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REVIEW

Early Stage Design Workflow for High Energy Performance Multi-storey Residential Buildings

Caroline Hachem*   Robert Beckett

Faculty of Environmental Design, University of Calgary, Calgary, T2N 1N4, Canada.

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ABSTRACT

This paper presents a methodology to optimize building envelope energy performance for multi-storey residential buildings using a design performance model approach. Five analysis techniques, applied to a database of parametric simulation results, are proposed to derive information on various building performance features that can support early design decisions. Information may include optimal combination of design parameter values to achieve lowest energy consumption, or the relative impact of design parameters on a given design, such as a base case. A workflow template is established to provide support for the design process of energy efficient multi-storey residential buildings. This template can form a basis for the development of an interactive tool that integrates energy performance principles into early stage design decisions. The application of this methodology to a building in Vancouver (BC, Canada, 49°N) is presented as a case study. Results of this application demonstrates that adopting a specific combination of building envelope parameters, thermal load can be reduced by up to 85% as compared to a base case designed according to commonly built apartment buildings in the studied location.

1. Introduction

The achievement of a highly energy efficient buildings, which aim at minimizing negative environmental impact, requires implementing energy efficiency principles at early design stages, with particular attention to envelope design [1,2]. Building envelope design plays a significant role in the energy performance of multi-storey buildings, both residential and commercial. Increasing the efficiency of building envelope, coupled with improved climate control technologies, is considered as one of the main design strategies in achieving highly sustainable buildings [3,4,5]. Moreover, the design of building envelope can be manipulated to increase the potential of buildings to generate renewable solar energy [6,7].

**Corresponding Author:*
Caroline Hachem,
Faculty of Environmental Design,
University of Calgary, Calgary, T2N 1N4, Canada;
E-mail: caroline.hachem@ucalgary.ca.

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Building simulation tools that allow flexibility in design, combined with feedback on energy performance, can be instrumental in exploring design solutions and their impact on building performance. Implementation of design performance models (DPM) is a convenient strategy for optimizing building envelope for energy performance at early design stages, allowing flexibility and ease of application in responding to design changes [8]

Several researchers have attempted to develop tools to facilitate the design and energy performance analysis of buildings, both in new buildings and for retrofit purposes. Ochoa and Capeluto [9] propose an interactive tool, based on the EnergyPlus simulation software, to provide alternative facade design configurations to support decision making during the early design stages of homes in hot climates. Alternative facade design scenarios are provided based on geographical location, building orientation, occupancy type, degree of automation, natural lighting, contextual setting, and building depth.

Attia et al. [10] propose an interactive tool, ZEBO, which employs a DPM approach to provide support for early design decisions based on building envelope parameters including orientation, shape, window size/type, wall/roof insulation, and passive solar shading controls. Hemsath [11] discusses the importance of using building performance simulations to inform decisions during the early stages of design for buildings. Conceptual design elements include building orientation, geometry/shape, envelope material/thermal resistance, window to wall ratio (WWR), shading, thermal mass, renewable energy, infiltration, and others.

The parameters that need to be considered in modelling buildings' energy performance in a given geographic location vary according to, the type of building, the stage of design and its complexity and the objectives to be achieved. A large body of research discusses various parameters implemented in the simulation of energy performance, methods of modelling of buildings, and different methods of performance analysis. Yıldız, and Arsan [12] employ sensitivity analysis to identify building parameters that influence thermal energy loads of apartment buildings in hot-humid climates, including design parameters such as window size, indoor space height, and features of materials. Samuelson et al. [13] employ an exhaustive parametric method to calculate all possible combinations of a discrete set of building envelope parameters, including WWR, glass type, building orientation, building shape and wall insulation. Echenagucia et al [14] employ genetic algorithm optimization to minimize the energy need of a 5-story office building for heating, cooling and lighting, by varying building envelope design parameters. These parameters include thickness of the masonry walls, number, position and shape of the windows and the type of windows.

Statistical methods are employed to obtain information related to the impact of various design parameters on performance. Hygh et al. [15] use a Monte Carlo algorithm and EnergyPlus simulations to develop a multivariate linear regression model based on a large number of design parameters for a rectangular office building. Standardized regression coefficients are calculated to show the relative impact of each of the input parameters on heating, cooling, and total energy loads. Tian [16] discusses a variety of sensitivity analysis methods that are applicable to building energy analysis.

While a rich literature exists on optimizing energy performance of buildings of specific configurations and environments[17,18], the objective of this paper is to present a generalized methodology to optimize building envelope energy performance of multi-storey buildings during the early design stage, while providing flexibility in setting design parameters. Despite the fact that the proposed methodology is developed with residential buildings in mind, it can be extended to include other types of buildings, including multifunctional. .

The proposed methodology includes five modelling analysis techniques that can be employed to analyse the output of exhaustive parametric study of building envelope design parameters. A simplified flow-chart is provided to illustrate the main stages of this methodology and the potential of each of these techniques to provide specific information to support design decisions.

A case study of a residential building in Vancouver (BC, Canada, 49°N) serves to illustrate the application of the methodology in a specific design.

2. Methodology and Simulations

The methodology presented in this paper consists of the following stages. First, a base model is developed at the suite level to represent typical multi-storey residential buildings in the relevant location (Vancouver, Canada in the case study). Next, a parametric study is designed to investigate the effects of selected building envelope parameters on energy performance. Finally, the output of the parametric study is analysed using design performance modelling techniques.

2.1 Parametric Study

An extensive parametric study is developed to investigate parameters associated with the building envelope expected to influence energy performance. Each of the parameters is incremented at discrete input intervals over a range of values expected to be valid for the considered design and combinations of parameters are simulated to measure the predefined energy performance. Once every combination

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of the parameter values has been evaluated, a database of response variables corresponding to all parameter combinations is created to serve as a base for further analysis. The simulations are performed separately for each residential unit of the base model, in order to account for differing climatic effects on energy performance of units of differing positions and orientations. The following sections summarize the simulation software utilized in this research, details of the parametric workflow, definitions of design parameters, and the response variables that are included in the analysis.

2.1.1 Simulations

EnergyPlus v8.5 is selected to conduct all building design simulations. These simulations aim at determining the annual thermal energy required for heating and cooling of the studied apartments, as well as the electric load for appliances and equipment, and the PV electricity generation potential. The weather file for the studied region (Vancouver, Canada in the case study – section 3, [19]) is employed in the simulations. The parametric study is conducted following the methodology of software package jePlus [20], where discrete values are assigned to variables defined in an EnergyPlus input data file. EnergyPlus simulations are performed for each combination of the input parameter values to build a database of annual energy performance associated with each of the residential suites.

This approach allows a full set of results to be computed without reference to order of precedence of parameters. There is, however, a practical limit to the number of simulations that can be included in the study, based on software and data processing resources. This limitation needs to be considered when selecting ranges and intervals of parameter values.

In the proposed modelling, residential suites are simulated individually, assuming that only the exterior wall interacts with the outside environment. All interior walls, floors, and ceilings are set to 'adiabatic', implying no heat transfer through these surfaces. This assumption reflects the scenario where the suite is mid-level in the building, and has neighbouring suites with similar temperature settings.

2.1.2 Input Parameters and Response Variables

Input parameters are selected, based on their anticipated influence on energy performance, as identified by large body of research [1,17,18,21]. The nature, and particularly values of parameters, depend on the climatic region considered. While the ten parameters considered in this investigation (see case study, section 3) are selected with northern climate in mind, primary parameters, such as wall insulation, thermal mass represented by a concrete slab, glazing size and properties, are expected to feature in the majority of climatic conditions, albeit at varying ranges of viable values. The increment of values for each parameter is set to provide sufficient data to define a trend, while keeping the overall number of simulations to a manageable number (due to software limitations, as mentioned above).

Typical response variables employed to indicate the performance of various building envelope designs are heating and cooling loads, heating and cooling energy consumption, electrical loads (including lighting, domestic hot water, and appliances), and, optionally, photovoltaic electricity generation potential. Heating and cooling loads account for various heat transfer mechanisms through the building envelope, solar heat gain and various internal heat gain sources (e.g. people, lights and appliances). Heating and cooling energy is based on heating and cooling loads, but may be modified by climate control devices, such as a heat pump. PV potential represents the amount of energy generated by photovoltaic cells integrated into the opaque surfaces of exterior façade surfaces, as well as the upper surface of window overhangs (when available).

The results from each simulation have a unique pattern of heating and cooling loads (and PV potential), depending on the geometry and materials used in the design. It is important to keep in mind that heat gain or loss can be either beneficial or costly depending on the need for heating or cooling. For example, solar heat gain can be beneficial to supplement mechanical heating during the winter, but can contribute to overheating of the suite during the summer. Similarly, the heat gains from internal loads (occupants, lighting, and equipment) can be a benefit or a cost depending on the interior temperature balance.

2.2 Design Performance Modelling Analysis Techniques

The American Institute of Architects (AIA) distinguishes two concepts for evaluating energy related design: design performance modelling (DPM) and building energy modelling (BEM) ([8]. Whereas a BEM is designed to reflect the detailed geometry and materials for a building to ensure compliance with energy codes and targets, DPM is a less complex and time-consuming procedure to evaluate energy use at the design stage before the building is finalized. The methodology employed in this study follows the concept of DPM by generalizing basic envelope parameters to allow designers to get rapid feedback on various configurations of envelope components without expending the effort to build a detailed energy model. EnergyPlus simulations are primarily based on forward modelling [22], and it supports both BEM and DPM approaches.

In this section, five data analysis techniques are pre-

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sented to analyse data created by the parametric simulation. These methods include reduction, extreme scenarios, sensitivity analysis, trend analysis and optimization. Trend analysis was employed by RDH Building Engineering [23] to optimize a base model for a typical multi-storey residential building in Vancouver. The sensitivity analysis technique is a statistical method applied by Hygh et al [15] to prioritize the significance of input variables. Extreme scenarios were introduced for an exhaustive parametric study by Samuelson et al[13]. The Reduction and optimization techniques are proposed in this research to explore the full population of simulation results created in the parametric study. Any combination of these analysis techniques can be employed in a given design based on design priorities.

2.2.1 Reduction

The reduction technique allows the user to set a performance threshold to remove design options that do not achieve the desired performance level. Some values of envelope parameters are complementary, while others are in conflict, resulting in poor energy performance. For example, designs that combine large windows, high solar heat gain coefficient (SHGC), and no solar shading controls are conducive to high cooling loads. On the other hand, designs that combine high infiltration rates, large windows, low U- values, and low wall insulation values have high heating loads. The worst performing designs combine parameters that result in high heating and cooling loads.

This analysis technique is proposed to allow users to filter out design options based on a threshold of energy performance. Using the results from all simulations in the parametric study, and a threshold setting for one or more response variables, a subset of the available design options is removed from consideration. In some instances, a design parameter will only be available when combined with certain elements. For example, if larger windows are desired, it may be necessary to include shading overhangs and low SHGC glazing in order to minimize cooling load requirements.

2.2.2 Extreme Scenarios

This technique, which is, in fact, a simplified optimization technique, queries the simulation database for extreme scenarios based on a selected metric. Examples of extreme scenarios include lowest net energy, lowest heating load, lowest combined heating and cooling load, and highest PV generation. Since the parametric study is conducted at the suite level, it is possible to query the database for scenarios where all suites have the same parameter values, as well as scenarios where heterogeneous designs among various suites are allowed. For example, the optimal windows to minimize net energy for the suites on the south orientation may differ from the north-oriented suites.

This DPM technique is a quick method to identify combinations of envelope parameters which yield the best outcome for a specific metric. When combined with the optimization technique, discussed in section 2.2.5 below, the designer can for instance start with an extreme scenario and make incremental changes until an acceptable balance between energy performance and other design requirements is achieved.

2.2.3 Sensitivity Analysis

Sensitivity analysis allows to recognise the most significant parameters, which affect building performance and, thus to concentrate design and optimization of buildings on these parameters [24]. Standardized regression coefficients (SRCs) are calculated to indicate the relative impact that input variables have on a selected output metric [25]. Hygh et al.[15] calculated SRCs to investigate the sensitivity of input variable changes on heating and cooling loads for a commercial office building. Calculating SRCs for a given scenario provides valuable context to prioritize design decisions based on maximizing impact. For example, if during the design process, limitations exist to select a number of design element of the building envelope to optimize energy performance while responding to budget constraints, this technique allows selection of the most impactful design parameters to adopt.

While sensitivity analysis is initially applied to the base case design, it can be re-calculated to analyse a subset of the data that remains after employing one of the other techniques listed in this section. For example, the designer may want to know which input variables will be most influential at reducing the heating load of a design with 80% WWR. The results of the analysis of this subset of data may vary significantly from the original scenario.

Once the most important variables are identified, the designer will need to know whether there are trade-offs or synergies associated with them. This analysis is discussed below.

2.2.4 Trend Analysis

A significant aspect of design performance modelling is to delineate the relationships between input and response variables for various design scenarios. Trends that are observed when altering the base model may not be consistent with trends that are observed for alternative starting points for the conceptual design. For example, if the design is constrained to have high WWR and low wall insulation, the relationships between the remaining input variables and results can vary significantly from the base model trends.

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Using the full set of results from the parametric study, or a subset of results defined by one of the other analysis techniques, trends can be investigated between the input and output variables. Plotting multiple input variables against a response variable can identify trade-offs or synergies that exist. For example, WWR and overhangs both affect the thermal loads of a building. As WWR increases, so does the heating load due to the relatively higher conductive heat losses through the glazed area. Also, as WWR is increased, the opaque area available to integrate solar technologies (if this is part of the design considerations) is reduced, limiting the capacity for renewable energy generation. As window overhangs are increased in length, cooling loads are decreased due to the reduction of unwanted solar heat gains, and available opaque area for potential integration of photovoltaic cells is increased. By combining these two input parameters in a trend analysis, the overall effect of these parameters on net energy consumption can be evaluated for a given design scenario.

This DPM analysis technique can be focussed by filtering the population of simulations to explore incremental changes to a specific design, or can be broadened by averaging a range of parameter values. It can be employed to showcase the interdependent nature of various design options. For example, the effect of changes in WWR, regardless of the window type, can be investigated by averaging the range of results for all values of U-value and SHGC.

2.2.5 Optimization

Optimization is defined, in the general sense, as a procedure minimizing or maximising the value of a parameter, subject to prescribed constraints. In the present context the parameters being optimised are energy performance parameters, in terms of selected response variables. Since all combinations of the input parameters are simulated in the parametric analysis and values of the response variables are stored in the data base, any design scenario that combines parameter values under given constraints can be investigated. The simplified optimization technique referred to under Extreme Scenarios (section 2.2.2), consists of selecting design parameter combinations that optimize selected response variables, such as minimizing total energy consumption or net energy consumption. The extreme scenario technique, which considers all parameter combinations in the data base can be modified to account for specific constraints applied to selected design parameter values, such as requiring a fixed value or a limited range of values. For instance, a minimal WWR or daylighting values may be prescribed for aesthetic and comfort considerations. However, the constraints may be more complex than specifying values to certain parameters. For instance, limiting costs involves a wide range of parameters and determining the values of the main parameters that govern cost is a more rigorous procedure than the extreme scenario. This procedure, that involves incremental changes to input parameters, is illustrated in the case study presented below.

2.3. Interactive Workflow template for Design Performance Modelling

Although design is an iterative process, energy performance characteristics of the building envelope are often determined during the conceptual design stages [8]. Design performance models (DPM) offer a direct, flexible approach to evaluating the energy performance at early stage building designs. The five design performance modelling techniques discussed above can be integrated into an interactive template of modelling workflow, to provide support for the design of multi-storey residential buildings. Figure 1 is a representation of the workflow template proposed in this paper. This template has the potential of being developed into an interactive tool for early design stage of energy efficient buildings.

The workflow consists of two phases. Phase 1 includes the construction of the base model and parametric simulation of energy performance of each unit to generate a data base of energy performance. Phase 2 involves the five data analysis techniques discussed above.

Stage 1 starts with input of the "background information" including location of the building , followed by geometric data and then followed by the parametric energy performance simulations and compilation of the database of response variables of all envelope parameter combinations (on individual unit basis). Stage 2 starts with reduction and the other analysis techniques, which produce as output the parameter levels and response variable values of the resulting design. Reduction technique is used to exclude all results that do not meet minimum energy efficiency requirements. An examination of the lowest net energy extreme case is presented to provide context around the range of possible outcomes. A sensitivity analysis indicates the parameters manipulation of which has the biggest impact on outcomes. Trend analysis is presented to showcase the interdependent nature of some of the design options. Optimization technique enables obtaining optimal set of parameter values that maintain specific constraints, such as relating to non-technical aspects like aesthetics, comfort etc.

An illustration of the implementation of the workflow template for design performance modelling of a residential building in Vancouver, Canada is presented in section 3.3 below.

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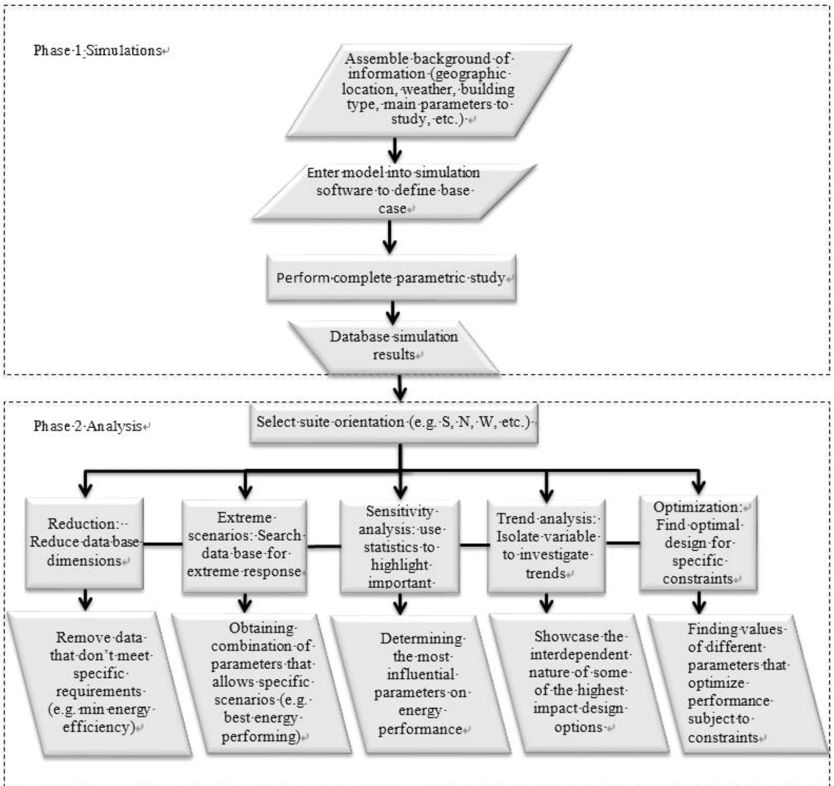

Figure 1. Design performance modelling workflow template

3. Case Study

In this section the methodology outlined in section 2 is applied to a residential building in Vancouver, Canada (49^{o}N). The presentation of the analysis and design procedures follow the general layout of section 2.

3.1 Base Case

The geometry of the residential suites that make up a sample floor plan is shown in Figure 2. This floor is assumed to be located in the mid-section of a 12-story building. Each suite has the same floor area of 90m^2, with full width windows on each exposed façade. Consequently, the corner suites on the SW, SE, NW, and NE have double the glazed area as the single-façade suites on the S, E, W, and N sides of the building. The central area, labelled 'C', is the common area that contains the corridors and service core of the building. This area is not included in the current study for the sake of simplicity.

The base case is designed to represent the existing multi-storey residential buildings in the Vancouver area built over the last 40 years, which is still representative of the majority of the existing building stocks. This base case is employed as a reference against which energy performance associated with building envelope improvements are measured. Table 1 shows the parameters adopted to represent the base case for the current study, together with the source for each parameter. Representative parameters for existing building stock are based on an analysis by RDH Building Engineering Ltd [23]. Data from Canadian Mortgage and Housing Corporation (CMHC)[26] is used

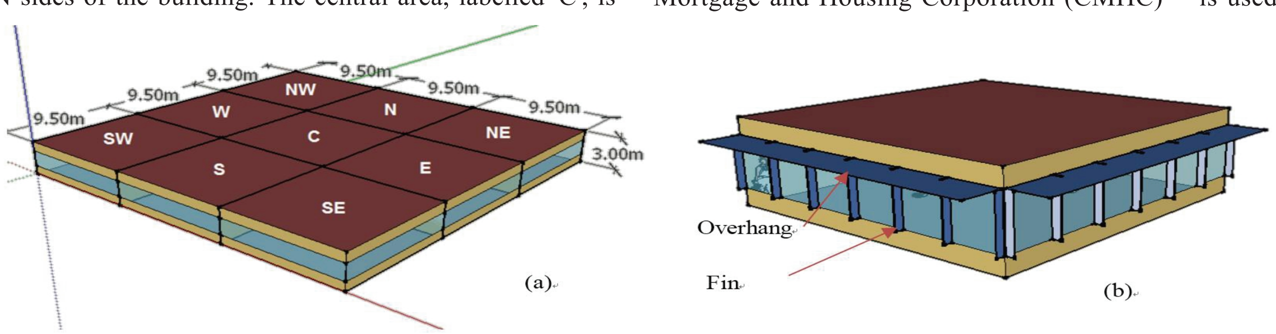

Figure 2. (a) Geometry of the eight unique suites of a story of the base case, and common area 'C'; (b) Illustration of the use of overhang and fins in the simulations.

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Table 1. Base case parameter values

Parameter	Value	Units	Source
Plug Load	5.6	W/m^2	RDH, 2012
Suite Lighting Load	8.7	W/m^2	RDH, 2012
Infiltration Rate	0.572	ACH	RDH, 2012
Ventilation Rate	0.35	ACH	ASHRAE 62.1
Temperature Setpoint (day)	22	°C	RDH, 2012
Temperature Setback (night)	18	°C	RDH, 2012
People Load	1.9	Persons per suite	CMHC, 2013
Suite Area	90.67	m^2	RDH, 2012
Window to Wall Ratio	46	%	RDH, 2012
Overall Wall R-value	0.63	m^2K/W	RDH, 2012
Overall Window U-value	3.97	W/m^2K	RDH, 2012
Window SHGC	0.67	dimensionless	RDH, 2012
Storey Height	3	m	Modified from RDH, 2012
Occupancy Schedule		fractional	NRCAN, 2011
Suite Lighting Schedule		fractional	NRCAN, 2011
Plug Load Schedule		fractional	NRCAN, 2011
Weather Data	Vancouver	.epw file	U.S. Department of Energy, 2016
Photovoltaic Cell Efficiency	12	percent	Installed in all opaque areas

for occupancy levels, ASHRAE 62.1 is referenced for the ventilation rate, and the schedules from the National Energy Code (2011) for Buildings [27] are used for all cases.

PV panels are assumed to cover all opaque areas (excluding the north facades), including overhangs when applied. A 12% PV efficiency is assumed in the simulations (using EnergyPlus). The study assumes all-electric scenarios, to allow valid comparison of PV electricity generation potential of the residential units, to their total electricity consumption.

3.2 Parametric Study

3.2.1 Input parameters and Response Variables

Parameters identified, with the objective of optimizing the performance of the base case, are listed in Table 2, with the discrete values that are substituted in the simulations. Parameters include wall insulation, thermal mass, represented by a concrete slab, infiltration rates, shading overhangs (presented as the ratio of overhang width to the height of the window), window fins (measured as ratio of the fin width to the window width) (see Fig 2), internal blinds, window U-value and solar heat gain coefficient (SHGC), window to wall ratio (WWR), ventilation heat recovery, and façade orientation. Although concrete slab and ventilation heat recovery are not associated with the envelope design of the building, they constitute important factors in designing energy efficiency, when considering passive solar gains capture and energy transfer mechanisms. The number of values for each parameter are set to provide sufficient data to define a trend, while keeping the overall number of simulations manageable.

The window U-value/SHGC values shown in Table 2 correspond to the window assemblies presented in Table 3. The base case window (see Table 1) is representative of the existing multi-story residential building stock in the Vancouver area [23]. The NECB 2011 minimum window is the prescribed U-value under NECB 2011 8 with an assumed solar heat gain coefficient (SHGC) and visible transmittance (VT) based on the triple, low-e, high SHGC, argon filled window.

The main response variables employed to indicate the performance of various building envelope designs are heating and cooling loads, heating and cooling energy consumption, electrical loads, and potential photovoltaic electricity generation assuming BIPV installed on all opaque surfaces and overhangs of east, south and west facades. Net energy is calculated for each suite based on the heating energy, cooling energy, electrical loads, and PV potential using the following formula:

Net Energy=Heating+Cooling+Lighting+Equipment+Hot Water-PV

Heating and cooling energy is calculated assuming

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Table 2. Envelope parameters and values considered in this research

Parameters	Units	Values							
Wall RSI	m^2K/W	1.76	3.6	6.2	8.8				
Thermal Mass		10cm slab with carpet	10cm slab	20cm slab					
Infiltration	ACH	0.03	0.09	0.27	0.57				
Overhang/Window Ratio	%	0	33	66	100				
Fin/Window Ratio	%	0	16	48	100				
Window U-value/SHGC	W/m^2K	0.77 / 0.41	1.08 / 0.18	1.14 / 0.41	2.2 / 0.41	3.57 / 0.26	3.63 / 0.38		
Window/Wall Ratio	%	20	40	60	80				
Internal Blinds		zone > cooling SetPoint	Always Off						
Heat Recovery	% Sensible	0	65	85					
Façade Orientation		SW	S	SE	W	E	NW	N	NE

Table 3. Window assemblies used for the base case and parametric study [28]

Assembly	Frame	U-Value	SHGC	VT
Base case window (RDH 2012)		3.97	0.67	0.7
Double, low-e, high SHGC, argon filled	Aluminium	3.63	0.38	0.61
Double, low-e, low-SHGC, argon filled	Aluminium	3.57	0.26	0.49
NECB 2011 minimum U-value window (NRCAN 2011)		2.2	0.41	0.50
Triple, low-e, high SHGC, argon filled	Improved non-metal	1.14	0.41	0.5
Triple, low-e, low SHGC, argon filled	Improved non-metal	1.08	0.18	0.37
Quadruple, low-e, high, SHGC, krypton filled	Improved Non-metal	0.77	0.41	0.36

that a heat pump with Coefficient of Performance (COP) of 4.0 is used to deliver heating and cooling to the suites. Electrical loads are associated with lighting and electrical equipment, excluding the heat pump. Energy requirements for lighting and equipment are based on NECB 2011[27], and domestic hot water requirements are set to 2.62 KWh/occupant/day[29]. Assuming an average occupancy of 1.9 people per suite[26] the energy required for domestic hot water (DHW) is 1817 KWh/year/suite. The energy requirements for the common areas (i.e.: corridor heating and lighting) and centralized services (i.e.: elevators, lobby) and the solar energy generation from the roof of the building are not included in the calculation.

3.3 Design Performance Modelling

This section details the application of the workflow template for design performance modelling (DPM) as outlined in Figure 1. The analysis techniques employed in the performance modelling in this case study are carried out primarily through Excel spreadsheet processing of the database generated by EnergyPlus simulations.

3.3.1 Sample Case

The example presented below represents an updated scenario of the base case corresponding to NECB 2011 minimum requirements (Tables 2, 3). A PV system, which is not included in the minimum requirements, is assumed. Figure 3 shows the total heating energy, cooling energy, PV potential, and electrical loads for this energy code scenario for the eight-suite floor plate. The Ratio of energy generation to total consumption for all eight suites reaches 26%.

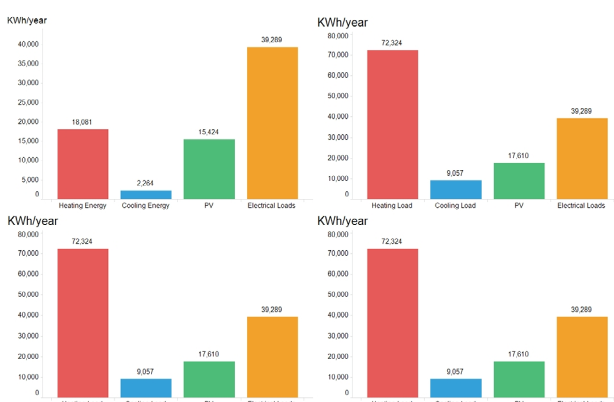

Figure 3. Sample case heating, cooling, PV, and electrical loads for the eight suite floor plate

At this point, the optimization technique (presented in detail below) can be used to explore the effects of modifying individual input parameters. However, for this case study, the reduction technique is used first to limit the field of

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possibilities to exclude any options that do not meet the minimum energy performance required by the energy code.

3.3.2 Reduction

In this stage of the workflow, design options that do not achieve the minimum standard set out in NECB 2011 are removed from the analysis. Figure 4 shows the range of combined heating and cooling loads for each of the eight suite locations for varying levels of WWR. The dotted line shows the minimum standard associated with NECB 2011 for each suite. Any simulations that have combined heating and cooling loads above the line are excluded from further analysis steps. Although the minimum standard for NECB 2011 can be achieved with any WWR from 20% to 80%, there are many combinations of input parameters that do not make the cut. For example, designs that combine large windows, low U values, low wall RSI, high infiltration rates, and no solar shading controls fail to achieve the minimum energy efficiency levels dictated by NECB 2011.

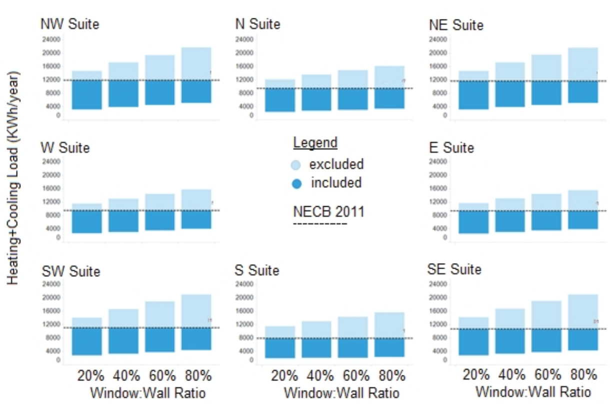

Figure 4. Range of combined heating and cooling loads for various windows to wall ratios by suite orientation

As performance requirement is set to stricter levels to achieve standards set by building certification programs, lower performing design parameters can be further eliminated from the list of acceptable combinations.

3.3.3 Extreme Scenarios

As mentioned in Section 2.2.2, this is a simplified optimization technique consisting of scanning the (reduced) data base for parameter combination that optimize a selected response variable, in the present example net energy consumption. Table 4 shows the parameters that combine to give the lowest net energy consumption for each of the eight suites.

The envelope parameter values for the eight suite types are uniform, except for the window type and shading control parameters. The N suite has a zero shading overhang and fin length with a relatively high SHGC window type (SHGC=.41) and automated blinds. E and W suites have no shading fins, 100% window overhangs, U-value/SHGC of 1.08/0.18 and no shading blinds. The remaining suites (NW, NE, SW, SE, S) have no shading fins, 100% window overhangs, U-value/SHGC of 0.77/0.18, and automated blinds. These differences highlight the benefit of non-uniform designs that optimize each face separately.

Figure 5 shows the detailed response variables related to heat gain and heat loss for each of the eight suites for the lowest net energy scenario. Heat gains and losses translate into heating and cooling loads only when the suite temperature crosses either the heating or cooling set-point.

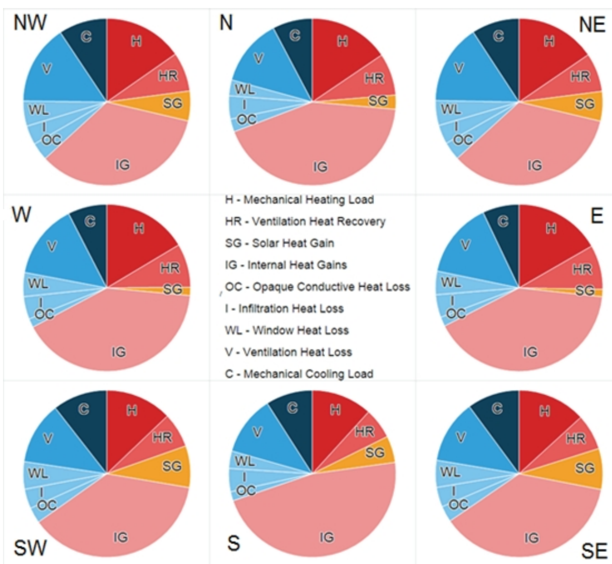

Figure 5. Response variables for lowest net energy scenario (heat losses in blues, heat gains in reds/orange)

Each of the heat loss categories (ventilation, window

Table 4. Parameters for lowest net energy scenario

Suite	Wall (RSI)	Thermal Mass	Infiltration (ACH)	Fin/Window	Overhang/ Window	Window U-value (W/m2K)	Window SHGC	WWR	Heat Recovery	Blinds
N	8.8	20cm Slab	0.03	75%	0%	0.77	0.41	20%	85%	On When Zone >= Cooling SP
E, W	8.8	20cm Slab	0.03	0%	100%	1.08	0.18	20%	85%	Always Off
NW, NE, SW, SE, S	8.8	20cm Slab	0.03	0%	100%	0.77	0.41	20%	85%	On When Zone >= Cooling SP

losses, infiltration, and opaque conductive losses) have been minimized in this scenario due to the selection of small, high quality windows, a high level of airtightness, good wall insulation, and ventilation heat recovery. The amount of solar heat gain is optimized to offset heating loads in winter, while avoiding unwanted heat during summer. The corner suites have higher solar heat gains due to the double glazed area compared to the N, E, S, W suites. Internal heat gains (lighting, occupants, and equipment) are the same for all suites, representing the dominant heat source affecting the suites. These loads can be further reduced by careful selection of equipment. Moreover, passive cooling strategies, such as natural ventilation, have the potential of further reducing cooling loads.

3.3.4 Sensitivity Analysis

In the example presented in this paper, the range of performance results is trimmed through the minimum requirements of the energy code and extreme performance scenario. The next step in the workflow is to highlight which of the envelope parameters has the highest impact on improving outcomes.

At this stage, the population of data is analysed statistically to highlight the relative significance of input variables. For the following analysis, only simulations that produce net energy performance greater than the NECB 2011 case are included. Figure 6 shows the standardized regression coefficients (SRCs) for each of the input variables to show their relative impact on net energy performance. Variable importance, using SRCs is a measure of the standard deviation change in the output variable (response parameter) that corresponds to standard deviation changes of the input variables (design parameters). Standardized regression coefficients permit comparisons of predictor-response variable relationships across studies in which the variables are measured using different units of measure [30].

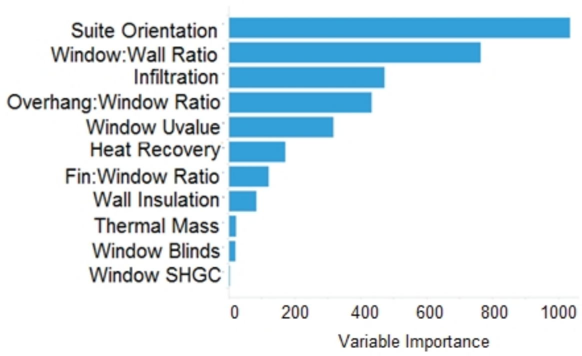

Figure 6. Relative impact of Input variable on net energy

Within the set of data and corresponding parameters values, the orientation of the suite has the highest influence on the net energy performance. The next highest impact parameter is the window to wall ratio (WWR). This parameter affects the overall insulation value of window and opaque areas, the amount of area available for solar cells, and the window area available for passive solar heat gain.

Four out of the six highest priority envelope parameters are related to windows – window to wall ratio, overhang to window ratio, window U-value, and fin to window ratio. For the next step in the workflow, trends in the data are identified to better understand the effects that window parameters have on the suite performance.

3.3.5 Trend Analysis

Windows play an important role in the design of multi-storey residential buildings. As the sensitivity analysis section shows, decisions on the size and characteristics of glazed areas and passive solar controls play an important role in the energy performance of the finished building. This section shows two types of trend analysis that delineate the relationships between input parameters and energy performance results. In the first representation, the values of each individual input parameter is plotted against the major response variables – heating and cooling loads, and PV potential. The second representation provides information on the interaction between pairs of input parameters by plotting them against a single response variable, in this case, net energy.

Figure 7 shows the relationship between WWR and the major response variables; heating load, cooling load, and PV potential for the average simulation in the parametric study.

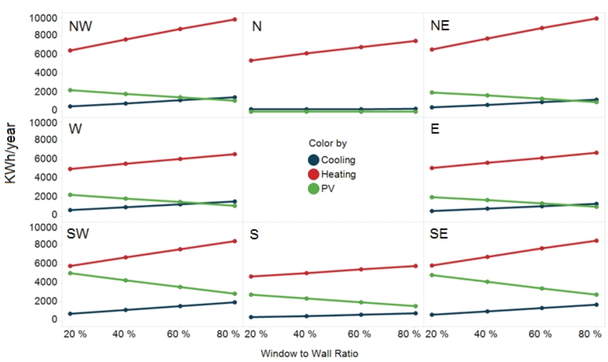

Figure 7. WWR vs heating and cooling loads and PV potential for eight suite types (all simulations)

PV potential is reduced with increasing WWR for each suite type due to the reduction in opaque area available for PV, except for the N suite, which has no photovoltaic cells. Cooling loads increase moderately for each of the eight suite types, except for the N suite, due to the increase in passive solar gains. Heating loads increase for each of the eight suites due to the relatively lower thermal resistance of glazing compared to opaque wall surfaces. These relationships represent a very broad view of the data, since they represent the average of all available

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simulations, and are not necessarily representative of all design scenarios in the study.

Figure shows the same set of relationships for the subset of simulations that include quadruple pane windows with high SHGC. (U-value 0.77, SHGC 0.41) The trends for PV potential are naturally not affected by window type, but heating and cooling load trends are significantly affected. The trends of increasing cooling load with increasing WWR are more pronounced, especially for the SW and SE suites that sustain increased solar exposure. Heating load trends, on the other hand, are flattened for all suites, showing a slight increase with WWR on the north side, and slight decrease on the south side. The additional solar energy captured by this subset of designs offset heat losses through the larger window surface area.

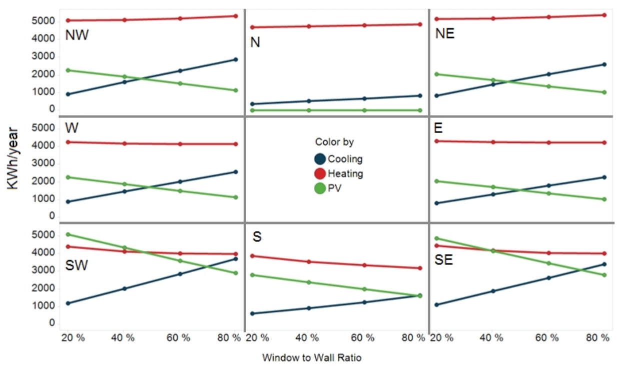

Figure 8. WWR vs heating and cooling load and PV potential for eight suite types with quadruple glazed, high SHGC windows

Figure 9 shows the interrelated nature of window size and shading devices. Darker colours on the map represent a relative improvement in energy performance, and the star marks the lowest net energy case. It is clear from the contrast between Figure 8 and Figure that there is interaction between the input parameters that needs to be better understood.

In general, the performance of the average suite improves as window size is reduced relative to opaque areas, and as the shading overhang length is increased relative to the window height. It is noted by the darkening colors of the cells in the chart that increasing overhang lengths are beneficial regardless of window size. Figure 9a shows that, for the average of the eight suites, the highest performing scenarios are related to a WWR=20%, while the lowest performance level is associated with WWR=80% and no shading overhangs, increasing the net energy consumption by 51% compared to the lowest net energy case. Figure 9b shows the relationship between window to wall ratio and fin to window ratio with respect to net energy. The effect of window size is dominant in this relationship, with a very moderate net energy performance trend towards shorter fins. Minimizing the width of fins is associated with a moderate improvement in performance, regardless of window size. Figure 9c shows the relationship between the length of fins and length of overhangs. The trend shows that higher net energy performance tends towards maximizing overhangs and minimizing fins.

3.3.6 Optimization

The Extreme Scenario example (section 3.3.3) demonstrates a simple optimization technique, consisting of scanning the data base for parameter combinations that optimize a selected response variable. It can be extended to allow for specific constraints on input parameters, such as prescribed values or range of values. The more rigorous procedure presented in this section can be applied to constraints that are not directly related to parameter values, such as material and construction costs and human comfort. The technique consists of determining incremental changes to the response variable being optimized (net energy in the present example) due to successive incremental changes to all parameter values, from a given set point. As the set point is moved in optimal trend, the interaction

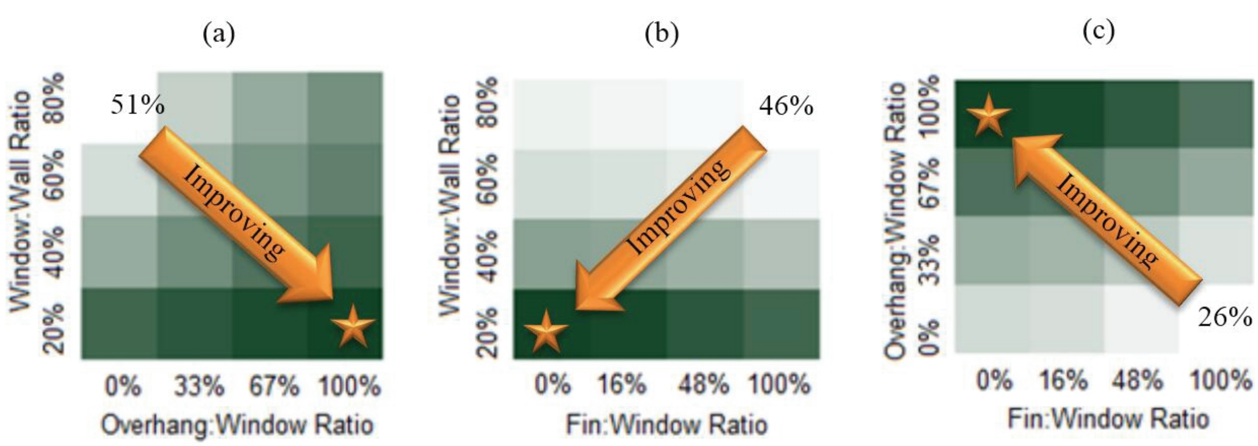

Figure 9. Qualitative trends in average net energy consumption for a) window to wall ratio vs. overhang to window ratio. b) fin to window ratio vs. overhang to window ratio, and c) overhang to window ratio vs. fin to overhang ratio

between parameters takes effect. It is, in a sense, a complex, sequential trend analysis.

Figure 11 shows the percentage difference dashboard for the average of all eight suites, evaluated against net energy consumption, with the objective of minimizing net energy. The 'Current Value' column shows the NECB 2011 minimum case, as discussed in section (3.3.1). Percentage differences in net energy consumption are shown in the '%diff' columns for incremental changes to each parameter (with + sign for increasing and – for decreasing increments), based on the discrete values defined in the parametric study (Table 2). Since the energy code case is the minimum (as set by the reduction technique in Section 3.3.2) there are only %diff+ viable options for improvement at this stage. Cells in the dashboard labelled 'min' and 'max' indicate that there are no further options of parameter values within the scope of the parametric study.

It can be observed for instance that the best incremental change is to improve the WWR by one step (i.e. from 40% to 20%), resulting in a 19% reduction in net energy consumption, while three increments (i.e. Increments by 3 consecutive values of the specific parameter- see values in Table 2) of infiltration have the highest potential for reducing net energy consumption, at 20% reduction. Since this is a live dashboard, each change to a parameter in the 'Current Model' will update all of the %diff values for each parameter. Using this technique, the user can 'wander' through the database to evaluate the energy performance of changing various design parameters.

The dashboard allows the user /designer to understand the impact of changing the value of individual parameters, and how this will affect the values of other parameters as well as the output in energy.

4. Discussion

This study presents a methodology to optimize the energy performance of building envelope of residential multi-storey buildings throughout the early design stage, using design performance modelling strategy. The methodology consists of applying a selection of analysis techniques to a database obtained from the results of extensive parametric simulations performed on an assumed base case design. The parameters selected for the simulations are based on their expected impact on the energy performance of buildings[18,1,21].

The objective of the five proposed analysis techniques is to explore impacts of various building envelope parameters on energy performance and to assist in selecting an optimal combination of parameter values. The analysis techniques include the following: Reduction – reducing the database to filter out all cases that fall below a certain threshold (for instance specific energy standards such as the NECB); Extreme Scenarios – searching the data base for parameter combinations that maximize or minimize selected performance criteria (e.g. total energy consumption, net energy consumption, etc.); Sensitivity Analysis– assessing the relative impact of design parameters on specific energy performance criteria; Trend Analysis – evaluation of the effect of varying a parameter value on a selected response; Optimization – evaluation of design parameter combinations that optimize a selected energy performance response, subject to constraints, through an incremental process of varying parameter values. The designer has the option of selecting the techniques that best fit the specific design under consideration.

Although a number of existing research focus on developing tools for early building design stages in specific applications, using, in some cases, some of the discussed techniques, the present methodology consists of a template that can be generally applicable to residential buildings. The originality of the proposed template resides in assembling a number of analysis techniques, which permit the user to extract useful information for specific design cases. In addition, the proposed method allows the user to visualize, and interactively appreciate, the impact of design decisions on the performance of the building and how this will affect the values of other parameters (as presented in Figure 10). Due to this, flexibility in the design can be attained, as wider understanding of the impact

Parameter	%diff--	%diff-	Current Value	%diff+	%diff++	%diff+++
Wall Insulation (m2K/W)	min	min	3.6	-1%	-2%	max
Thermal Mass	min	min	10cm slab, carpet	-1%	-2%	max
Infiltration (ACH)	min	min	0.572	-13%	-19%	-20%
Fin:Window	min	min	0%	max	max	max
Overhang:Window	min	min	0%	-7%	-12%	-15%
Window Uvalue (W/m2K)/SHGC	min	min	2.2/0.41	-6%	-6%	-8%
WWR	min	min	40%	-19%	max	max
Heat Recovery (% Sensible)	min	min	65	-2%	max	max
Blinds	min	min	Always Off	-1%	max	max

Figure 10. Optimization dashboard showing NECB 2011 parameter values and incremental %diff for net energy consumption

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of design parameters is gained. While the current methodology was developed with residential buildings in mind, it can be readily applicable to a variety of building types.

A case study is employed to illustrate the application of this methodology to a residential multi-storey building in a cold climatic zone (Vancouver, BC, Canada, 49°N). The case study demonstrates that achieving high performance is significantly affected by the design of envelope parameters such as wall insulation, window type and size, air tightness, PV generation, and passive solar controls. For instance, combined heating and cooling load can be reduced by up to 85% as compared to the base case designed according to commonly built apartment buildings in the studied location (Vancouver, Canada). This performance is associated with a number of high-energy performance measures including the application of high insulation in opaque portions of the envelope, high performance windows (e.g. triple glazing, low-e coating, argon fill), relatively small window size constituting 20% of the façade area, and airtightness. Sensitivity analysis indicates that for the studied location and the range of parameters considered, apartment orientation, window-to-wall ratio (WWR) and airtightness have the highest impact on energy performance, respectively.

The case study presented in this paper relates to a simple rectangular geometry. Often in the design of buildings, variations of design are expected, including shape, height, and façade details. Some of these design aspects may affect the performance as for example a self-shading geometry (e.g. L shape, U shape,[31]). Representing this variability in detailed building energy models requires significant effort, and therefore a barrier to improving energy performance, in the early design stage. The presented methodology can constitute a first stage in the design process, applied to demonstrate the impact of building envelope components, to achieve high-energy performance, generally applicable regardless of geometry variations. A second stage might consist of integrating shape and other geometrical aspects that can affect building loads, and often implying change in some design elements (e.g. location of windows, size and type of shading devices, etc.).

Decisions made during the early design stages set the foundation for the energy performance of the final building model. By focusing efforts on the most relevant interdependencies, trends, and sensitivities that influence energy performance, rather than on the construction of fully detailed building models, design professionals can build knowledge to improve the energy performance of buildings. The workflow provided in this study allows for a staged and customizable presentation of results depending on the nature of the inquiry and the level of knowledge of the user. As the questions into energy performance impacts become more sophisticated, the template provides options to explore varying frames of reference based on the five data analysis techniques presented. The ability to drill down into individual response variables allows professionals with advanced levels of training to leverage the data to develop more advanced scenarios. For a more accurate assessment of full building energy performance, additional information about energy flows between adjacent suites and between floors, as well as energy requirements of common areas and mechanical systems, should be implemented in the energy models, in more advanced stages.

5. Concluding Remarks

This study provides a novel approach to influencing energy performance design decisions for multi-storey residential buildings during early design stages. The proposed approach allows the visualization of the impact of specific design decisions on the overall building performance as well as on other design parameters. This approach permits customizable presentation of results, depending on the nature of the inquiry and the level of knowledge of the user. The methods of interpretation of energy performance results, proposed in the template, allow the user to extract information that can be tailored to specific design cases. The methodology provides basic knowledge of the influence and interrelation between different components of building envelope, that can be applied to high-energy performance building regardless of other design elements (such as shape).

By understanding envelope energy performance of a residential multi-storey building at the suite level, and standardizing parameters based on an analysis of local building stocks, the task of optimizing the entire building is greatly reduced. This methodology can be further developed into an interactive tool that can support professionals in building design, with possibility of extending the type and range of parameters.

The methodology presented can be applied to other types of buildings such as office or institutional building, with some modification to the type of parameters and their range, taking into account the internal thermal building loads that may affect this selection.

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References

[1] Hachem, Caroline, Andreas Athienitis, and Paul Fazio. 2014. "Energy Performance Enhancement in Multistory Residential Buildings." Applied Energy,2014,116,9–19. doi:10.1016/j.apenergy.2013.11.018.

[2] Sozer, H., 2010. Improving energy efficiency through the design of the building envelope. Building and environment, 2010, 45(12), 2581-2593.

[3] Li, D.H., Yang, L. and Lam, J.C., 2013. Zero energy buildings and sustainable development implications–A review. Energy, 2013, 54, 1-10.

[4] West, S., 2001. Improving the sustainable development of building stock by the implementation of energy efficient, climate control technologies. Building and Environment, 2001, 36(3), 281-289.

[5] Khan, M.A., Mishra, S. & Haque, A. A Present and Future State of Art Development for Energy Efficient Buildings using PV Systems. Intelligent Building International (Taylor and Francis),2018.

[6] Hachem, Caroline, and Mohanmed Elsayed. "Patterns of Facade System Design for Enhanced Energy Performance of Multistory Buildings." Energy and Buildings, Elsevier B.V.2016, : 366–77. doi:10.1016/j.enbuild.2016.08.051.

[7] Khan, M.A., Mishra, S. & Harish, V.S.K.V. Grid Connected Energy Efficient Building with Roof Top SPV. IEEE second International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE), Amity University, Noida, https://ieeexplore.ieee.org/document/8358252/.

[8] (AIA) The American Institute of Architects. 2012. "An Architect's Guide to Integrating Energy Modelling in the Design Process."

[9] Ochoa, Carlos Ernesto, and Isaac Guedi Capeluto. 2009. "Advice Tool for Early Design Stages of Intelligent Facades Based on Energy and Visual Comfort Approach." Energy and Buildings ,2009, 41 (5), 480–88. doi:10.1016/j.enbuild.2008.11.015.

[10] Attia, Shady, Elisabeth Gratia, André De Herde, and Jan L.M. Hensen. 2012. "Simulation-Based Decision Support Tool for Early Stages of Zero-Energy Building Design." Energy and Buildings ,2012, 49, 2–15. doi:10.1016/j.enbuild.2012.01.028.

[11] Hemsath, Timothy L. "Conceptual Energy Modelling for Architecture, Planning and Design: Impact of Using Building Performance Simulation in Early Design Stages." Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association, 2013, 376–84. http://www.scopus.com/inward/record.url?eid=2-s2.0-84886645991&partnerID=tZOtx3y1.

[12] Yıldız, Y. and Arsan, Z.D.. Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates. Energy, 2011, 36(7), 4287-4296.

[13] Samuelson, Holly, Sebastian Claussnitzer, Apoorv Goyal, Yujiao Chen, and Alejandra Romo-Castillo. "Parametric Energy Simulation in Early Design: High-Rise Residential Buildings in Urban Contexts." Building and Environment, doi:10.1016/j.buildenv.2016.02.018.

[15] Hygh, Janelle S., Joseph F. DeCarolis, David B. Hill, and S. Ranji Ranjithan. "Multivariate Regression as an Energy Assessment Tool in Early Building Design." Building and Environment. doi:10.1016/j.buildenv.2012.04.021.

[16] Tian, Wei. "A Review of Sensitivity Analysis Methods in Building Energy Analysis." Renewable and Sustainable Energy Reviews . doi:10.1016/j.rser.2012.12.014.

[17] Harish, V. S. K. V., and Arun Kumar. "Reduced Order Modeling and Parameter Identification of a Building Energy System Model Through an Optimization Routine." Applied Energy , 2016a,162: 1010–1023.

[18] Harish, V. S. K. V., and Arun Kumar. "A Review on Modeling and Simulation of Building Energy Systems."Renewable and Sustainable Energy Reviews, 2016b, 56, 1272–1292. doi:10.1016/j.rser.2015.12.040.

[19] U.S. Department of Energy. 2016. "EnergyPlus." https://energyplus.net/downloads.

[20] Zhang, Yi. 2012. "Use jEPlus as an Efficient Building Design Optimisation Tool." CIBSE ASHRAE Technical Symposium.

[21] Hachem C., A. Athienitis, Effect of Residential Building Design on Energy Performance, ASHRAE journal, 2013, 55(1), 72-74.

[22] Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, W. F. Buhl, Y. Joe Huang, Curtis O. Pedersen, Richard K. Strand, et al. 2001. "EnergyPlus: Creating a New-Generation Building Energy Simulation Program." Energy and Buildings,2001, 33 (4), 319–31. doi:10.1016/S0378-7788(00)00114-6.

[23] (RDH) RDH Building Engineering Ltd. "Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia." doi:10.1017/CBO9781107415324.004.

[24] Heiselberg, P., Brohus, H., Hesselholt, A., Rasmussen, H., Seinre, E. and Thomas, S., Application of sensitivity analysis in design of sustainable buildings. Renewable Energy,2009, 34(9), 2030-2036.

[25] Schroeder, Larry D. 1986. Understanding Regression Analysis An Introductory Guide. Beverly Hills: Sage Publications.

[26] (CMHC) Canada Mortgage and Housing Corporation. 2013. "CANADIAN HOUSING OBSERVER." http://www.cmhc-schl.gc.ca/odpub/pdf/67989.pdf.

[27] (NRCAN) National Research Council Canada. National Energy Code of Canada for Buildings . 2011.

[28] Carmody, John, and Kerry Haglund. "Measure Guideline : Energy-Efficient Window Performance and Selection,"2012.

[29] Sartori, Igor, Sonja Geier, Roberto Lollini, Andreas Athienitis, and Lorenzo Pagliano. "Comfort and Energy Efficiency Recommendations for Net Zero Energy Buildings." Energy, doi:10.1111/j.1945-1474.2011.00166.x.

[30] Landis, R.S., Standardized regression coefficients. Wiley StatsRef: Statistics Reference Online. 2005.

[31] Hachem C., A. Athienitis, P. Fazio, Parametric investigation of geometric form effects on solar potential of housing units, Journal of Solar Energy, 2011, 85(9), 1864-1877.

  DOI: https://doi.org/10.30564/jaeser.v1i1.218