Using BIM to Facilitate Generative Target Value Design for Energy Efficient Buildings

Bhilare, Saurav[1], Khatri, Diya[1], Rangnekar, Salonee[1], Chen, Qian[1]
[1] University of British Columbia, Okanagan Campus, Canada
E-mail: saurav15@student.ubc.edu

Abstract –

Buildings are one of the major energy consumers and the biggest producers of greenhouse gases, accounting for close to half of all energy emissions in construction industry. Construction stakeholders have been increasingly focusing on the broad idea of sustainable building design and construction technologies. The goal of sustainable design extends beyond project design development to take into account its significance at an early stage, before any detailed design, or even before a decision is taken to move forward with development. Although Building Information Modeling (BIM) and energy simulations have been integrated into early design processes, the integration method has not yet been further explored to enable multi-criteria design analysis (e.g., energy and solar performance) by varying design options to a defined energy target. This study proposes a BIM-based Target Value Design method to inform optimal energy-efficient building designs. The proposed methodology is primarily used for preliminary sustainability analysis such as solar and energy analysis. Campus building A is used as a case study to demonstrate the usefulness of the method and results showed a potential of 360 kWh/m^2/yr reduction in annual energy consumption compared to the traditional sustainable design approach. The suggested new design workflows will substantially facilitate early design decisions of project clients, architects, civil engineers, and urban planners.

Keywords –

Generative Design; BIM; Building design; Target Value Design; Sustainable buildings; Energy Analysis; Solar Analysis

1 Introduction

The construction sector is one of the crucial contributors to Canada's economy. Construction activities account for around 6.5% of its Gross Domestic Product (GDP). Construction activities have a significant impact on all three pillars of sustainability; i.e. social, environmental, and economic. According to Industry Canada (2011), the built environment consumes 50% of extracted natural resources and 33% of total energy use in Canada. In addition, buildings produce 25% of the landfill waste, 10% of airborne particles, and 35% of greenhouse gas emissions. The construction industry employed 1.2 million workers in 2010 which is 7.1% of the total workforce in the economy (Human Resources and Skills Development Canada, 2013). From 2000 to 2010 construction GDP in Canada increased by 42.7%, whereas GDP for all industries increased by 20.2%.

The building industry's inability to genuinely integrate sustainable practices is one of the biggest obstacles to the implementation of sustainable construction (Hollberg et. al., 2019). A lack of knowledge or a lack of general awareness of sustainability can inhibit the development of sustainable structures. Designers generally exhibit trust in their capacity to access and apply knowledge, but this confidence wanes when sustainable construction challenges are brought up. There are other difficulties in stakeholder integration, including a lack of standard data protocols, lack of coherent information, and a lack of measurement instruments, among others (Chen et al., 2020). Instead, novel coordinating processes and role for building authorities and other public players in the construction industry are required. Efficient design and planning methods are desired to address the current challenges in improving sustainability in construction. This study proposes a target value design method to inform optimal energy-efficient building designs when adopting consistent BIM design workflows.

The remainder of this paper is structured as follows. Section 2 includes an overview of the relevant studies on Sustainable Design, Generative Design (GD) and Target Value Design (TVD). Section 3 introduces the methodology. Section 4 presents a case study. Section 5 provides the discussion related to the advantages and disadvantages of the proposed workflow, followed by the conclusions and future work in Section 6.

2 Literature Review

2.1 BIM-based sustainable design

The digital parametric data of building components in BIM offer an analysis and control function that may be connected to sustainability building design. The capacity of BIM tools for energy modelling and sustainable material selection to reduce environmental effect illustrates the functional support of BIM for sustainable designs. Integrating BIM with sustainable design analysis tools (e.g., Energy plus) makes it easier to conduct thorough environmental trade-off analyses in the early phases of design (Kofi et al., 2020).

Building environmental performance assessments may be facilitated with the help of digital solutions based on BIM (Ilhan and Yaman, 2016). Recently, a number of technologies have been developed that base Life Cycle Assessment (LCA) on a BIM model for automatic quantity take-off (Azhar et. al., 2011). Using the integrated BIM-LCA design processes, a real building's embodied global warming potential (GWP) may be assessed throughout the entire design process (Hollberg et al., 2019)

2.2 Generative Design for buildings

Generative Design (GD) is the process of inputting design goals, constraints and other data into software that evaluates all possible solutions. It has been extensively utilised in the manufacturing sector, and the architectural, engineering, and construction sector is paying more attention to it as it relates to space design, sustainability research, and urban planning.

The use of BIM in the design phase is primarily restricted to the latter design stages, despite the fact that it is relevant throughout the whole life cycle of the project. By filling in each other's shortcomings, the GD and BIM integration benefit each other by increasing their respective capabilities (Gan 2022). The integration enabled the buildability of these GD solutions, supports automatic and quick design explorations, and increases the utility of BIM during the early design stage. In order to implement the integration, the BIM API offers platforms and options.

2.3 Target Value Design

Target Value Design (TVD) is a management practice that drives the design to deliver customer values within project constraints. A project environment with advantageous features can provide value using the TVD. However, as cost is the TVD's main criterion for evaluation, the goal cost may be met while the project's full potential remains unrealized. This study uses a value analysis model to analyze the value generation of the project and applies the action research methodology to implement TVD in a housing project. It also studies the balance between cost and value fulfilment in the product and design process. It mostly focuses on value and cost aspect. There is the scope of work in TVD with respect to sustainability using Revit and Dynamo for GD of buildings.

A team may offer the characteristics of a building that add value to the owner while staying under budget with the aid of TVD. Since its beginnings, TVD has made it possible to finish numerous institutional projects on time and on budget while also delivering more value to the client. Regarding their cost performance, several projects that explicitly used TVD have reported two consistent results: (1) The projects were completed below market cost, and (2) the estimated costs typically decrease as designs are developed.

2.4 Integration of GD and TVD

Researchers have identified the potential of GD and TVD in construction projects, but there has been lack of research regarding integrating these concepts. Study by Ng, C., & Hall, D (2021) shows how TVD can help in completing projects in a shorter time, with lower cost and higher profits without compromising design goals. Meanwhile, Schwartz et al. (2021) present a decision support tool that uses generative design to achieve the best possible design outcome. If these concepts are combined, it will help to streamline the design process and achieve high performance buildings that meet requirements of various stakeholders. This study is built on basis of the existing integrated GD and TVD processes and puts a focus on the *energy target*, instead of the cost target, to facilitate the sustainable designs.

3 Methodology

The aim of this work is to assess how GD analysis and TVD process can be combined to optimise and automate the building sustainability assessment in the early design stage. A problem-orientated approach will be used – developing a method that generates preliminary building design based on the target sustainability values. For this purpose, a proposed campus building will be considered as the case study and will be studied in order to evaluate the potential of GD for accessing sustainability criteria. Therefore, criteria such as window to wall ratio and orientation of the building will be considered for multi-criteria optimization using GD to find the best possible solution. The study will consider Autodesk Revit (version 2023) software since it is one of the most used BIM modeling software. In addition, GD analysis will be performed using ‘Autodesk Generative Design’ platform and Dynamo studio.

In the following stage, based on the result of the previous analysis, the applicability of Target Value based Generative Design (TVGD) to optimise the sustainability assessment process will be assessed. The suggested framework will define the workflow to automatically generate preliminary designs based on the targeted energy efficiency values.

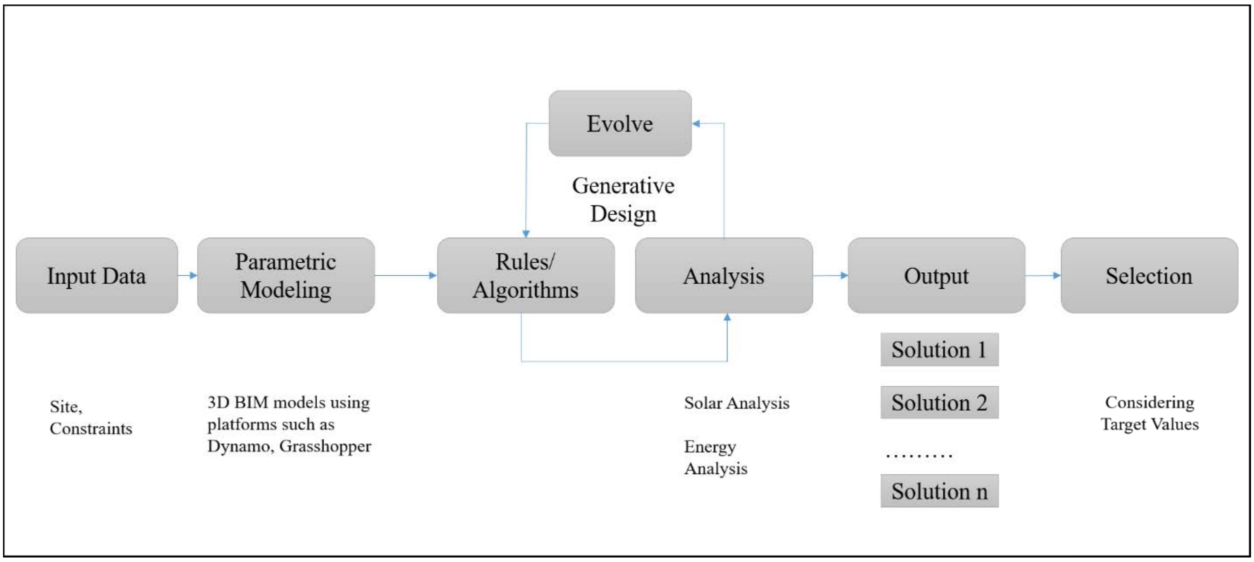

Fig 1: Generative Target Value Design Framework

The proposed framework includes the following components:

(1) Input data

For the GTVD, the first step is to create a BIM model of the site considering all the inputs such as location, surrounding buildings and site boundary for the project.

(2) Parametric modeling

The building structure was modeled using parametric design. Instead of considering fixed values, parameters and rules were used to determine the relationship between the design intent and response. In addition, algorithms were created for linking external sources for solar and energy analysis.

(3) Generative Design

In the GD analysis the parameters and rules from the Dynamo graph were analysed in cloud using AI and Machine Learning to generate a pool of design options.

(4) Target value consideration

The outputs of the GD analysis were filtered by energy target values according to the design goals.

4 Case study – Campus building A

The building considered for case study is a proposed institutional building in British Columbia. Four target value goals were considered for this case study: (1) Minimizing the annual energy consumption of the building, (2) Minimizing total solar incident radiation on the building façade, (3) Reducing the form factor of the building, (4) Increasing renewable energy generation by the roof top solar panels.

The proposed approach described above was used for the case study.

4.1 Model creation for analysis

Autodesk Infraworks was used to model the 3D site using the GIS data layers from various online sources. This model was then imported in Revit to be used for sustainability analysis. The faces of the surrounding buildings were considered for the solar analysis as they will cast shadow on the proposed building and the weather conditions of the area were also considered.

Fig 2: 3D Site model

A parametric model was created in Dynamo Studio plugin for Revit. First, constraints were defined for the model creation:

a) Parcel restrictions: The plot boundary was created in Revit model, which acted as a restriction for the design options generated.

b) Floor height: For this analysis the floor height was considered as 4m and non-parametric.

c) Built-up area: The built-up area of the project was limited to that of the proposed building which was 14000 m^2.

Then parametric inputs were added, which provided flexibility to generate and analyse various design approaches. We considered the following parametric inputs:
a) Floor plan: We considered a floor plan consisting of 10 faces. Each face was first modeled as a line, thus forming a continuous polygon with 10 connecting points. Each point was a given a range of values such that the lines do not intersect each other. This created various design options of the floor plan for analysis.

b) Number of floors: The overall built-up area is constant but the number of floors was considered variable which allowed for the variation in the floor area and form factor of the building.

c) Window-to-wall ratio: The window to wall ratio was considered between 0.4 to 0.8. This affects the overall energy consumption of the building.

d) Orientation of the building: The orientation of the building was considered as a variable because it affects the annual energy consumption as well as the average solar incident radiation on the surface of the building.

4.2 Target value calculations

4.2.1 Total annual energy consumption of the building

The Dynamo package 'Energy predict ML' was used for this workflow. The inputs for this calculation were surfaces of walls, windows, floors and shading. After providing inputs, the main node of the package uses an algorithm trained by machine learning on top of Autodesk Insight 360 database to predict energy performance.

4.2.2 Solar incident radiation on the building facade

The Dynamo package 'Solar analysis for Dynamo' was used for this workflow. The inputs for this calculation were weather conditions, analytical surfaces for walls, shading surfaces of surrounding building and duration of study (Jan 2023 to Dec 2023). This package makes external calls to a web service to get required data for the analysis.

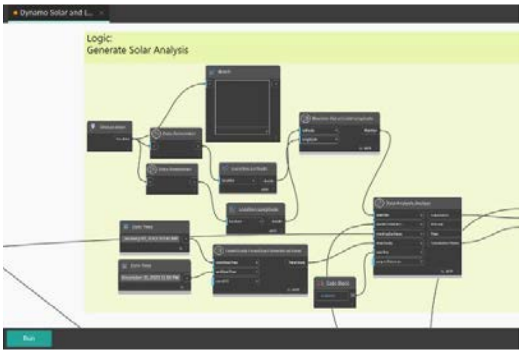

Fig 3: Dynamo graph for solar analysis

4.2.3 Form Factor of the building

Building envelope area and total volume is calculated. Form factor is calculated by dividing surface area by volume.

4.2.4 Renewable energy generated by the rooftop solar panels

The area of the analytical roof surface is variable which is calculated to find the renewable energy generation capacity of the building.

4.3 Generative Analysis

4.3.1 Data export

First the graph was validated by running the complete workflow once. Then the graph was exported for the GD analysis. All the dependency files required for the analysis were automatically generated by Dynamo.

4.3.2 Performing Generative Analysis

In the GD process the parameters and rules from the Dynamo graph are analysed in cloud using AI and Machine Learning algorithms to generate a pool of design options. We performed 5 iterations for the GD analysis while considering the following goals: Minimizing annual energy consumption, solar incident radiation on façade and Form Factor, while maximizing the surface area for rooftop solar panels.

As compared to our previous study, we increased the population size for the GD analysis and choose to maximize the built-up area[1]. We increased the population size from 10 to 20. Population size is the initial number of individual options used by the genetic algorithm. Each individual option has a unique set of features that serve as the genes to evolve the design, so higher the population size, the more the design is optimized. Also, we choose to maximize the built-up area along with other target goals to increase the utilization of the building.

[1] For the Canadian Society of Civil Engineering (CSCE) Annual Conference, Moncton 2023, we performed GD analysis for our paper "BIM-based generative design processes for targeted value design of low-carbon buildings." Compared to that, our aim in this study was to specifically target energy performance optimization, so we made two changes to the GD analysis - increased population size and optimized rooftop solar panels).

4.4 Results of the analysis

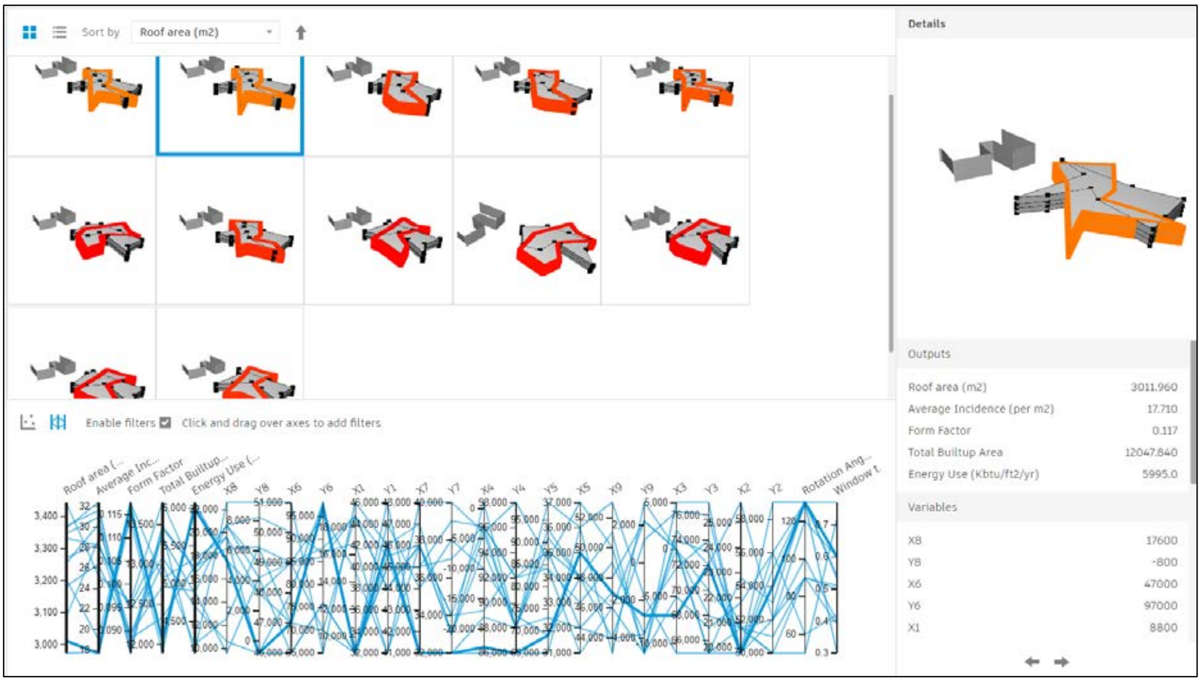

Fig 4: Outcomes generated after GD analysis

Table 1: Generative Design outputs

Sr. No.	Energy Use (kWh/m²/yr)	Average Incident solar radiation (kWh/ m²)	Roof area (for rooftop solar panels) (m²)	Form Factor	Total Built-up Area	Rotation Angle	Window to Wall Ratio
1	1561.98	19.11	3205.16	0.12	12820.64	130.00	0.77
2	1196.03	30.87	3345.96	0.09	13383.84	50.00	0.72
3	1427.50	28.22	3331.46	0.10	13325.84	90.00	0.39
4	1779.39	17.84	2972.86	0.11	11891.44	130.00	0.53
5	1436.87	26.34	3180.46	0.09	12721.84	130.00	0.30
6	1230.31	30.17	3252.56	0.09	13010.24	60.00	0.42
7	1378.27	28.29	3270.96	0.09	13083.84	130.00	0.54
8	1530.05	28.64	3084.06	0.09	12336.24	120.00	0.60
9	1501.92	25.27	3443.56	0.10	13774.24	100.00	0.40
10	1756.54	17.71	3011.96	0.12	12047.84	130.00	0.60
11	1523.31	31.53	3369.56	0.09	13478.24	90.00	0.50
12	1527.12	32.36	3361.46	0.09	13445.84	90.00	0.51

For each generated design options, the initial 3D model of the building is shown in grey colour and solar analysis is performed after considering various orientations.

4.4.1 Optimized design options

Twelve design options were generated after the analysis. Each option can be selected to view all the input and output values for that option on the right side of the interface. Also, a graph showing all values for all the options is generated at the bottom of the interface, which can be used to understand the relationship between the variable inputs and outputs. There is an interdependency between all the target values calculated. Change in value of one parameter can positively affect one of the target values, while negatively impacting another value, so it is still challenging to improve all the target value outputs at the same time.

4.4.2 Selection of preferred design options based on target values

We can select multiple combinations of the output values to select the optimal solutions. For this case study we selected two outputs: annual energy consumption and area for rooftop solar panels. The target values for annual energy consumption were considered to be below 1500 $kWh/m^2/yr$ and for area of rooftop solar panel the value was considered to be above 3300 m^2.

After adding the target values as filters, two design options were displayed as the optimal solutions (Option 2 and Option 3). Final selection can be done based on the client's preference such as the shape of the building. We selected option 2 as it has the lowest annual energy consumption.

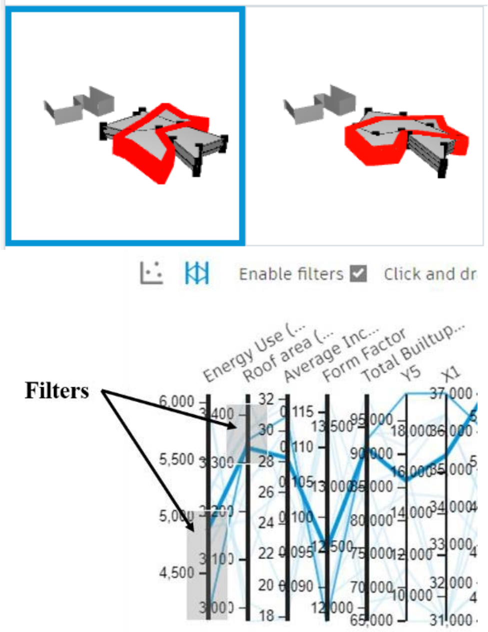

Fig 5: Filtering design options

4.4.3 Comparison with original layout of the building

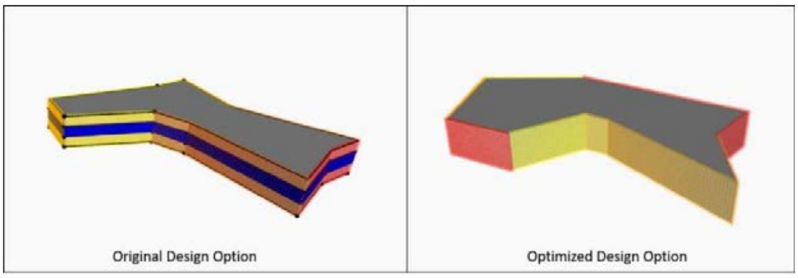

Fig 6: Comparison of original and optimized design option

Table 2: Comparison of target values of original and optimized design options

Sr. No.	Output	Original Design Option	Optimized Design Option
1	Annual energy consumption ($kWh/m^2/yr$)	1559.35	1196.03
2	Average incident solar radiation (kWh/m^2)	15.92	30.87
3	Roof area (m^2)	3192.52	3345.96
4	Form Factor	0.093	0.085
5	Total Built-up area (m^2)	13770.00	13383.84

The values shown in Table 2 were calculated in Dynamo Studio for both the options. It shows that there is a significant difference in energy consumption values. The optimized building consumes around 360 kWh/m^2/yr less energy that the original building design.

4.4.4 Detailed Visualisation in Dynamo

The final selected option can be viewed in detail in Dynamo. For this study we selected the design option with the minimum annual energy consumption (i.e. option 2). In Dynamo we can view details such as the solar incident radiation value on a particular face of the building and also adjust the parameters such as duration of study to get outputs for a specific season.

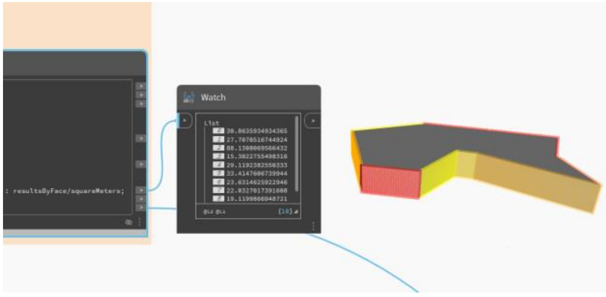

Fig 7: Final output visualisation in Dynamo

Also, the design option can be viewed in Revit to give better perspectives with respect to the complete site.

Fig 8: Final output visualisation in Revit

5 Discussion

GD is a computer-aided design approach that has the ability to revolutionize the design process. It can generate new and innovative design solutions that may not have been considered by human designers, enabling designers to push the boundaries of what is possible. Moreover, GD has the capability to explore a wide range of design solutions, providing designers with a greater understanding of different design possibilities, which in turn can lead to better design decisions and outcomes. With this technology, designers are able to experiment and explore more options, which can lead to a more efficient and effective design process.

Dynamo is a powerful tool for BIM that allows for the analysis and optimization of building systems. However, it has some limitations that need to be considered before implementing it [14]. One limitation is the limited ability to analyze complex building systems. Complex systems such as HVAC are made up of large number of interconnected components, which makes it difficult to accurately capture and represent all dependencies and interactions between the various elements using Dynamo. Another factor is the high cost of implementation, as BIM software and hardware can be expensive to purchase and maintain, and requires specialized training for users [15]. Additionally, the risk of errors is increased in Dynamo models due to their complexity and data-intensive nature, making proper management and maintenance crucial to ensure the accuracy and consistency of the models.

Manual output of energy efficiency is the traditional method of designing buildings for energy efficiency, which requires architects and engineers to manually calculate and analyze the energy performance of different design options. This approach can be time-consuming and may not result in the most efficient design. In comparison, Generative Target Value Design can help to increase the efficiency and speed of the design process and can also provide more accurate and efficient results than traditional energy efficiency calculations.

6 Conclusions and future work

The use of BIM tools such as the use of Dynamo scripting can facilitate Generative Target Value Design (GTVD) for energy efficient buildings through the proposed design framework/workflows. Different from traditional 2D or 3D design means, a visual programming tool allows for the automation of design processes, which can improve accuracy, speed, and efficiency in the design phase. The proposed workflows allow for the integration of various design elements and the ability to analyze and simulate different scenarios, which can help identify the most efficient and effective solutions for delivering an energy-efficient building. Additionally, the proposed workflows focus on the “energy target value” that allow for the integration of various simulation tools, which can help designers to evaluate the energy performance of the building and identify opportunities for improvement. The proposed workflows were demonstrated in a case study to show the potential in the design and construction of energy-efficient buildings, and the use of GTVD could be considered in any type of project pursuing this goal. However, for this research, it was considered that all the stakeholders have collaborated to finalize the target values before the GD analysis. This does not take into consideration the continuous collaboration between the stakeholders for cost-based TVD. This scope can be added in future research.

GD used within a BIM environment helps to explore and optimize multiple design options for energy efficiency. This can be used to generate design options that meet specific energy performance criteria, such as reducing energy consumption or increasing renewable energy use. By using BIM in conjunction with Dynamo Revit and GD, architects, and engineers can more easily and effectively design buildings that are energy-efficient and optimized for performance. Canada is taking steps to ensure a clean energy future through investments in innovation that enhance the country's economy, create clean jobs, and help the citizens save on household energy costs. GTVD can contribute to this goal by significantly reducing the energy consumption of buildings and decreasing the carbon footprint

Acknowledgments

We would like to thank UBC Property Trust for providing the schematic design information about the case study building project.

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