 10]. At this point, the use of object-based parametric modelling or Building Information Modelling (BIM) provides possibilities for interoperability information sharing between prevalent simulation tools and thereby between building professionals [10]. Having constructive communications between professionals through the implementation of BIM not only helps to improve buildings performance, but also can significantly reduce the required time, effort and unpredicted errors in building design process [11]. At this point, Sakikhales and Stravoravdis [12] and Rahmani Asl et al. [10] discussed that benefits from the implementation of BIM can be complemented by integrating it with optimization. Because, the integration not only provides abovementioned benefits with using BIM but also it allows to use optimization to expands the set of design alternatives investigated [10]. Furthermore, the integration helps professionals to resolve the conflicts among at the most three design objectives, such as visual or thermal comfort, energy consumption and life cycle cost [13] and find a trade-off design alternative. Accordingly, the integration allows professionals to make suitable decisions in early stage of building design process [14].

But, at the presence of more than three objectives, the integration between BIM and optimization is incapable of resolving conflicts. At this point, Mosavi [15] discussed that a multi-criteria decision-making (MCDM) method can help to overcome the limitation in using optimization. The integration between BIM, optimization and a MCDM method allows (i) to generate and use a BIM model for establishing a constructive communication between professionals, (ii) to generate multiple design alternatives using optimization and (iii) to solve conflicts between more than three objectives and find a trade-off design alternative using a MCDM method and making suitable decisions. However, to the best of authors knowledge, the integration between BIM, optimization algorithm and a MCDM method was not previously employed to solve conflicts among visual comfort, thermal comfort, energy consumption and life cycle cost. Considering the mentioned need, this study aims to apply the abovementioned integration on an office building.

43.2 Methodology

The applied methodology for employing the abovementioned integration on the office building follows three main sections, including the generation of BIM model, preparing the BIM model for performing an optimization, and performing the optimization and using a MCDM method.

43.2.1 BIM

A BIM model of an office building was generated using Revit Autodesk tool. The office building was in Gothenburg municipality, Sweden. It had three heated floors above the ground with a total area of 2821.5 m^2. Each floor comprised offices, meeting and lecture rooms. The fourth floor, with a total area of 278 m^2, was an unheated area and equipped with heating, ventilation and air conditioning (HVAC) systems.

Revit provides possibilities to develop a model of a building and allows several professionals to access the model simultaneously, thereby improves communications between them and reduces unpredicted errors in the building design process [16]. The generated BIM model was then exported as a Green Building xml (gbxml) format file. The gbxml format helps to share building information between different simulation tools [16]. In this study, the gbxml file included information regarding the location and geometry of the office building, material specifications of building envelopes, heating, ventilation and air conditioning system, occupancy and operation schedules. The information, included in the gbxml model, were provided by several professionals, including architects, energy experts and engineers from different specialties.

43.2.2 Preparing the BIM Model for Performing an Optimization

The gbxml file was converted to EnergyPlus Input Data File (idf) using Design Builder simulation tool, version 5.0.3.007. Design Builder is a graphical user interface for EnergyPlus and allows to perform various evaluations considering visual comfort, thermal comfort, energy consumption and life cycle cost [17]. The office building was connected to district heating system, which provided energy need for space heating and domestic hot water. Furthermore, the office building was equipped with an exhaust ventilation with a heat recovery system. The efficiency of ventilation fan and the heat recovery was 60 and 76% respectively. The air tightness was 0.1 (ach) at differential pressure of ±50 (Pa). The occupants' activity level was set to 1.2 (met) and their clothing resistance was set to 0.5 (clo) in summer and 1 (clo) in winter [18]. A fluorescent electrical lighting with 9.9 (W/m^2) power was also considered in the simulations. The heat gain from electrical lighting was assumed to be around 82%. The building occupancy schedule during working days was set to be between 07:00 am to 18:00 pm.

Finally, the idf file was modified using EnergyPlus version 8.5.0. Various building envelopes, including 3 types of windows and 5 types of external wall, ground floor and external roof constructions were specified in idf file. This decision was made due to efficacy of building envelopes in improving visual comfort, thermal comfort and reducing energy consumption and life cycle cost. Table 43.1 shows the considered building envelopes in this study. The U-values of external wall, ground floor and roof constructions were changed by modifying the thickness of insulation layer within the construction of these building envelopes. The U-value of the building envelopes in Table 43.1 were equal or lower than the requirements of the Swedish building code for new buildings (BBR 2015) [19].

The visual comfort evaluations in this study comprised the calculation of daylight illuminance and daylight glare index. For this purpose, 3 reference points on the second floor and 4 reference points on the fourth floor were specified at 0.8 m from floor level (Appendix 1). This decision was made because the large glazing area in the second and third floor may deteriorate visual or thermal comfort. The visual comfort evaluations were performed by (i) obtaining the number of hours, when daylight illuminance at the reference points exceeded 500 lx and (ii) obtaining the number of hours, when daylight glare index at the reference points exceeded 22. The reflectance of interior surfaces including walls, ceiling and floor follows the Swedish standard [20] and was defined as 60, 80 and 20% respectively.

Thermal comfort, energy consumption and life cycle cost evaluations were accomplished by calculating predicted percentage of dissatisfied (PPD), total energy consumption (E_t) and present value (K_n) respectively. Total energy consumption comprised energy need for space heating, cooling, electricity for lighting and ventilation system. According to National board of housing building and planning [19], the total energy consumption in office buildings in Sweden should be at most 70 kWh/m^2. To calculate the present value, the investment cost of different windows, external wall, ground floor and external roof constructions were obtained using EnergyPlus. The investment cost refers to the material cost, used in external wall, ground floor and external roof constructions, which was derived from Wikells construction calculations [21]. The investment cost of windows was based on the unit price of each window multiplied by the total window area, that was collected from Elitfonster [22]. Table 43.2 shows the U-value and investment cost per 1 m^2 of 3 types of windows and 5 types of external wall, ground floor and external roof constructions.

43.2.3 Optimization and MCDM

An optimization is mainly performed to find an optimal design alternative by interacting optimization variables [23]. According to Uy and Telford [24], Design of Experiment (DOE) is a statistical technique, which allows to optimize the performance of a system with determined optimization variables. To perform DOE, EnergyPlus was coupled to modeFRONTIER platform. The modeFRONTIER platform enable to perform an optimization and allows to use a MCDM method to find a trade-off design alternative [25]. The coupling process was accomplished by writing a DOSBatch file.[2] DOSBatch file allows to run the EnergyPlus via modeFRONTIER.

Later, optimization variables and constraints were defined in modeFRONTIER platform. In this study, all building envelopes, stated in Table 43.1 were considered as optimization variables. The combination of 3 types of windows and 5

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[2] modeFRONTIER has various of nodes including logic nodes, data nodes, file nodes, application nodes, script nodes, CAD nodes, CAE nodes and networking nodes. Nodes are executable components, which have data and accomplish some transformations over the data, later forward the data to the next node [26]. DOSBatch node is one of the available script nodes.

Table 43.1 Considered building envelopes

	Building envelopes
Windows	Three types of glazing systems with U-value of 1.2, 1 and 0.9 W/K.m^2
External walls	Five types of external walls with U-value of 0.18, 0.14, 0.12, 0.1 and 0.09 W/K.m^2
Ground floor	Five types of ground floors with U-value of 0.15, 0.12, 0.1, 0.09 and 0.08 W/K.m^2
External roof	Five types of external roofs with U-value of 0.13, 0.12, 0.1, 0.09 and 0.08 W/K.m^2

Table 43.2 Different building envelopes

Building envelopes	U-value (W/K m^2)	Investment cost (SEK/m^2)[a]
Windows		
Type 1	1.2	3786
Type 2	1	4360
Type 3	0.9	5831
External walls		
Type 1	0.18	1403.6
Type 2	0.14	1433
Type 3	0.12	1505.7
Type 4	0.1	1530
Type 5	0.09	1599
Ground floor		
Type 1	0.15	589.5
Type 2	0.12	711.4
Type 3	0.1	758
Type 4	0.09	880
Type 5	0.08	956
External roof		
Type 1	0.13	389
Type 2	0.12	411
Type 3	0.1	426.2
Type 4	0.09	445.4
Type 5	0.08	463.4

[a] SEK: Swedish crowns

types of external wall, ground floor and roof constructions generated 375 design alternatives. The DOE allowed to analyze the performance of the all 375 design alternatives with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Furthermore, PPD less than 10 was considered as an optimization constraint. According to Pourshaghaghy and Omidvari [27], a PPD less than 10 represents a comfortable thermal environment.

Considering life cycle cost, investment cost of building envelopes and the energy consumption for space heating, cooling, electricity for lighting and ventilation system were obtained by EnergyPlus. The total investment cost of 3 types of windows and 5 types of external wall, ground floor and roof constructions were calculated based on total area of the building envelopes multiply the unit price of them, stated in Table 43.2.

Later, a calculator node in modeFRONTIER was used to calculate the present value of all 375 design alternatives using Eq. 43.1.

$$\begin{gathered} K_n = \sum_{t=0}^{n} (D_t + U_t) * \frac{1}{(1+r)^t} + I_0 \\ D_t = E * \alpha(1+\beta)^t \end{gathered} \tag{43.1}$$

where

K_n is present value during lifespan of n year;
U_t is annual maintenance cost;
D_t is annual energy consumption cost;
r is interest rate;
t is lifespan of n years;
E is annual energy consumption (kWh/m^2);
α is energy price per kWh/m^2;
β is inflation in energy price (%); and
I_0 is the investment cost.

In calculating the present value, a discount rate of 3%, an inflation rate of 1% and a lifetime of 30 years were considered. The heating and electricity energy price was set to be 0.74 (SEK7 kWh) and 1.38 (SEK/kWh) respectively [28]. Table 43.3 shows the lifetime of investigated windows, external wall, external roof and ground floor constructions and their maintenance cost.

Equation 43.2 shows the mathematical formulation of the optimization problem in this study.

$$\begin{gathered}\min_{x \subset X} F_1(x) = [H_{DGI>22}, E_t, K_n] \\ \text{and} \\ \max_{x \subset X} F_2(x) = [H_{illu>500}] \\ \text{Subject to: } PPD < 10\end{gathered} \tag{43.2}$$

where

$H_{DGI>22}$ represents the number of hours, when daylight glare index at the reference points exceeded 22;
$H_{ill>500}$ refers to the number of hours, when daylight illuminance at the reference points exceeded 500 lx;
E_t refers to the total energy need for space heating and electricity for lighting and artificial ventilation;
K_n represents the net present value of different window designs;
$PPD < 10$ refers to the predicted percentage of dissatisfied smaller than 10, which was considered as an optimization constraint.

The developed workflow in modeFRONTIER platform was illustrated in Appendix 2.

To find a trade-off design alternative among all 375 alternatives, Analytical Hierarchy Process (AHP), as a MCDM method, was employed using modeFRONTIER platform. AHP was used to find a design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost by using mode-FRONTIER platform. The first step in using AHP is to develop a hierarchy model, which comprises the goal of using AHP, objectives and their respective criteria [29].

Figure 43.1 shows the developed hierarchy model in this study.

Later pairwise comparisons, based on a scale of importance, presented in Table 43.4, were performed between objectives of AHP and their criteria [29].

Performing pairwise comparisons generates a comparison matrix. Matrix A shows the performed pairwise comparisons among the objectives in Fig. 43.1. The weight of each objective was calculated (i) by calculating the sum of each column in the matrix A; (ii) by dividing each value in the matrix to its respective column sum, calculated in previous step and (iii) by obtaining the average of each row.

Table 43.3 Lifetime and maintenance cost of building envelopes

Building envelopes	Lifetime (years)	Maintenance cost (SEK/m^2)
All 3 types of windows	30	0
All 5 types of external walls	30	0
All 5 types of ground floors	30	0
All 5 types of external roofs	30	0

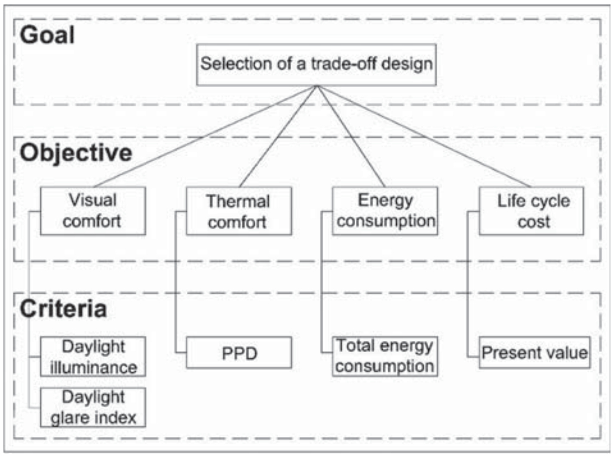

Fig. 43.1 An illustration of the developed hierarchy model

Table 43.4 Scale of importance applied in using AHP

Scale	Description
1	Two objectives/criteria are equally importance
3	Objective/criterion *i* is moderately more importance than the objective/criterion *j*
5	Objective/criterion *i* is strongly more importance than the objective/criterion *j*
7	Objective/criterion *i* is very strongly more importance than the objective/criterion *j*
9	Objective/criterion *i* is extremely more importance than the objective/criterion *j*

$$A = \begin{array}{lccccc} & \text{Visual comfort} & \text{Thermal comfort} & \text{Energy consumption} & \text{Life cycle cost} & \text{Weight} \\ \text{Visual comfort} & 1 & 2 & 7 & 7 & 0.52 \\ \text{Thermal comfort} & 1/2 & 1 & 7 & 7 & 0.36 \\ \text{Energy consumption} & 1/7 & 1/7 & 1 & 1 & 0.06 \\ \text{Life cycle cost} & 1/7 & 1/7 & 1 & 1 & 0.06 \end{array}$$

Matrix B shows the performed pairwise comparisons among visual comfort criteria. The weight of each criteria in matrix B was calculated following 3 abovementioned steps. Furthermore, the pairwise comparisons in matrix A and B follows the applied comparisons in the work presented by Jalilzadehazhari et al. [30].

$$B = \begin{array}{lccc} & \text{Daylight illuminance} & \text{Daylight glare index} & \text{Weight} \\ \text{Daylight illuminance} & 1 & 2 & 0.667 \\ \text{Daylight glare index} & 1/2 & 1 & 0.333 \end{array}$$

Considering thermal comfort, energy consumption and life cycle cost, since PPD, E_t and K_n were the only criteria, used for evaluating them, no pairwise comparisons were performed.

43.3 Results

Performing DOE allowed to analyze the performance of all 375 design alternatives with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Considering visual comfort criteria, the number of hours, when daylight illuminance exceeded 500 lx at 7 reference points was varied according Table 43.5.

Table 43.5 Variation in number of hours, when daylight illuminance exceeded 500 lx among 7 reference points

Reference points	Window type 1	Window type 2	Window type 3
	(h)	(h)	(h)
Second floor, point 1	1890.5	1722	1718
Second floor, point 2	1273	1076	1071
Second floor, point 3	3450	3362	3361
Third floor, point 1	1851	1684	1681.5
Third floor, point 2	1263	1082.5	1078
Third floor, point 3	1274.5	1140	1134.5
Third floor, point 4	1301	1207	1192

The daylight glare index was exceeded 22 on the second floor at point 2 and on the third floor at point 2 and 4. But, the daylight glare index was less than 22 at the other reference points during the full year. Table 43.6 shows the number of hours when daylight glare index was exceeded 22 with respect to 3 types of windows.

Considering thermal comfort, the PPD among the initial 375 design alternatives was changed between 6 and 13. As result, only 70% of design alternatives (262 of 375) had a PPD smaller than 10 and was considered as designs, which provided a comfortable thermal environment.

With respect to energy consumption, the E_t varied between 67 and 77 kWh/m^2. However, only 67% of the design alternatives (250 of 375) had a total energy consumption less than 70 kWh/m^2 and fulfilled the Swedish National board of housing building and planning [19] requirements. Considering life cycle cost, the K_n was changed between 8.4 million SEK and 9.5 million SEK.

In using AHP, only design alternative with a PPD less than 10 and E_t less than 70 kWh/m^2 were considered. This decision was made to ensure the minimum requirements considering thermal comfort and total energy consumption. Accordingly, AHP was applied on 250 design alternatives and remaining designs were excluded from the pairwise comparison process.

The results show that the combination between window type 1 with U-value of 1.2 (W/m^2. K), external wall type 5 with U-value of 0.09 (W/m^2. K), ground floor type 1 with U-value of 0.15 (W/m^2. K) and external roof type 5 with U-value of 0.08 (W/m^2. K) is the best design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost. Considering visual comfort, the window type 1 provided a larger amount of daylight into the interior environments. Since visual comfort was specified as the most important objective, the abovementioned design alternative with window type 1 was selected as the trade-off design. Considering thermal comfort, including or excluding PPD into the pairwise comparison had no effect on the results, because all 250 design alternatives had a PPD less than 10. With respect to energy consumption, the E_t of the trade-off design alternative was 67.3 kWh/m^2. External walls with a total area of 1872.3 m^2 shared the largest building envelop among the other building envelopes. Accordingly, external wall type 5 enabled to reduce the total energy consumption significantly.

The external roof and the ground floor had an identical area. However, the temperature difference between inside and outside of the external roof was larger than the temperature difference between inside and outside of the ground floor. Accordingly, the external roof type 5 could notably reduce the total energy consumption.

With respect to the life cycle cost, the K_n of the trade-off design alternative was 9.2 million SEK. About 80% of the investigated design alternatives (250 of 375) had a K_n smaller than the trade-off design alternative.

Table 43.6 Variation in number of hours, when daylight glare index exceeded 22

Reference points	Window type 1	Window type 2	Window type 3
	(h)	(h)	(h)
Second floor, point 2	2164	2010.5	2010.5
Third floor, point 2	2187	2045	2045
Third floor, point 4	1898	1729.5	1729.5

43.4 Conclusions

European Energy Performance of Building Directive (EPBD) demands all new constructed buildings, within the EU region, to be near zero energy buildings by the end of 2020. Furthermore, EPBD asked all European countries to ensure the minimum comfort threshold, defined at the national level, while calculating the total energy consumption. According to International Energy Agency, reducing energy consumption can contribute in economic growth at the national level. In line with abovementioned statements, improving indoor environment comfort, including visual and thermal comfort, can also provide economic benefits by enhancing occupants' health and productivity. At this point, building professionals are expected to reduce energy consumption and cost also improve visual and thermal comfort simultaneously. However, the main problem is the existence of conflicts between visual comfort, thermal comfort, energy consumption and life cycle cost. To overcome the abovementioned problem, this study aimed to apply an integration between building information modelling, optimization and a multi-criteria decision-making method on an office building in Sweden. Because, the integration allows (i) to establish a constructive communication between professionals for reducing unpredicted errors in the building design process, (ii) to generate multiple design alternatives and (iii) to find a design alternative based on trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost.

The office building model was generated using Revit Autodesk and exported as a gbxml format. Later, the gbxml file was converted to EnergyPlus idf file, using Design Builder simulation tool. Then, the idf file was modified in EnergyPlus to be used during the optimization process. In this study, the optimization was performed by running DOE technique in modeFRONTIER platform. The optimization variables comprised 3 types of windows and 5 types of external wall, external roof and floor constructions with different U-values. The combination between the optimization variables generated 375 design alternatives. Later, AHP method was used in modeFRONTIER to find a design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost. The results show that the combination between window with a U-value of 1.2 (W/m^2. K), external wall with a U-value of 0.09 (W/m^2. K), ground floor with a U-value of 0.15 (W/m^2. K) and external roof with a U-value of 0.08 (W/m^2. K) is the trade-off design alternative. The total energy consumption and present value (representing life cycle cost) of the trade-off alternative were 67.3 kWh/m^2 and 9.2 million SEK respectively.

Currently, making decisions based on the life cycle cost of various design alternatives is prevalent in Sweden. Because, present value not only considers the energy cost during the lifetime of a building but also takes the investment and maintenance costs into the account. At this point, the design alternative with 8.4 million SEK, corresponding the lowest present value, could be considered as a remarkable design alternative. However, the applied method is this study took one step further, as it integrated BIM, DOE and AHP and selected a design alternative based on trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost. Furthermore, the applied method enabled to fulfil the EPBD's target.

However, the result was strongly dependent on the pairwise comparisons, performed between objectives of AHP and their respective criteria. The applied methodology in this study, based on integration between BIM, optimization and a MCDM method, can be applied both in designing new buildings or retrofitting existing buildings.

The future work includes the expansion of the optimization variables, as various heating, cooling and air conditioning systems together with different window size and forms will be considered in the application of the integration. Furthermore, the sensitivity of the results considering changes in pairwise comparisons, will be analyzed.

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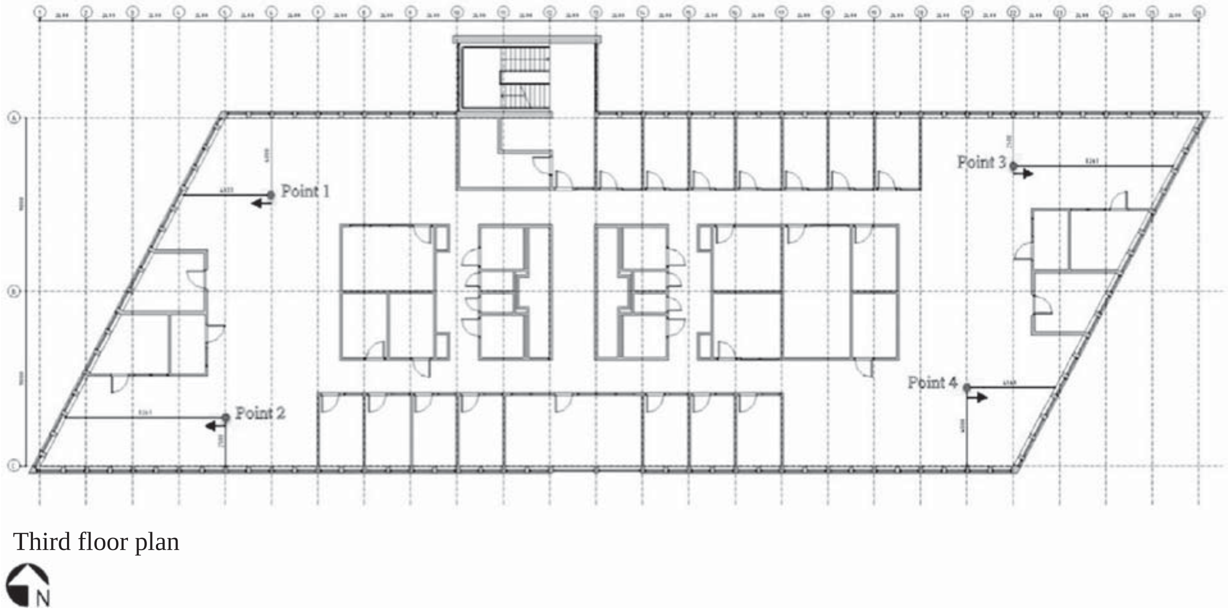
Appendix 1

First floor plan

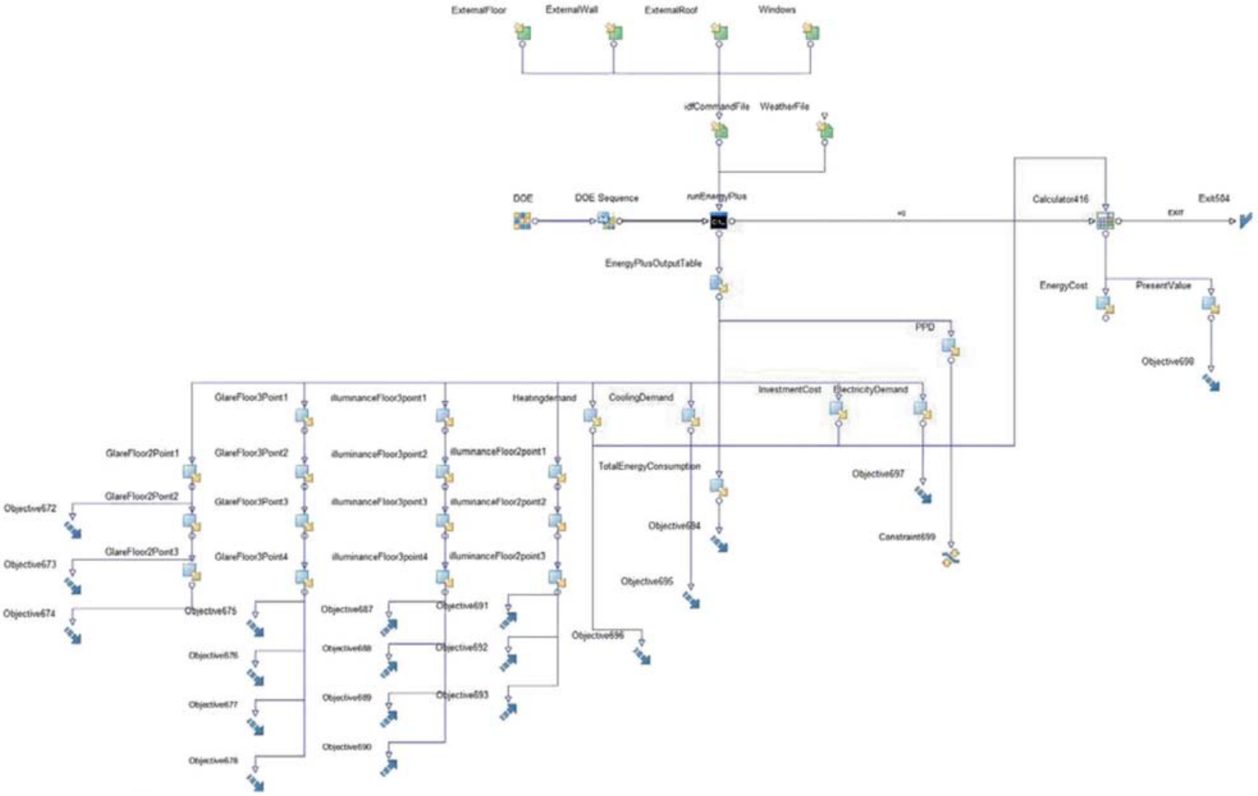
N

Second floor plan

N


Point 1
Point 2
Point 3
Point 4
Third floor plan
N

Appendix 2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Windows
idfCommandFile
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DOE
DOE Sequence
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Calculator416
EXIT
Exit504
EnergyPlusOutputTable
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PresentValue
PPD
Objective698
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illuminanceFloor3point1
Heatingdemand
CoolingDemand
InvestmentCost
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