Target Cost Modelling for Offsite Construction Projects

by

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Abstract

The fast-paced progress associated with offsite construction projects necessitates special attention toward project design, estimation, and planning. Traditionally, the relationship between project design and cost lacks clarity during the early design stages of a project. While design efforts aim to improve the project performance, compromises are made in order to meet a desired targeted cost. Target cost modelling (TCMd) provides an ideal environment to explore the available alternatives and reveal the associated financial and environmental impact on the project. Structural design, building envelope, heating and cooling systems, delivery of modular units, and onsite assembly are analyzed and standardized through a set of construction, costing, and energy factors in order to illustrate their indirect/direct effect on the project design, cost, and energy efficiency.

This research presents a novel solution for standardization of best practices for offsite construction projects, where a target cost model of the project is developed dynamically and interactively as the design/planning matures. Such advances for offsite construction as improved project performance, reduced energy consumption, and enhanced design and estimating processes are expected. Data is collected from 25 projects constructed between 2010 and 2015, located in 12 cities spanning four Canadian provinces—Alberta, Saskatchewan, British Columbia, and Ontario, including eight offsite manufacturing facilities and three on-site assembly management branches. The diversity of the collected data provides a good sample representation of offsite construction projects.

Acknowledgments

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AS	Assembly system
CC	Construction component
CF	Costing factor
CnF	Construction factor
DSS	Decision support system
Eng	Energy factor
EUI	Energy use intensity
Est	Estimated budget
GBS	Green building studio
PM	Project manager
Pr	Priority
Prj	Project
Pt	Priority iteration number
RBA	Rule-based analysis
Res	Residual
Rn	Ranking value
SA	Simulated annealing
SAS	Sub-assembly system
SAt	Sub-assembly alternative system
TC	Target costing
TC$	Target cost
TCMd	Target cost modelling

Chapter 1: Introduction

1.1.Motivation

Despite advancements in the construction industry through the introduction and application of the technological concepts and tools, the cost of construction projects has been steadily increasing with no comparable improvements in overall performance metrics. In a survey presented by Statistics Canada in 2016, the construction cost index of apartment building projects was reported to have increased 9.6% between the years 2011 and 2015; this cost escalation is projected to expand steadily in the coming decades, which could present a financial burden hindering the advancement of the construction industry. To solve this challenge, a shift in both the construction methods and design and estimating processes is needed. While construction technologies have been extensively studied and analyzed as a result of their direct influence on the overall project cost and performance, studies targeting the collaboration between project design and estimation have yet to reach an acceptable practical application in the construction industry; this is due to the complex nature of construction projects, which hinders practitioners' comprehension of the influential effects of design changes on the project performance metrics during the early decision making stages. Target costing (TC) sets the main guidelines for the design-estimate process that allow the efficient exploration of available construction systems, thereby helping construction companies to reduce cost-to-design and cost-to-build, to improve the quality of construction components, and to produce more energy-efficient buildings.

The successful application of TC for alternative value analysis requires a clear understanding of the interactions among construction components in order to achieve desired outcomes. Traditionally, project managers (PMs) count on their experience in reallocating the necessary cost for project components in order to achieve a balanced budget capable of meeting the client's requirements while keeping the building unit cost within a desirable range. An estimation of the direct cost of the selected alternative can be calculated from the material cost, necessary labour hours for manufacturing, and onsite installation cost; however, the estimation of indirect costs can be time-consuming as a result of the ambiguity surrounding the complex interactions among construction components in terms of installation requirements, onsite safety procedures, and overall project risk. Realizing the allowable cost requires a number of iterations between the design and estimation in order to achieve a satisfactory distribution of the project cost over the construction components that fulfil the customer's design requirements. The distribution of unit cost percentage is affected mainly by the type of construction project (i.e., residential single-family, residential multi-family, hotel, workforce camp, etc.). Further classification of project type is governed by factors such as location, building codes, and construction technology. Consequently, decision makers face a challenge in realizing the full effect a given element has on the total project cost (direct cost, indirect cost, and operational cost), which not only affects the cost saving opportunities realized from the proper selection of construction components and systems, but also intensifies the financial and environmental effect of the design and estimating process on the overall project cost.

In an attempt to explore the connection between project capital cost and multidisciplinary design aspects, studies available in the literature have presented a set of tools and models capable of evaluating the influence of construction components on project performance in terms of cost, quality, energy consumption metrics, and greenhouse gas emissions (Cole 1998; Rose 2000; XiaoChuan 2004; Hauschild et al. 2004; Lindahl 2005Kim & Dale 2005; Soytas et al. 2007; Nugent & Sovacool 2014). However, they lack a well-structured framework capable of meeting desired goals; improvement measures are heuristic in nature and rely on the intuition of designers, which reduces the efficiency of design-estimate studies as a decision support system (DSS) during the early design stages.

The proposed target cost modelling (TCMd) approach examines the relationships among the building components, as well as their direct and indirect costs, through the development of a hierarchical framework of project assemblies, sub-assemblies, and components that improves the quality of the construction components delivered as well as the overall energy efficiency of the project. The proposed TCMd considers energy efficiency as the key overall performance evaluation metric due to the environmental impact it has on the project lifecycle. Decisions made during the early design stages may significantly influence the overall energy performance metric, which not only affects the project financials and occupancy comfort level, but also has an impact on greenhouse emissions, which are key contributors to global warming and environmental degradation.

1.2.Research Objectives

This research is built upon the hypothesis that:

"*Automation of target costing analysis improves project value and energy performance by facilitating efficient exploration of all available and compatible construction systems that meet a desired project cost*."

The aim of this research is divided into two sequential objectives: the development of the value ranking target cost modelling (TCMd) process, and the energy-based TCMd for offsite construction projects (See Figure 1-1). The manufacturing technology and the utilization of best practises for offsite construction manufacturing are incorporated through the utilization of a representative set of factors and rules that capture human intelligence applied during the early design stages.

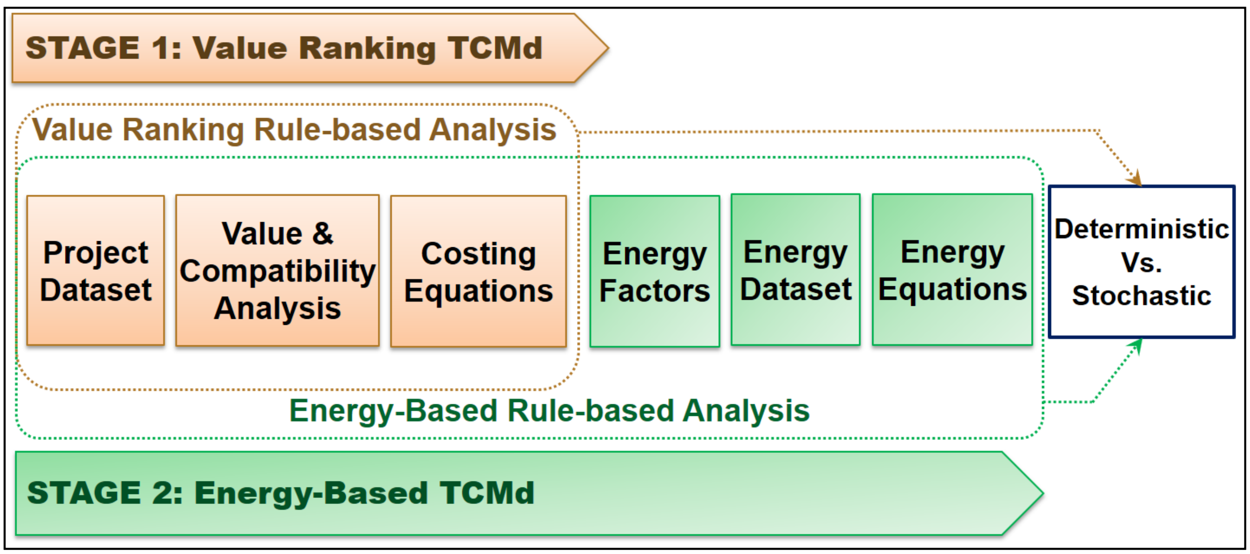


Figure 1-1: Research objectives

The objectives of this research are as follows:

1- To develop a value ranking target cost modelling tool for offsite construction projects. The development of this tool follows four steps:

   a. Developing an offsite construction project dataset that stores and organizes all the design and estimate data under a three-level work breakdown structure (WBS): (i) assembly systems, (ii) sub-assembly systems (SASs), and (iii) construction components (CCs).

   b. Establishing a value ranking system through the standardization of construction characteristics under a set of construction factors based on the SAS level, and developing a compatibility matrix that governs the relationship among available SAS alternatives.
   c. Formulating costing equations in order to automatically generate project cost through the utilization of costing factors that translate a project design into quantifiable parameters.
   d. Developing a deterministic value ranking TCMd tool through the incorporation of rule-based analysis under a programming environment, Visual Basic Applications (Excel Macro), in order to automatically provide the cost breakdown (SAS cost percentage) according to a defined cost target.

2- To develop an energy-based target cost modelling tool for offsite construction projects. The development of this tool requires the incorporation of energy analysis through the following four steps:
   a. Developing a set of energy factors that links between building envelope, mechanical systems design, and the overall energy consumption of a building.
   b. Building an energy dataset through the energy simulation of representative offsite construction projects.
   c. Formulating energy equations that generate fuel and electrical consumption according to a specific project design.
   d. Developing a deterministic energy-based TCMd by exploring all available energy models of an offsite construction project.

3- To perform stochastic multi-objective optimization modelling on TCMd to compare and evaluate the developed deterministic rule-based models.

1.3.Thesis Organization

This thesis is organized in five chapters starting with the Introduction in Chapter 1, Literature Review in Chapter 2, Research Methodology in Chapter 3, Implementation and Application—Case Study in Chapter 4, and finally the Conclusion and Recommendations in Chapter 5

Chapter 2 has two main sections. The first section focuses on target costing(TC) history and application in western countries, in particular the opportunities realized and challenges faced while applying its concepts into the construction industry through the development of new concepts such as target value design (TVD). The second section focuses on the energy modelling of an offsite construction project, the environmental impact, and the potential energy improvements.

Chapter 3 outlines the proposed methodology of the two TCMd tools, value ranking TCMd, and energy-based TCMd. It begins with the establishment of a three-level structured dataset that facilitates the analysis of project cost and performance, and then the value ranking TCMd methodology describes the generation process of two sets of factors: construction factors that control the project performance and compatibility analysis, and costing factors that contribute to the formulation of costing equations. These equations are then integrated into rule-based analysis (RBA) using VBA by means of Microsoft Excel in order to automatically generate project cost and specification list. Similarly, the development of energy-based TCMd is described through the formation of a set of energy factors and equations that explore available energy models for the purpose of improving project energy efficiency. Stochastic multi-objective optimization tools are then utilized to compare the results generated from the deterministic supervised RBA against a probabilistic simulated annealing optimization method.

Chapter 4 describes the case study applied to validate the developed TCMd.

Chapter 5 summarizes the general research outcomes and their contribution to industry practice. It also offers recommendations for future research.

Chapter 2: Literature Review

2.1. *Introduction*

The literature review in this chapter focuses on two main subjects central to the methodology of the present research: target costing technology and energy modelling for offsite construction projects. For the purpose of finding articles relevant to these subjects, major construction journals, such as *Automation in Construction*, *Journal of Computing in Civil Engineering*, *Journal of Construction Engineering and Management*, and *Journal of Management in Engineering*, are targeted.

2.2. *Target Cost*

In the early 1960s, target costing (also known as Genka Kikaku) emerged as an effective cost management technique in Japanese industry. It began with the adoption of the value engineering (VE) concept by Toyota in an attempt to reduce overall product cost during the early design stage (Feil et al. 2004; Ansari et al. 2006). The strong competition and challenging financial conditions in the Japanese industry drove the leading innovative companies to introduce target costing (TC) as a viable vessel to continuously improve product costing when associated with lean manufacturing techniques (Kato 1993). Western industries, such as automobile manufacturing companies, have utilized TC since the early 1990s and reported significant advancements in their product development (Chan et al. 2011; Zimina 2012) as a result. TC has been utilized in all types of industries in Japan during the planning and design stages to produce new products with higher quality and lower cost in order to keep up with the increased level of modernization customers demand (Tani et al. 1994). TC has become well established due to its capability of delivering a desired financial return from product and service design while satisfying increasing customer demand for technological advancement (Cooper & Kaplan 1999).

TC has not been established on a theoretical basis, but rather on an experience basis where intuition has played a key role in developing costing strategies in response to a competitive market. Early scholars who studied it could not come to an agreement for the exact translation of *Genka Kikaku*, which has been perceived by the Western industry as target costing. In spite of the vast wealth of literature covering the TC concept, researchers do not seem to be in agreement when it comes to its definition, propositions, and procedures. TC has been described as a cost calculation tool, a cost control technique, a cost management system, and a profit management system (Dimi

& Simona 2014). It has been classified as a cost management tool in the context only of the engineering of new products, and as a profit management tool when considering the effect of life-cycle cost on overall profit (Feil et al. 2004). The lack of consensus on the rules governing TC structure has limited the adoption of TC among Western industries (Ax et al. 2008). Company managers maintain the perception that TC is a traditional costing accounting process, and are unable to capture the full potential of TC as a comprehensive profit management system (Ansari et al. 2006). Despite the various research that examines the application of TC, the extent of adoption remains low in Western countries (Yazdifar & Askarany 2012). The small number of construction projects employing TC has resulted in a debate as to whether or not TC is an appropriate tool for the construction industry (Jacomit & Granja 2011). Moreover, the ambiguity surrounding TC practices and procedures correlates to its limited implementation within the construction industry (Cooper & Slagmulder 1997; Cheah & Ting 2005). A better understanding of the guiding principles of TC is essential in order for its full potential and benefits to be realized.

In Western countries, TC has been established on the principle of incorporating the cost and performance metrics in the planning process during the early design stages, rather than developing a full design and later pricing the material and resources needed to satisfy its requirements. The dynamic relationship between design and estimation has set the guidelines for TC, and, over the years, the adoption of TC in manufacturing has been enhanced through progressive research attempts, defining a number of steps to link the fundamental characteristics of the costing process with a structured framework in an effort to bridge the gap between a target cost and actual cost, both directly and indirectly (Ewert & Ernst 1999; Everaert et al. 2006; Ibusuki & Kaminski 2007; Ax et al. 2008). Service firms have also examined the application of TC as a cost reduction strategy for accounting purposes through a number of studies with a focus toward adopting and improving the TC concept. A study performed by Kee (2010) has revealed a deficiency in the traditional application of TC due to its inability to capture the effect of the cost-of-capital, which results in products being overlooked that may have a positive effect on the net present value. Kee has proposed the incorporation of the economic value added (EVA) concept into the existing TC paradigm to account for the return on capital investment. Yazdifar and Askarany (2012) conducted a questionnaire among a group of Chartered Institute of Management Accountants (CIMA) qualified accounting firms for the purpose of analyzing the levels of TC implementation in service firms. The survey was intended to measure the attributes of innovation associated with TC based on a set of factors governing the adoption of TC application. The study results indicated a moderate influence of TC on service firms. In spite of the comparable adoption rate between manufacturing and service firms, the level of implementation was found to be significantly less in the latter, resulting from the low influence of TC on the characteristics of innovations in the service firms, as described by Rogers (2003).

In the construction industry, the effectiveness of TC in managing contract risk has motivated researchers to investigate the application of TC in construction contract management, and many efforts have been steered toward analyzing the influence and implementation of TC on the contracting process (Perry & Barnes 2000; Broome & Perry 2002; Sobotka et al. 2007; Chan et al. 2011; Pishdad-Bozorgi et al. 2013). From a contractual point of view, the realization of optimum product selection within a target cost is dependent on a balanced risk-reward system, permitting multi-disciplinary teams on construction projects to synchronize efforts toward the same goal under a well-structured set of rules governing the scope and timing of each party's involvement during the life of the project. An example of target cost contracting (TCC) research is represented in the work of Lahdenpera (2010), who has proposed a two-stage TCC system where a group of pre-qualified builders become involved in setting the tendered price and target cost based on a conceptual design, and the builder who wins the tender refines the project scope without exceeding the target cost. The shared risk in this exercise was found to increase the team's commitment and involvement, and to improve the overall project performance.

The adoption of target cost as a construction management mechanism is another application for TC in the construction industry. The high level of uncertainty associated with construction project delivery has precipitated the shift toward TC as a construction management tool, and its successful application in manufacturing and servicing industries signifies high potential for cost reduction (Zimina et al. 2012). Driven by the industry's specific needs and requirements, researchers have introduced different frameworks to facilitate the implementation of TC in the construction industry. Target value design (TVD), the most common adaptation of TC for the construction industry, was first experimented with by Boldt Construction and Sutter Health in the Tostrud Fieldhouse at St. Olaf's College in Northfield, Minnesota, which was completed in 2006 and has reported a savings in the overall project cost of 19% below the market benchmark (Denerolle 2013). In 2007, TVD was officially introduced as a framework for TC in an attempt to create a link between construction project cost and performance metrics, and to develop a structured framework for its adoption (Ballard 2007; Macomber et al. 2007). The proposed TVD constitutes a comprehensive management system, taking into consideration the effect collaborative behaviour among the multi-disciplinary team members has on the overall project delivery (Jung et al. 2012). Ballard (2007) introduced a five-step process for the application of TVD, and has formed the first construction-based framework of TC as follows: (1) develop project business plan; (2) validate project business plan against client expectations; (3) set targets for values and conditions of satisfaction; (4) steer design to targets; and (5) steer construction to targets. The first two steps deal with understanding the client needs, and the latter three focus on translating those needs into tangible outcomes, during which a TC is set in place. In the TC process, the target cost is allocated into systems, subsystems, and components, where the number of subsystems depends on the complexity of the project. The construction market sets a range of acceptable costs for each type of project; this cost is represented in dollars per building area unit (project unit cost), and is used to provide guidelines to the designers before the design commences. Value engineering (VE) tools and techniques are incorporated into the design process in order to achieve the best monetary value. Both the design and costing undergo a number of iterations until the project cost reaches the project target cost (Ballard 2007).

As a management tool, TVD utilizes several management concepts to improve its propositions. Value engineering plays a key role in the process of achieving the two main objectives of TC; it facilitates the improvement of the overall value of the project while contributing to cost reduction (Denerolle 2013). Building information modelling (BIM) and lean manufacturing have also been incorporated into TVD processes to enhance the value driven from its application in the construction industry (Pishdad-Bozorgi et al. 2013). Traditionally, material quantities can be calculated, to a large extent, during the early design stages after the designers have translated the client requirements into a refined conceptual design, and unit cost is determined at a later stage of the design, after which estimation efforts can be initiated. The application of BIM in TC provides the basis for a value-based design strategy capable of delivering improved quality within a target cost. During the early design stages, a detailed set of material take-off lists covering the project's various components is generated from the BIM model, and a component-based cost is constructed prior to the commencement of a detailed design process. The established links among design, project components, and overall cost steer the design process and help the project management and design teams to reach a mutual understanding in regard to the effect of design decisions on the overall project cost (Pennanen et al. 2011). In studies performed on a number of construction projects, TVD has contributed to an overall cost reduction between 15% and 20% below the market benchmark cost (Ballard & Rybkowski 2009; Zimina et al. 2012). Collaborative efforts bringing together the various disciplines on a project during the implementation of TVD has led to lower costs without compromising project quality (Lavy 2011); moreover, TVD has proven its efficiency in managing project contingencies as a result of its ability to control project cost overrun (Do et al. 2014).

While TC has been extensively studied and analyzed, a gap remains between the proposed principles and practical implementation of the concept in the various sectors of the construction industry (Sampaio 2014). Unlike the manufacturing industry, where the mass production of a product justifies heavy upfront time and cost investments in product development, the construction industry is unique in nature and variant in magnitude, complexity, and repetition. The smaller the project magnitude, the less opportunity there is to fully explore a sufficient pool of alternative designs. Although TVD has proven to be an effective tool in cost reduction and overrun management, it is a highly demanding process in terms of time, effort, and cost, which is detrimental to its adoption as an effective decision support tool. TVD is a manual, time-consuming process that largely depends on the expertise of the project team. It lacks shared uniformity and standardization basics, making it a highly interpretive process. Moreover, the absence of a structured project database reduces the accuracy of benchmark cost due to the high dependency on intuitive decisions to convey the influence of market conditions on setting a target cost according to a desired project design (Zimina et al. 2012). The development of a structured project database is essential for TC as a systematic management approach, as it provides opportunities to standardize construction project characteristics. Standardization of construction projects intensifies the effectiveness of TC application by establishing a set of criteria applicable to a wide range of projects (Jacomit & Granja 2011). The convertibility rate of a construction project into measurable parameters defines its capability for standardization, and, consequently, the project design-estimate automation compatibility. Automating the TC process allows for rapid estimating during conceptual design, resulting in a positive impact on project value-driven design efforts (Pennanen et al. 2011). An intelligent system purposed for embedding the interactions among construction project components, through a set of standardized rules and factors, can provide clear understanding of a construction project as a distinct product with distinguishable characteristics and features, thereby ensuring that the customer's desired product performance is met or exceeded while remaining within the targeted cost. Offsite construction projects' special design requirements set the foundation for design standardization making it the ideal candidate to investigate the automation of the design-estimate process utilizing the TC concept.

Building on the foundation of the original concept of TC in the Japanese manufacturing industry, and driven by the readiness for standardization of the offsite construction industry, the proposed research contributes to the advancement of costing mechanisms applicable to TC by adapting a novel conceptualization suitable for offsite construction projects built on a performance-based evaluation of the constituting sub-systems. In the context of the proposed research, target cost modelling (TCMd), is defined as "*a hierarchical value-oriented cost management technique standardizing offsite construction design-estimate practices by subdividing the project target cost into smaller manageable sub-targets, thereby driving the improvement process through a well-defined set of offsite construction sub-systems with distinct characteristics influencing the overall performance and cost according to specific project design requirements.*"

The representation of design-estimate relationships through a set of dynamic factors capable of identifying and distinguishing the value-added activities maximizes the potential of TC application (Moisello 2012). The proposed TCMd establishes the links between design requirements, project performance, and target cost through the sub-systems' distinct characteristics, which are grouped into two main sets of factors, namely construction and costing factors, with measurable and comparable parameter values. The project scope sets the values of costing parameters governing the cost values of sub-system alternatives, and, through construction factors, project design requirements constrain the range of compatible alternatives with their corresponding performance values.

2.3. *Energy Modelling*

Global awareness of natural resource depletion, greenhouse gas emissions, and environmental pollution has been motivating research efforts toward taking measures during the design stage to reduce the environmental impact of construction projects. The relationship between energy consumption and greenhouse gas emissions has been extensively investigated, for both the manufacturing and construction industries, proving that overconsumption of non-renewable energy resources increases the amount of CO_2 released into the air, which in turn accelerates the deterioration of the environment (Cole 1998; Kim & Dale 2005; Soytas et al. 2007; Nugent &

Sovacool 2014). Researchers have investigated the concept of Design for Environment (DFE), or eco-design, to enhance product performance, optimize energy use, improve material utilization, and reduce cost (Rose 2000; XiaoChuan 2004; Hauschild et al. 2004; Lindahl 2005). Eco-design has been implemented in the manufacturing industry through a well-structured framework with a focus on cost reduction and energy efficiency, the two key factors for the success of DFE as a strategic design system. Energy efficiency is defined as the ratio of a useful output to an energy input. Improving the energy efficiency may correlate positively or negatively with the development cost, which makes understanding the financial impact of reducing energy consumption essential to achieving a balanced energy and cost-efficient design. The implementation of the target costing (TC) concept establishes the ideal environment to link between cost reduction and energy efficiency by incorporating energy consumption measures and analyzing its effect on the overall production cost (Bierer & Götze 2011).

While the manufacturing industry strives to improve the environmental impact and reduce the CO_2 emissions of their products, the construction industry is responsible for an average of 38% of the total greenhouse gas emissions in the U.S., according to the institute of Leadership in Energy and Environmental Design (LEED). The significance of the construction industry's impact on greenhouse gas emissions and global warming is the primary driver of net-zero initiatives aimed at developing more environmentally-friendly buildings (Pless et al. 2009; Kolokotsa et al. 2011; Attia el al. 2013; Cellura et al. 2015; Arroyo et al. 2016). Energy consumption in manufactured products refers to the energy directly spent in the development and utilization of the product. Buildings, on the other hand, are complex systems with multiple functions and utilizations, and each requires a certain amount of energy in order to function. The U.S. energy information administration (EIA) annual report on fuel consumption for 2015 indicates that 37.74% of the total energy consumption is put toward heating and cooling loads versus 11.37% for lighting (see Figure 2-1). Several studies have shown that the vast majority of energy consumption and airborne emissions occur during the occupancy phase of building construction, and that operating energy consumption accounts for over 90% of the total lifecycle consumption (Russell-Smith et al. 2015). Furthermore, the difference between heating and cooling and lighting energy consumption is expected to increase dramatically in colder countries, such as Canada due to the severe weather conditions. Consequently, heat exchange analysis between the building interior and exterior weather has been a major aspect for energy modelling in the consturction industry as a prequisite to enhancing the energy efficency.

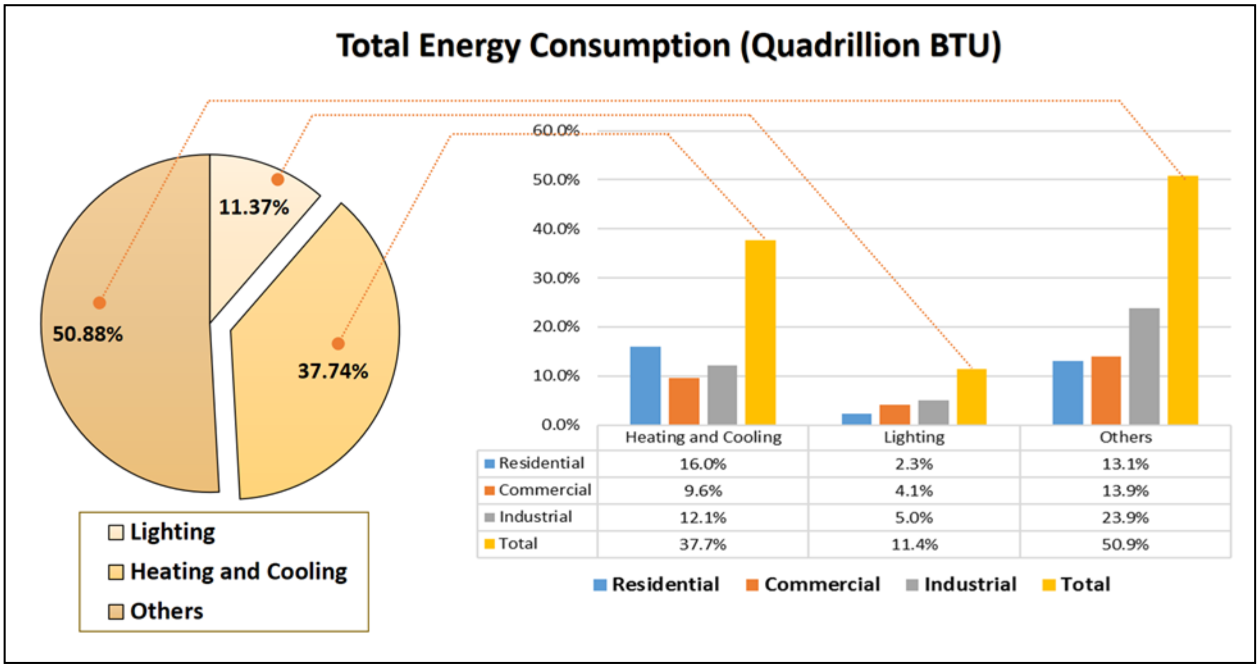


Figure 2-1: Energy consumption by sector (EIA Annual Report 2015)

Energy modelling provides insight into the effect of design decisions on the overall energy performance. Building envelope and heating, ventilation, and air conditioning (HVAC) systems are the two pillars of energy design. Proper HVAC selection governs the operational performance of a building, which makes HVAC energy analysis a key contributor to energy optimization (Salsbury & Diamond 2000).

Although energy simulation models enhance the optimization of energy consumption by allowing alternative evaluation prior to the final design stages (Verl et al. 2011), the accuracy of an energy forecast depends on the appropriate selection of an energy modelling tool (Kośny & Kossecka 2002). The complexity of building structures necessitates a sophisticated modelling software capable of adequately capturing the thermal behaviour of multi-layered building envelope elements. The building envelope, it should be noted, separates the indoor conditioned air from the outdoor air by a group of construction components, including exterior walls, exterior windows and doors, roof systems, and floor and ceiling systems. The two surfaces of building envelope elements usually have two different temperatures, and heat transfers from the hot side to the cold side. In the case of composite multi-layered elements, heat travels faster through the layers with lower heat resistance, which accelerates heat gain and loss though what is referred to as thermal bridging (American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE 2001). Improving building envelope design is essential for the economization and conservation of building energy consumption. The simulation process of the thermal behaviour of building envelope should take into account the interactions among the complex elements. Early energy modelling software for construction projects has failed to accurately reflect a precise thermal behaviour due to the false assumption of building envelope elements as consistent volumes with no effect on the heat transfer path or speed. Kośny & Kossecka (2002) have proposed a three-dimensional analysis to account for building envelope complexity and to precisely model its energy and thermal behaviour.

Despite the vast amount of research targeting the simulation of energy performance during the design stages, the lack of assessment quantification increases the uncertainty of the design evaluation process. The development of measurable and quantifiable factors guides the alternative selection process and improves building performance (De Wit & Augenbroe 2002), and the standardization of energy factors as thermal parameters under a well-structured systematic design approach contributes to the optimization of the process of evaluating building envelope alternatives (Oral et al. 2004). While some design efforts have focused on the holistic process, other researchers have driven the innovation toward the basic element level. The development and utilization of innovative material for construction projects has proven to be a key role in the enhancement of overall energy efficiency (Bribián et al. 2011; Sadineni et al. 2011).

Seeking to improve the environmental impact by economizing the energy consumption without exceeding a determined construction cost for the project, some researchers have studied the interaction between target value design (TVD) and overall lifecycle analysis (LCA). Russell-Smith (2015) has introduced the concept of sustainable target value (STV), which helps to diminish the environmental impact and reduce the construction cost of a building by defining sustainable targets that guide the design process. The development of two STV modelling tools, assessment and validation software, enables the designer to dynamically evaluate different design options for the same project through the development of a set of key construction materials with a predefined pool of alternative values linked to the overall environmental performance. Environmental targets are swiftly met through a number of design iterations by exploring the optimum combination of construction elements that satisfy the environmental requirement and fall within a desired cost.

Although STV provides a good indicator of the environmental effect, it lacks a structured modelling methodology to link the design factors (namely the assemblies) to the energy outcomes. The simplicity in representing design requirements through a high level and small number of assemblies reduces the accuracy of outcomes. Moreover, outcomes are calculated based on static historical data tables for the construction elements with no tangible modelling effort in order to display the interchangeable effects among the different elements. Developing a well-structured energy modelling mechanism requires a comprehensive set of energy factors to cover all aspects of project design and with the ability to quantify the performance difference among each factor alternative individually (or factor-based: how this alternative is better or worse than the rest according to a set of design requirements), and globally (or project-based, which reflects the effect of one factor on the remaining factors, and, eventually, on the project performance).

The present research introduces an innovative collaboration between TCMd and DFE by establishing a well-defined framework for energy modelling that contributes to the optimization of energy consumption and lifecycle cost. Energy factors are defined and standardized in order to build the guideline for selection among alternatives. Mathematical tools, such as neural network, depict the relationship between the energy factors as the key input and energy consumption as the key output.

The incorporation of energy modelling with the TC accounts for the interchangeable effect among the compatible pool of alternatives for all the building components with respect to environmental performance and lifecycle cost.

Chapter 3: Research Methodology

Offsite construction supports the realization of the benefits of advancements in construction technology. In this paradigm, the majority of construction tasks are carried out off site under controlled conditions, reducing and/or eliminating potential waste and deficiencies in the construction process, which translates into reduced cost and improved quality. The special design requirement associated with the shift toward modular construction increases the dependency on project managers' and designers' expertise to achieve a healthy balance between project performance and construction cost, which calls for a comprehensive well-structured decision support system (DSS) to accommodate the manufacturing process and onsite assembly needs. DSS provides the basis to manage project design and cost during the pre-construction phase, as well as to monitor and control the project schedule throughout the offsite manufacturing and onsite assembly phases. Clearly understanding the interaction between the offsite manufacturing and onsite assembly tasks is essential for the success of offsite projects. Figure 3-1 highlights the road map for offsite construction DSS.

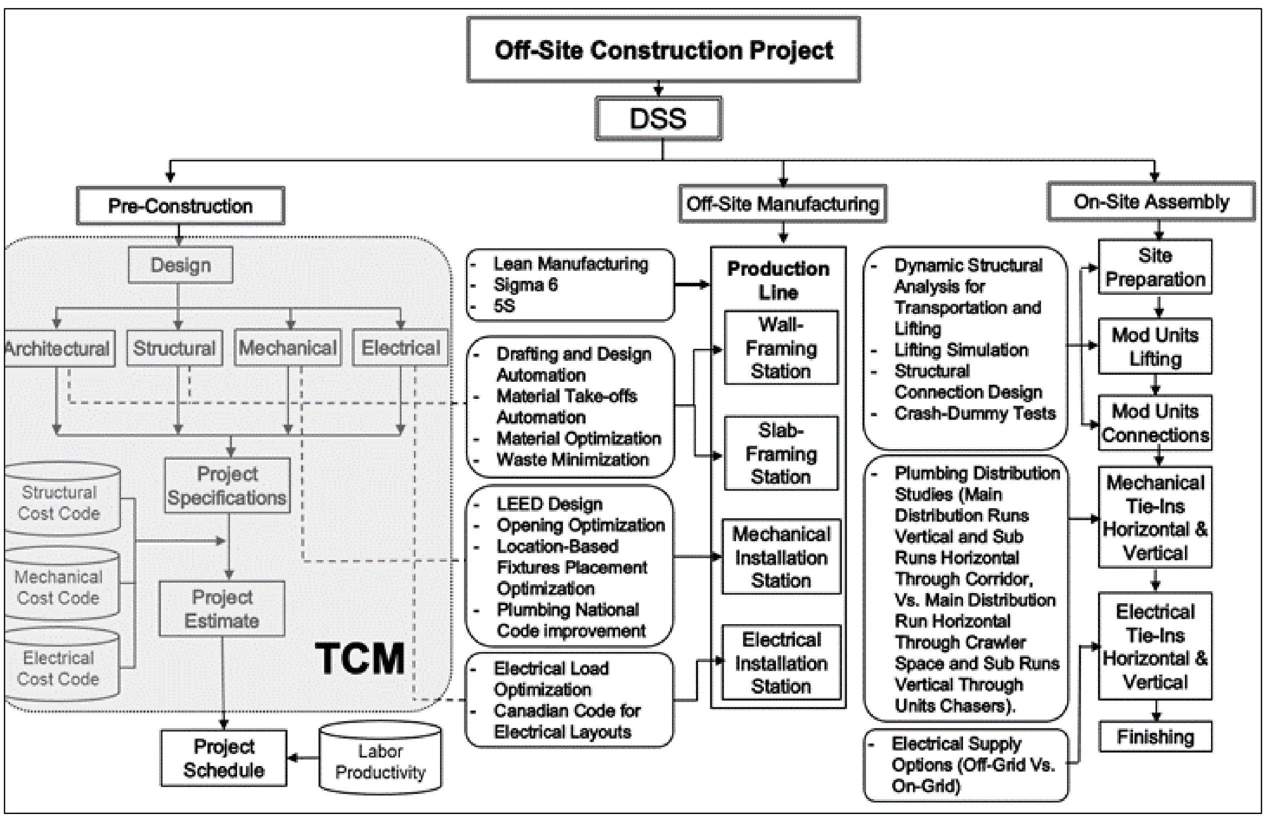


Figure 3-1: Comprehensive modular construction DSS

Offsite construction projects undergo the design-estimate cycle until the project design satisfies the project scope defined by the client, and the project estimate falls within a desired cost. The project schedule establishes a timeline in order for the project to meet a specific completion date. Onsite activities commence with the site preparation tasks, and the offsite manufacturing phase begins with the selection of a modular manufacturing facility to produce the required number of modular units to be delivered on site by a specific date. The modular delivery date is scheduled shortly after the completion of site preparation tasks, which are then followed by modular unit lifting tasks. Concurrently, support structure and insulation components are installed by onsite crews in preparation for the lifting tasks. Upon having the modular units set in place onsite (completion of lifting tasks), structural, mechanical, and electrical tie-in tasks are initiated. Once all the mechanical and electrical tasks are accomplished, the onsite crew performs interior finishing tasks concurrently with exterior finishes. Target costing, lean manufacturing, material optimization, LEED design concepts, and dynamic structural analysis are potential research areas related to composing a comprehensive DSS. As an industrialized process, offsite manufacturing has been the focus of several which have attempted to improve the modular factory productivity and reduce or eliminate waste through the utilization of lean manufacturing, 6 Sigma, and 5S (Tommelein et al. 1999; Orr 2005; Meiling et al. 2012; Moghadam et al. 2012; Brege et al. 2014; Said et al. 2014). Drafting and design automation, material optimization, LEED design, location-based analysis, electrical load optimization, and code studies are all potential research areas to further advance the manufacturing process (Alwisy & Al-Hussein 2010; Smith 2011; Patlakas et al. 2015). That being said, offsite manufacturing studies are outside the scope of the present research; thus, further analyses are recommended for future research in order to develop a comprehensive DSS for offsite construction.

The proposed research focuses on the development of a target cost modelling (TCMd) tool to advance the design-estimate process by enhancing project performance while maintaining a target cost. TCMd provides a complete estimate package including a detailed estimate breakdown associated with a complete project specifications list. As illustrated in Figure 3-2, the key inputs for the TCMd are project design and target cost. Project design defines the project scope, construction systems, and the fundamental project components. Data mining techniques, such as regression analysis, have the ability to capture the relationship between a set of inputs and the respective output. In the design-estimate process, appropriate data-mining can extract trends and hidden patterns from a set of collected modular project information, and can present the links among design inputs and cost output in the form of tangible cost equations for construction components, which allows TCMd to develop costing equations to assess the cost of construction systems based on a given design. Consequently, a design-based project estimate is generated with a predefined combination of project systems.

Rule-based analysis enables TCMd to mimic experts' practices to understand the inter-changeable effect one construction system may have on the entire project. These rules represent the relationship between each of the construction system, and define the compatibility between different systems. Rule-based analysis defines the relationship among modular construction components, laying the foundation for the automation of the target costing process. Programming tools, such as Visual Basic Application (VBA), provide the ideal environment to integrate the costing equations and rule-based analysis to automate the target costing process. Automated TCMd mitigates the risk associated with human error, and enhances the design-estimate process.

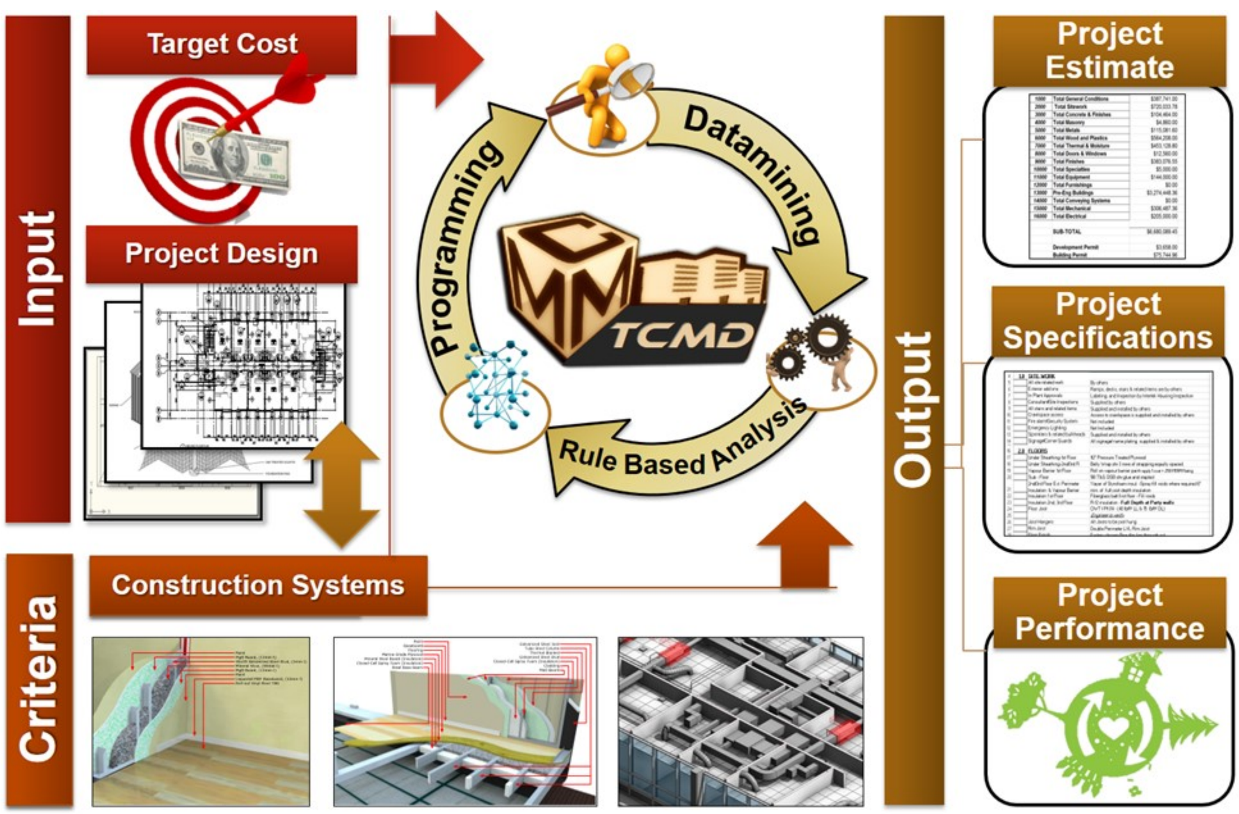


Figure 3-2: Target cost modelling

3.1. Value Ranking Target Cost Modelling (TCMd)

Traditionally, construction projects begin with a high-level scope reflecting requirements put forth by the client. A multi-disciplinary construction team translates the scope into quantifiable project data, defining a set of construction criteria to initiate the design phase. Project type, size, location, and occupancy play key roles in steering the design toward the desired outcome. Project design begins with an architectural design, followed by structural, mechanical, and electrical designs. Once the complete design package is established, a full set of specifications is developed which addresses the various project aspects and provides the necessary baseline information to build a conceptual estimate. Project scope update, represented by design and specification revisions, is required when the project estimate varies from the desired cost. Consequently, a large number of iterations may be necessary during the design-estimate phase. Scope changes create further challenges that result in increased delays, potential revenue loss, and increased design cost.

TCMd involves a systematic approach capable of automatically transforming a set of distinct design inputs into desired outputs by following a well-structured process built upon the clear understanding of project components and interchangeable interactions governing the project cost and quality. TCMd allows the client to set the key input values represented by a target cost (TC$), high-level scope, and a conceptual project design. It then examines the validity and compatibility of input values by comparing the target cost against the minimum project estimate that satisfies the required design. A low value of TC$, i.e., less than the minimum project estimate, entails the need to terminate the process and propose a scope change and/or a target cost increase; on the other hand, an appropriate TC$ value results in a compatible set of input values and the development of a project estimate along with a complete set of specifications (the desired modelling output). Scope change effect is minimized as a result of the automated process. Figure 3-3 shows a comparison of the traditional and TCMd cost-estimate processes during the pre-construction phase.

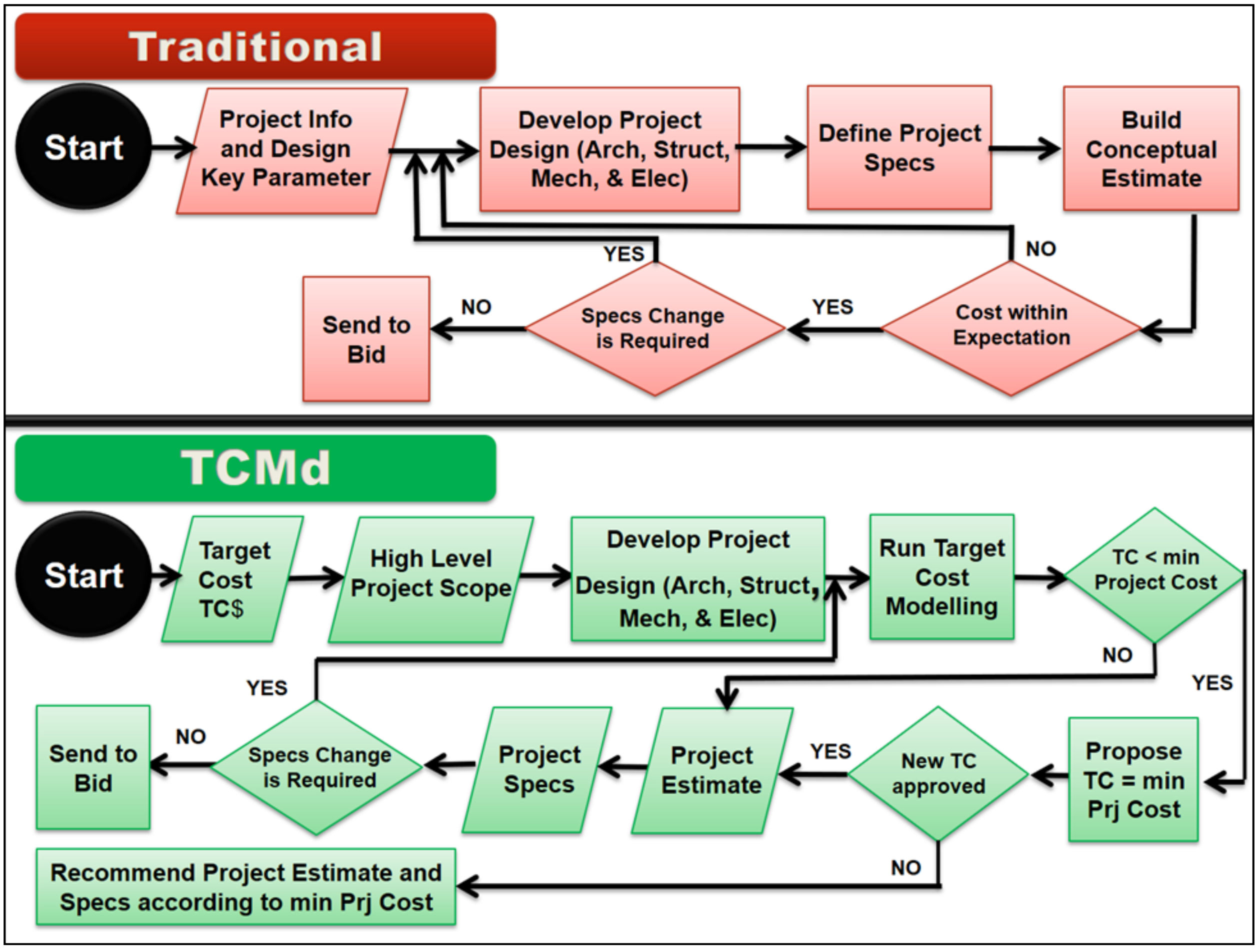


Figure 3-3: Traditional & TCMd design-estimate process

The successful application of TCMd is closely linked to its ability to translate the interchangeable effect among construction components into quantifiable functions that control project cost and performance through a distinct set of measurable construction and costing factors working together under well-structured rules. Construction projects are complex systems with a number of multi-level interactive components, each having direct and indirect effects on the overall project performance. The individual attributes or characteristics of construction components account for the direct effect; indirect effect is defined through the interactions among project components, where each construction component influences a group of components, i.e., dependent set $\{Dd_i\}$, and is influenced by other groups of components, i.e., depending set $\{Dg_i\}$ (see Figure 3-4). Construction components, which form the depending and depended sets, may interact with one another, thereby creating other levels of dependency. A given construction component (CC_i) may be affected by another component (CC_j), which in turn is affected by a third component (CC_k), and the latter is controlled by the first. The circular interaction among construction components is a key factor in the ambiguity and complexity of construction projects. In the context of the present research, component interaction is referred to as component interchangeable relationship effect.

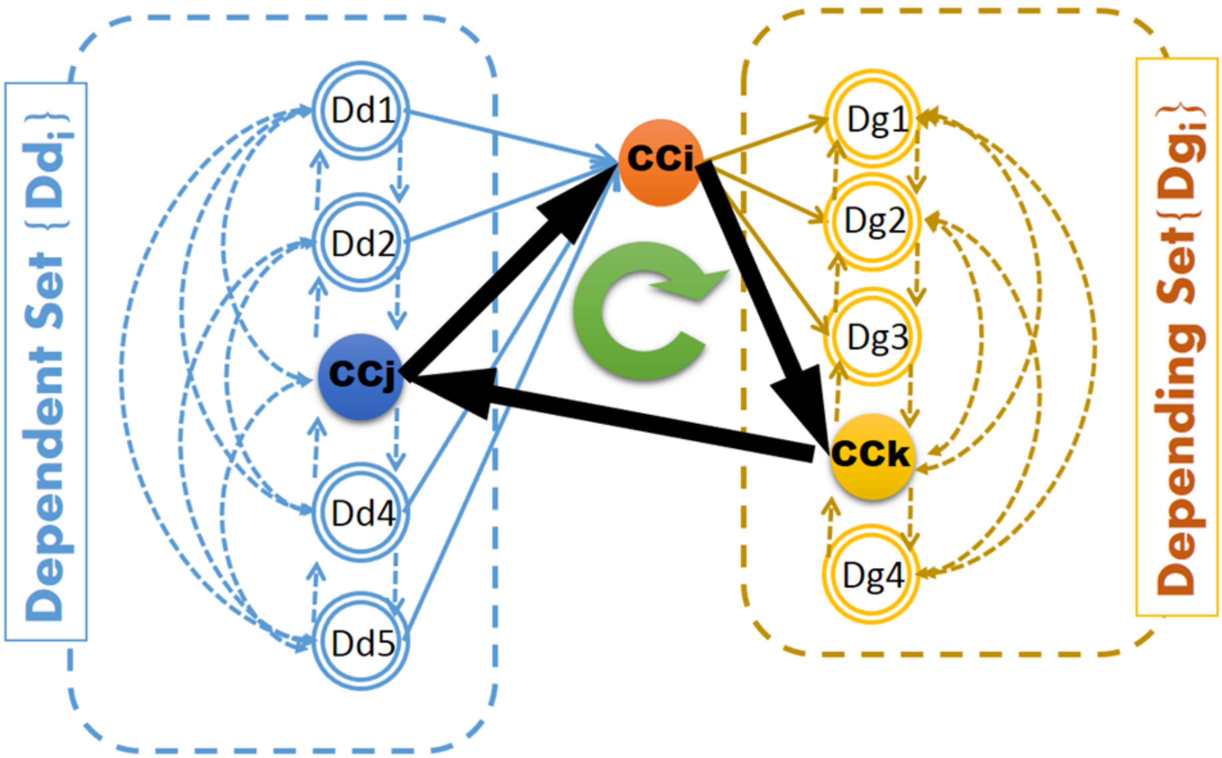


Figure 3-4 Construction component interchangeable relationship

Moreover, the unique nature of construction projects introduces another challenge to the implementation of TCMd: different project types have different design criteria, rules, and requirements. This variety of design standards increases the complexity of construction projects, and reduces the accuracy of the mathematical representation of component interactions, which makes finding the appropriate construction systems essential to efficiently applying TCMd as a design-estimate management tool. Offsite construction projects provide the ideal venue for exploring the implementation of TC in the construction industry, the well-structured rules followed during the modular-driven project design facilitate the standardization of the relationships between design and cost, and the similarity between offsite construction and the manufacturing industry facilitates the adequate representation of key construction characteristics into a predefined set of construction and cost factors, which in turn establishes a link between project designs and desires.

A clear understanding of the fundamentals of offsite construction best practice is essential to any effort to highlight the underlying rules and criteria utilized during the development of construction and cost factors necessary to support the transformation of interchangeable effects into measurable mathematical functions capable of adequately representing the relationship between project design and desired outcome.

To remain congruent with the proposed research objective, value ranking TCMd requires the achievement of four main tasks as follows:

1- Offsite construction project dataset development
   a. Offsite project data collection
   b. Offsite sub-assembly alternatives
2- Sub-assembly system value and compatibility analysis
   a. Offsite construction factors
   b. Value ranking system
   c. SAS compatibility matrix development
3- Costing equation formulation
   a. Offsite costing factors
   b. Regression analysis
4- Value ranking rule-based analysis
   a. First alternative filtering (design factors)
   b. Second alternative filtering (baseline SAS distribution)
   c. Priority factors iteration process
   d. TCMd performance-based iteration process

The developed dataset provides the framework for target cost unit distribution, whereby utilizing data-mining techniques costing equations are defined. A compatibility matrix interprets the interactions among the various alternatives on the three levels of WBS and constrains the selection process. Rule-based analysis supervises the alternative selection process based on design and performance factors. Figure 3-5 shows the principal target costing methodology, where market conditions, competition, and financial forecast influence the expected targeted price and targeted profit for a given project. Client requirements refine the design process, and TCMd provides project cost and specifications.

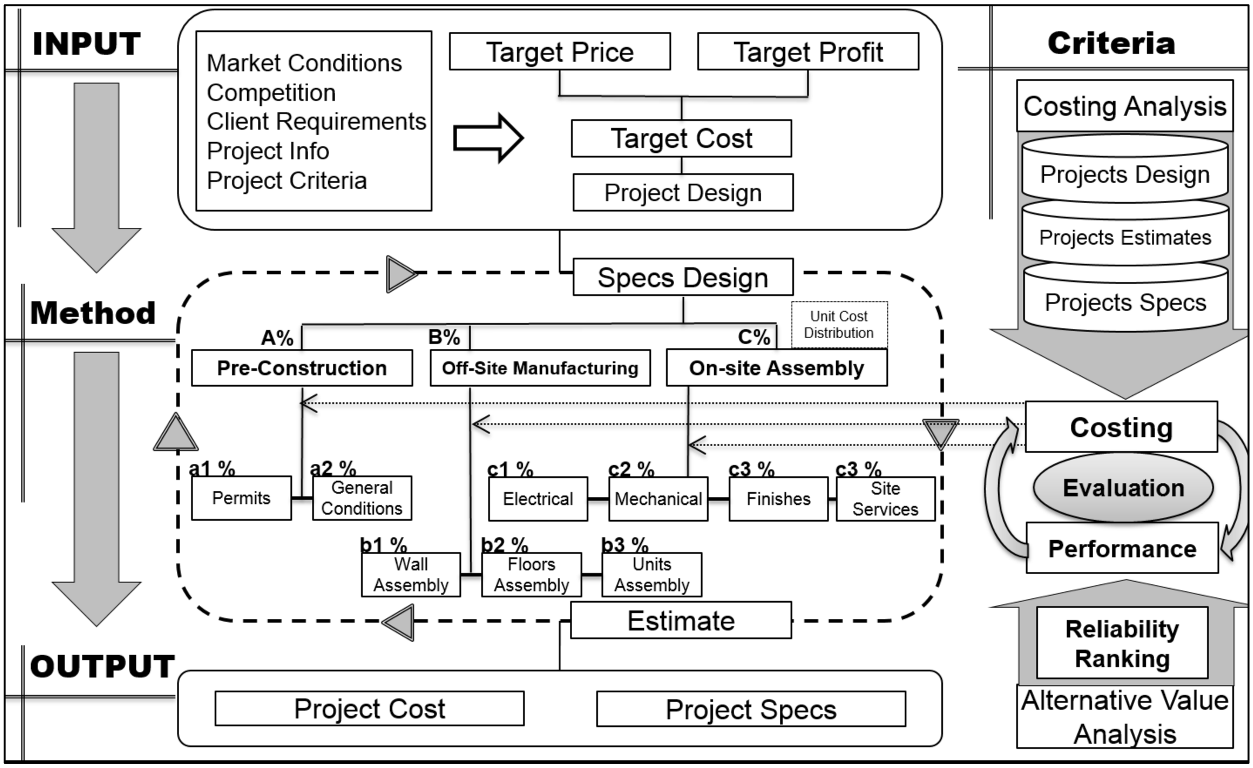


Figure 3-5: TCMd principal methodology

3.1.1. Offsite Construction Project Dataset Development

TCMd identifies and groups offsite construction projects under a three-level hierarchical work breakdown structure (WBS); each project has (n) number of assembly system (AS_i), and an assembly system (AS_i) contains (n_i) number of sub-assembly systems (SAS_{ij}), which, in turn, is composed of (n_{ij}) number of construction components (CC_k). Figure 3-6 illustrates one of the assembly systems (plumbing system), which has a number of assembly systems, such as the plumbing distribution SAS, which in turn has a number of construction components such as plumbing pipes and fittings.

The present research identifies six core assembly systems: (1) site work, (2) building envelope, (3) plumbing systems, (4) HVAC systems, (5) electrical work, and (6) finishing. Each assembly is made up of a number of sub-assembly systems. Table 3-1 lists the main assembly system breakdown according to the proposed research.

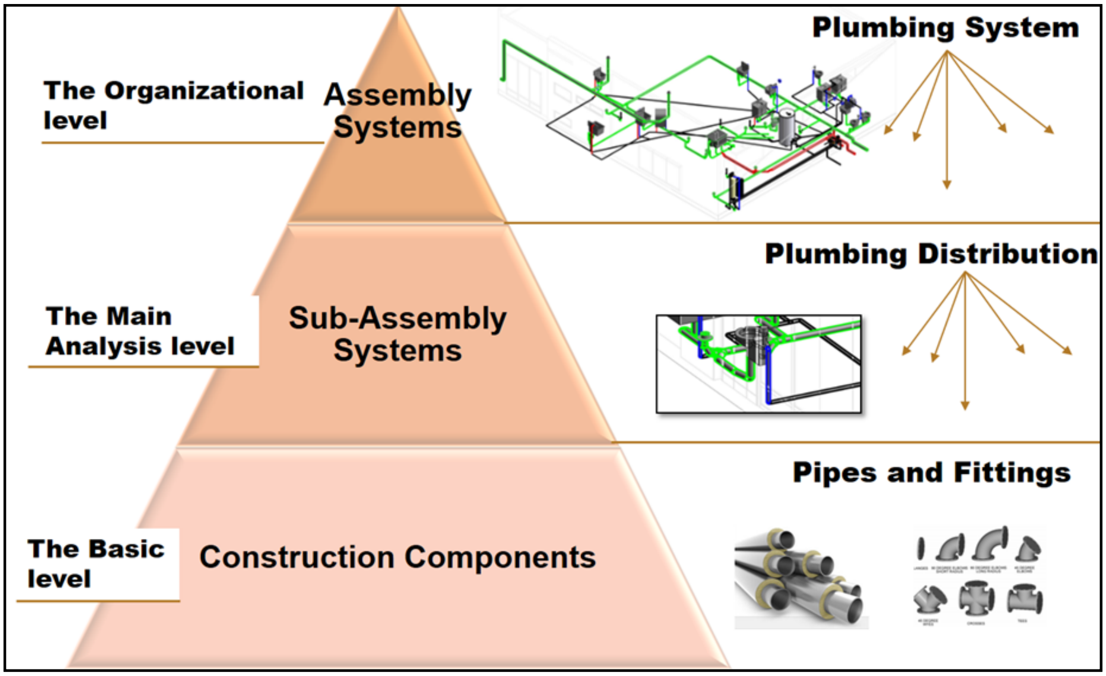


Figure 3-6: TCMd three-level hierarchical structure

Table 3-1: Main assembly systems breakdown

		Assembly Systems					
		Site work	**Building Structure**	**Plumbing System**	**HVAC System**	**Electrical Work**	**Finishes**
Sub-assembly System (SASs)	**1**	General Conditions	Exterior Walls	Plumbing Fixtures	Heating and Cooling System	Electrical Service/Distribution	Exterior Finishes
	2	Site	Interior Walls	Plumbing Distribution	Ducting	Lighting and Branch Wiring	Wall Finishes
	3	Foundations	Windows		Fire Protection Systems	Other Electrical Systems	Floor Finishes
	4		Doors				Ceiling Finishes
	5		Roofing Systems				Millwork
	6		Floor Systems				Cabinets & Countertops
	7		Ceiling Systems				Furniture & Appliances
	8		Modular Onsite Connections				

SAS involves a unique structure based on the key construction components which constitute it. SAS cost and performance are controlled by available alternative values, where components interact among one another to draw the guidelines for a sub-assembly's key properties. For instance, an exterior wall sub-assembly system comprises 14 key components (see Table 3-2), and the wall heat transfer coefficient (U-value) is influenced mainly by the insulation, one of the construction components; other components, such as stud dimensions, spacing distance, spacing pattern (uniform, staggered, etc.), sheathing type and thickness, and drywall, also have a significant impact on the R-Value.

While Heating resistance is one of the performance factors to be considered for an exterior wall sub-assembly system; other factors include loading capacity, fire resistance, sound isolation, and rigidity, all of which are directly influenced by the 14 key CCs.

Table 3-2: Exterior wall components

Sub-Assembly System (SAS)	**Construction Components (CCs)**	
Exterior Walls	Weather protection - temp	Bottom-plate
	Building paper	Belt rail/Mid span blocking
	Exterior sheathing	Vapour barrier
	Exterior fasteners	Interior sheathing
	Insulation	Gypsum
	Studs	Gypsum fasteners
	Top-plate	Gypsum finish

In the context of this research, CCs are defined as the basic building blocks of an offsite project, having distinct and measurable properties in terms of cost and performance. CCs take one of two forms—either complex or simple. A window with a defined exchange heat coefficient (R-Value) is considered a complex component, while a 2×4 wood stud is a simple one.

The three-level structure clarifies the integration of unit cost from the component level to the total project unit cost. Construction Component unit costs are integrated to determine the SAS unit cost, and, in turn, the integration of SAS unit cost gives the assembly system unit cost, and the project total unit cost is the sum of all main assembly systems. In this respect, the construction unit cost can be defined satisfying Eq. 1.

$$U(\$/\text{ft}^2) = \sum_{i=1}^{n_1} X_i = \sum_{i=1}^{n_1} \sum_{j}^{n_2(i)} Y_{i,j} = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2(i)} \sum_{k=1}^{n_3(j)} Z_{i,j,k} \qquad [1]$$

where the construction unit cost U is expressed as a sum of the unit costs of the main building assembly systems $\{X_i\}_{i=1,2,\cdots,n_1}$, which, in turn, are related to those of the sub-assemblies $\{Y_i\}_{i=1,2,\cdots,n2}$, and finally to the unit cost of the construction components $\{Z_{i,j,k}\}_{k=1,2,\cdots,n_3}$. Note that the upper limits for sub-assemblies, $n_2(i)$, as well as for the sub-assembly components, $n_3(j)$, depend on the indices associated with the main assembly and sub-assembly, respectively.

3.1.1.1. ***Offsite project data collection***

Data collection is performed by means of structured data collection forms in order to build a well-structured dataset for each assembly (AS), sub-assembly (SAS), and construction component (CC), which includes parameters related to the cost of fabricating and installing these assemblies and sub-assemblies. TCMd data structure is hierarchical and template-based, with interactive parameters accounting for the unique nature of construction projects. Construction components are organized into a set of sub-assembly templates, from which the assembly templates are formed, and project templates are composed of a specific combination of assembly templates. Table 3-3 illustrates the SAS data collection form for an exterior wall. Data is collected for the 14 components associated with the offsite construction project's exterior wall sub-assembly system.

Table 3-3: Exterior Wall SAS Data Collection Form

Exterior Walls System - Load Bearing	**Construction Component Values**
Weather Protection - Temp	N/A
Building Paper	Tyvek House wrap or equal
Exterior Sheathing	3/8″ OSB
Exterior Fasteners	5/8″ GlasRock Gold - Type X
Insulation	R-20 fiberglass batt insulation
Studs	2×6 @ 16″ oc - (c/w double top plate)
Top plate	2 - 2×6 KD SPF - # 2 or better
Bottom Plate	1 - 2×6 KD SPF - # 2 or better
Belt Rail/Mid Span Blocking	N/A
Vapour Barrier	6 mil poly
Interior Sheathing	3/8″ OSB
Gypsum	1 layer 5/8″ type "X" gypsum board,
Gypsum Fasteners	Staples
Gypsum finish	Gypsum board glued and screwed to interior sheathing, Painted Finish

The left column represents a generic list covering all possible construction components that a SAS may contain whereas the right column characterizes the values collected from a specific project from the pool of available datasets. It is important to note that, for the purpose of computer implementation, the SAS-related data listed in Table 3 can be formalized according to Eq. 2,

$$SAS_i: \ \{(CC_j, VC_j)\}_{j=1,\cdots,n(i)} = \bigcup_{p=1}^{P} \{(CC_{j,p}, VC_{j,p})\} \quad [2]$$

in which $\{(CC_j, VC_j)\}_{j=1,\cdots,n(i)}$ is the set of construction components, CC_j, and their corresponding values, VC_j, describing sub-assembly SAS_i, which, in the case of P projects, are obtained through the union of all project-based construction components and values, ($CC_{j,p}$, $VC_{j,p}$) In the same way, project data is analyzed on the lowest level of the predefined work breakdown structure (WBS)—the construction component level. Project layouts, estimate sheets, and specification lists are studied to supply sufficient details necessary to store the data under the three-level structured framework.

TCMd is based on the clear understanding of the fundamental technical specifications of each of the SA, SAS, and CC of a project, which sets the foundation for the development of construction and costing factors required for the presented process. What follows is a technical review of the illustrated example of the construction components (14 CCs) of the exterior wall SAS as listed in Table 3-3.

The first component (CC_1), temporary weather protection, is not provided a value, which indicates that there are exterior finishes attached to it, as weather protection is essential in order to account for any external effects from the weather. CC_2, building paper, is listed as a typical commercial brand (Tyvek). CC_3 is 3/8″ OSB sheathing, which is attached to the external face of the wall using 5/8″ gold screws, listed as CC_4. Exterior sheathing provides the required rigidity for the wall and minimizes the building settlement—compression of shrinkage of a building components—after the project is assembled and all the loads have been applied. CC_5, wall insulation, is composed of R-20 fiberglass batt insulation, which has the most significant impact on the wall heating resistance among the components. CC_6 refers to typical 2×6 SPC studs that are used to frame the wall with a bottom-plate, which is noted as CC_8, as well as double-top-plates, which are listed as CC_7. The spacing of 16″ O.C.—measured from centre-to-centre of two adjacent studs—and the 2×6 dimension, governs the load bearing of the wall. Depending on the dead and live loads calculated for a specific project, spacing may be reduced to 12″ to provide higher loading capacity. The displayed example illustrates a project where the lateral load is minimal, and there is no need for belt rail/mid span blocking, which is indicated as CC_9. In other cases, when the exterior wall extends more than 12 ft, it will be considered a tall-wall, and in these cases the national building code requires a special structural detail to prevent wall buckling. Dynamic loads, which are applied during the modular unit loading, unloading, travelling, and craning, are considered in the design of wood stud dimensions and spacing. Sheathing type, number of layers, and thickness also influence the wall rigidity necessary to resist dynamic load deformations. CC_{10}, vapour barrier, is a typical 6 mm polyethylene sheet which serves to prevent moisture from reaching the drywall layer. CC_{11} is interior sheathing of 3/8″ OSB, which serves to increase the wall rigidity. CC_{12}, 5/8″ Type-X gypsum board, is fastened to the wall studs with staple (CC_{13}) to account for the interior face of the wall; and finally, a typical 3-coat paint (CC_{14}) is applied.

As per the illustrated sample, project data is analyzed on the lowest level of the predefined offsite construction project WBS, the construction component level. Project layouts, estimates sheets, and specification lists are studied in order to supply sufficient details necessary to store the data under the three-level structured framework. Different projects provide different component alternative values, and the total number of construction component alternative values is equal to the number of projects collected, (n) projects. Consequently, the number of SAS and AS alternative systems gathered is also equal to (n). The displayed values in Figure 2-6 illustrate one type of exterior wall in a modular unit, where the wall is part of the building envelope and is defined as an exterior wall; other scenarios include a wall facing a corridor or the wall between units, as shown in Figure 3-7.

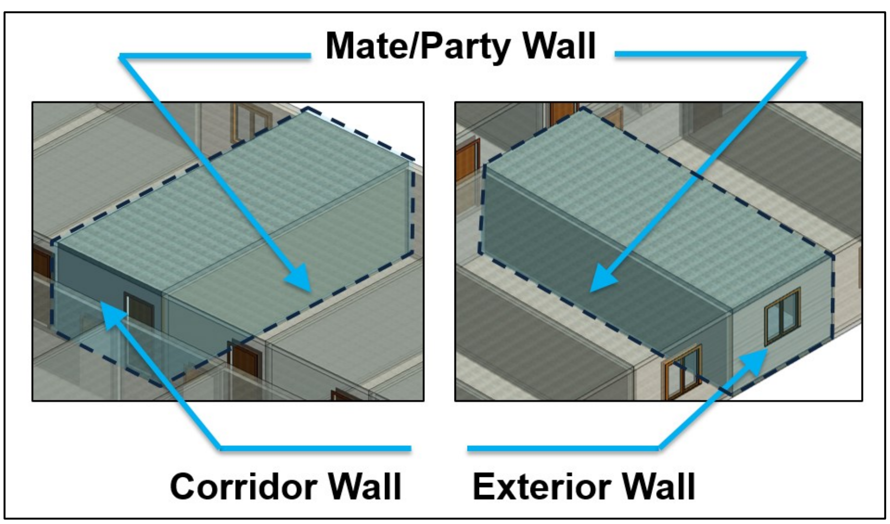


Figure 3-7: Modular unit exterior walls

3.1.1.2. ***Offsite sub-assembly alternatives***

The proposed TCMd analysis considers SASs as the key representatives of all the relationships in offsite construction projects. SASs represent the fundamental level on which costing and performance studies are implemented, as CC behavioural interactions and effects are characterized through their respective SAS. Consequently, a further analysis on the (n) SAS alternative values from the collected dataset is required. During the data collection process, two key properties are associated with SAS alternative values: a description of construction elements, and a cost value for a specific project. The description of construction elements reflects the alternative construction system used according to some desired performance criteria, and the cost value, represented by a unit cost or cost distribution, is influenced by design criteria including project size, type, location, and complexity.

The data collected from the available pool of offsite projects—25 projects in total—shows that only 10 exterior wall systems exist, and different projects, such as P14 and P16, can have the same systems. Figure 3-8 shows SAS alternative values for an exterior wall. In summary, the number of construction systems used for offsite construction projects is less than the number of projects collected, as different projects can use the same construction system on the sub-assembly level.

	A	B	C	P	Q	R	S	T	U
1		Project Components	Description	P13	P14	P15	P16	P17	P18
736		Building Structure							
737		*Exterior Walls*							
738		Ex W 1.1	Exterior Walls System - Load Bearing 1						
751		Ex W 1.2	Exterior Walls System - Load Bearing 2						
764		Ex W 1.3	Exterior Walls System - Load Bearing 3			$/SF			
777		Ex W 1.4	Exterior Walls System - Load Bearing 4	$/SF					
790		Ex W 1.5	Exterior Walls System - Load Bearing 5						$/SF
803		Ex W 1.6	Exterior Walls System - Load Bearing 6 - Steel						
816		Ex W 1.7	Exterior Walls System - Load Bearing 7						
829		Ex W 1.8	Exterior Walls System - Load Bearing 8		$/SF		$/SF		
842		Ex W 1.9	Exterior Walls System - Load Bearing 9					$/SF	
855		Ex W 1.10	Exterior Walls System - Load Bearing 10						

Figure 3-8: Exterior wall SAS alternative values

3.1.2. Sub-assembly system value and compatibility analysis

Compatibility matrix is essential for the understanding of construction projects. It is an expert system that defines the interactions among the available SAS alternatives influencing the overall performance of an offsite project. As each sub-assembly can take one of several available alternatives for an offsite construction project, compatibility rules limit the selection process to those well-suited to work with one another without any conflict. Some rules are based on design criteria, while others are related to improving the project performance in a specific area, in which

PM experience plays a vital role in the selection process. For instance, shingles cannot be used on a flat roof, as a minimum slope of 2.5/12 is necessary to achieve the desired waterproofing for the roof. This is a design criteria based on building code. Another example is related to the decision of using a central hydronic heating system for a commercial building, rather than an electrical baseboard or a forced air heating system, depends heavily on the design/PM expertise and practical knowledge; while all systems can satisfy the code regulations, the hydronic system is proven to have the lowest operating cost suited to the large open spaces associated with commercial design.

The comparative analysis of SAS alternatives entails the development of a set of key factors for each system to provide the guideline for the compatibility study and clarify the relationship between a specific SAS alternative and the corresponding performance or design effect. Offsite construction factors clarify the relationship between SAS by translating their interactions into distinct factors, and value ranking is performed based on the values given to SAS to reflect the associated performance value for each alternative. The following sections will describe the standardization of SASs through a set of construction factors in order to analyze SAS performance value and compatibility in the context of off-site construction.

3.1.2.1. ***Offsite construction factors***

Construction factors (CnFs) are the main prerequisite for the compatibility matrix; they define the baseline rules for the selection process by focusing on the parameters that distinguish the performance difference among SAS alternatives. Construction factors are divided into three central streams:

1) *Quantitative:* a numeric value is translated into a distinct value based on a defined range. For instance, a project is defined based on the floor area (FA) as illustrated in Eq. 3.

$$\begin{cases} X_1 \leq FA & \text{Large project} \\ X_2 \leq FA < X_1 & \text{Regular project} \\ X_2 < FA & \text{Small project} \end{cases} \qquad [3]$$

2) *Descriptive:* factors take a value of Yes/No; they express the inclusion or exclusion of a certain sub-assembly in an offsite construction project. For example, a building can be built with or without a deck.
3) *Qualitative:* the key properties of a construction sub-assembly govern its performance in a specific area. For instance, in the context of this research, the key properties distinguishing exterior wall alternatives for a specific design are as follows: (*i*) *Rigidity*, which represents

the resistance of a specific wall against bending forces during the shipping and craning tasks. A wall with low rigidity suffers major cracks in the gypsum board layer, which requires significant repairs on-site, and limits the ability to finish the wall in the controlled and efficient environment of the factory. (*ii*) *Heat Resistance*, which is represented by R-value, and is mainly controlled by the wall thickness, stud framing technique (uniform or staggered), and the type of insulation. (*iii*) *Fire-Rating*, whether it is 45 minutes of fire resistance, 1 hour, or 2 hours. The number and type of sheathing and drywall used in a certain wall determine its fire rating; other factors, such as building structure, loading, loading capacity, insulation type, and sound isolation, influence the wall performance and cost. Similarly, construction factors are defined for the SASs constituting an offsite construction project. Figure 3-9 shows the key construction factors associated with an exterior wall sub-assembly.

26	**Building Structure**			
27	*Exterior Walls*			
28	***Fire-Rating***	*High*	*Low*	*Non*
29		FR>2 hr	2>FR>=45 min	FR<45min
30	***Building Structure***	*Wood*	*Steel*	*Pre-Engineered*
31				
32	***Loading***	*Load bearing*	*Non-Load Bearing*	
33				
34	***Building Envelope***	*On the exterior side*	*between mod units*	
35				
36	***Loading capacity***	*High load*	*medium load*	*low load*
37		LL>=50	50>LL>=40	LL<40
38	***Wall Insulation***	*Batt*	*Rigid*	*Foam*
39				
40	***Wall R-value***	*High*	*Medium*	*Low*
41		R>=20	20<R<=12	R<12
42	***Sound Isolation***	*Good*	*Normal*	
43		Staggerd Framing	Uniformed Framing	
44	***Rigidiity***	*High*	*Medium*	*Low*
45		Sheating >= 3x 5/8"	3x 5/8" >Sheating>=2x 1/2"	Sheating < 2x 1/2"

Figure 3-9: Exterior wall construction factors

Offsite construction factors shed light on the hidden links connecting the different SASs in an offsite construction project by establishing measurable and comparable ranges of values that define the inter-changeable effects one system has on another. For instance, key factors defining the interaction between an offsite project's electrical system and HVAC system, as two distinct SASs, are the "main panel capacity" of an electrical system and the "electrical requirement" of an HVAC system. In the scope of the present research, an electrical system is considered high-capacity when the panel capacity is greater or equal to 200 Amp, and low-capacity when it is less than 200 amp. HVAC system electrical requirement is defined within a range of three values (high demand, medium demand, and low demand), where any electrical-based heating system, whether an electric packaged terminal air conditioner (PTAC) system, or electric baseboard heating, is categorized under the high demand category, and the electrical system used must have a high-capacity main panel.

3.1.2.2. *Value ranking system*

In the scope of the present research, *SAS value ranking is a ranking system that evaluates the performance of SAS alternatives according to key construction factor values.*

The value ranking of a SAS is based on the value of its construction factors and the quality of a specified SAS alternative value system. Alternative value rankings are generated by evaluating SAS alternatives against their key construction factors, and a 5-point ranking system is followed, where $Rn(CnF_{ij}) = 1$ is the lowest ranking, and $Rn(CnF_{ij}) = 5$ is the highest for a construction factor. SAS alternative quality is represented by assigning percentage values for each of the construction factors, where $W_{ij} = 100\%$ indicates that the alternative is of the highest possible quality for the specified construction factor, and $W_{ij} = 0\%$ represents frequent quality problems with the selected alternative. Based on focus group meetings with industry representatives, the quality reflected from the collected data ranges between $W_{ij} = [50\%, 95\%]$. The present research represents quality through a defined set of weights (W_{ij}) associated with each construction factor value sub-ranking [$Rn(CnF_{ij})$]; for instance, the quality of window framing can be dependent on the manufacturing company, window series, and installation parts (fixed, casement). The SAS alternative ranking factor is equal to the total ranking values of all its construction factors, as expressed in Eq. 4.

$$SAS_{\mathrm{i}}: Rn_i = \sum_{j=1}^{n} Rn\ (CnF_{ij}) \times W_{ij} \qquad [4]$$

For instance, in the context of the present research, a window SAS has four construction factors: window glazing, window type, window material, and window R-value.

Window Glazing (CnF_1) indicates the number of glass panes in a window; typically, in the Canadian construction market, the alternatives are either double-glazed or triple-glazed windows. Double-glazed windows form a void in the window structure that is usually filled with air, or more recently low E argon gas, that acts as an insulation layer in the window body. Triple-glazed windows contain two layers of void, which provides higher heat resistance, and, in turn, a higher ranking value (R): *Double:* $Rn \in [1, 3]$, *Tripe:* $Rn \in [4, 5]$.

Window Type (CnF_2) is defined based on the function of the window, namely slider or awning. Awning is preferred to slider due to its superior performance during freezing conditions compared to slider window. *Slider: $Rn \in [1, 3]$, Awing: $Rn \in [4, 5]$.*

Window Material (CnF_3) designates one of three values a window frame can derive: PVC, metal, or wood. Generally, metal windows are made of aluminum frames that are more durable than PVC or wood windows, thereby providing a longer lifespan before the need for replacement due to cracks or deformation. Wood-framed windows possess a higher R-value than PVC windows, and are considered a high-end window due to their aesthetic contribution to the building, which may be a client requirement. Consequently, the ranking of windows based solely on the lifespan of framing material is 40 years for aluminum, 35 years for wood, and 22.5 years for PVC (Asif et al. 2002). *PVC: $Rn \in [1, 2]$, Wood: $Rn \in [3, 3]$, Metal: $Rn \in [4, 5]$.*

Window R-value (CnF_4) is the heat resistance coefficient, where, the higher the R-value is, the less heat exchange (loss/gain) occurs. The most commonly used window R-value ranges between 1.2 (h F ft^2/BTU) for single pane and 4.1 (h F ft^2/BTU) for triple pane. Consequently, the ranking value of CnF_4 is divided into three levels: low— $1.2 \leq RV < 2$, medium— $2 \leq RV < 3$, and high— $RV \geq 3$. Each level is assigned to a specific range to reflect the correspondent ranking value: *Low— $Rn \in [1, 2]$; Medium— $Rn \in [3, 4]$; High— $Rn \in [5, 5]$.*

The four construction factors of the window SAS have the following (user or expert-defined) scores, as listed in Table 3-4.

Table 3-4: Illustrative example of value ranking using a window SAS

Construction factors	Expert-defined score options		
Glazing	Double: $Rn(CnF_{ij}) \in [1, 3]$	Triple: $Rn(CnF_{ij}) \in [4,5]$	
Type	Slider: $Rn(CnF_{ij}) \in [1, 3]$	Awing: $Rn(CnF_{ij}) \in [4,5]$	
Material	PVC: $Rn(CnF_{ij}) \in [1, 2]$	Wood: $Rn(CnF_{ij}) \in [3,3]$	Metal: $Rn(CnF_{ij}) \in [4,5]$
R-value	Low: $Rn(CnF_{ij}) \in [1, 2]$	Medium: $Rn(CnF_{ij}) \in [3,4]$	High: $Rn(CnF_{ij}) \in [5,5]$

Using the data in Table 4, the scores associated with any given window SAS can, therefore, be represented by a vector in R4, as per Eq. 5,

$$(\text{Glazing} = \text{Double}, \text{Type} = \text{Awning}, \text{Material} = \text{Wood}, \text{R-value} = \text{Medium}) = (2, 5, 4, 4) \quad [5]$$

Alternative value factors play a vital role during the optimization of the project cost against a desired target. Figure 3-10 shows the ranking result for one of the window alternative systems, which includes the expert-defined scores and the weights for each construction factor.

Windows					Window Glazing			Window Type			Window Material			Window R Value
W 1.1	PVC Slider 1	2.08	65%	3	Double Glazing	85%	2	Sliding	75%	3	PVC	80%	3	Medium
Exterior Window	White Vinyl c/w Low-E Argon c/w PVC Liner, Horizontal Sliders-, c/w Grace Vycorner-no expanding foam around window	-												
Window Flashing/Liner	Window flashing and end dams - Onsite	-												
Window Coverings		-												

Figure 3-10: Window value ranking

3.1.2.3. ***SAS compatibility matrix development***

Compatibility matrix rules constrain the selection of SAS alternatives during the optimization process. There are two key types of compatibility rules necessary to capture the acceptable links within the pool of available SASs: **(1) Design-based rules (DBR)**, which are governed by the design requirements specified by the project layouts as well as client requirements and preferences; and **(2) Performance-based rules** (**PBR**), where practical knowledge of construction projects is used to evaluate the different construction components and sub-assemblies. The benefits of PBR realized during the construction phase are represented in terms of improving the constructability of onsite assembly and reducing installation cost. Enhancing the building performance and reducing the maintenance cost during the operational phase of the project are other direct results of PBR application.

At the component level, the compatibility matrix is mainly related to the constructability of the sub-assembly associated with the components. For instance, when using an open web truss (OWT) joist, the floor rim joist must be made of engineered laminated veneer lumber (LVL). A solid lumber dimensional rim joist cannot be associated with OWT as it has standard dimensions (2×6, 2×8, 2×10, etc.), which can only suit a solid lumber floor joist system. Another example is the use of mechanically graded lumber versus visually graded lumber. Mechanically graded lumber is of higher quality than the latter: it is straighter and easier to install on site. Modular factories that utilize a machine-based production line require mechanically graded lumber due to its higher quality and consistency, as the use of visually inspected lumber could result in a complete shutdown of the production line if a blockage in the manufacturing machinery occurs due to a quality issue with the lumber. Compatibility rules on the component level are embedded within the pre-defined SAS structure collected from the pool of selected offsite construction projects. The proposed research focuses on the compatibility matrix at the sub-assembly level. In this research offsite construction projects are divided into six assembly systems and 26 SASs. During the rule-based analysis, the relationships among the 26 SASs are analyzed using construction factors.

Understanding the relationships among the construction factor values enables the understanding of the relationships among the SASs and their alternatives. Compatibility matrix analysis of two construction factors can yield one of three values: (1) YES, which means the two factors from two SASs can work together in the same project; (2) NO, in which case the selected alternative SAS is considered incompatible with the other SAS; (in this case, an evaluation is carried out as to which SAS should be retained or discarded based on the priority, cost, value, and energy performance); and (3) the N/A value, which indicates that there is no direct relationship between the two factors, and therefore no study is required. If all the factors for a certain alternative have a YES value in the compatibility matrix, then the two SAS alternatives are considered compatible to work in the same system under the targeted project (see Table 3-5).

Table 3-5: Compatibility matrix structure

Compatibility Matrix		CnF1		CnF2			…..	CnFn
		V1	V2	V1	V2	V3	……	…
CnF1	V1	N/A	N/A	N/A	YES	NO	……	NO
	V2	N/A	N/A	NO	NO	YES	……	N/A
CnF2	V1	N/A	NO	N/A	N/A	N/A	……	YES
	V2	YES	NO	N/A	N/A	N/A	……	YES
	V3	NO	YES	N/A	N/A	N/A	……	NO
….	…	…	…	…	…	…	……	…
CnFn	…	NO	N/A	YES	YES	NO	……	N/A

An example of a compatibility matrix analysis is illustrated in Figure 3-11, depicting the interaction between offsite construction HVAC systems and electrical systems through predefined construction factors. The highlighted area studies the relationship between PTAC type, a construction factor defined to reflect performance and design criteria of an HVAC system, and the main panel capacity of an offsite construction electrical system. The study results show that, if an HVAC includes an electric heat pump PTAC unit, then the main panel capacity cannot be of a low capacity; the cell representing the intersection between the two construction factors (represented by ID 161,168) has a “No” value. The compatibility matrix is thus complete, providing a guideline for TCMd RBA.

ID	Assembly System	Sub-Assembly		Construction Factor	Values	Description	154	155	156	157	158	159	160	161
							Electrical Requirement			HVAC Capacity			PTAC Type	
							High Demand	Meduim Demand	Low Demand	High Capacity	Meduim Capacity	Low Capacity	Heat Pump	Electric Heat
							Main Panel >200 Amp	Main Panel 200 Amp	MP < 200 Amp (usually 100 Amp)	BTU>=50,000	50,000>BTU>=30,000	BTU<30,000		
167	Electrical Work	Electrical Service /Distrib	P	Main Panel Capacity	High Capacity	C>=200 Amp	Yes	Yes	Yes	N/A	N/A	N/A	Yes	Yes
168					Low Capcity	200 Amp >C>= 100 Amp	No	Yes	Yes	N/A	N/A	N/A	Yes	No
169		Lighting and Branch	D	Building Type	Hotel		Yes	Yes	No	Yes	No	Yes	No	Yes
170					Residential		Yes	Yes	Yes	No	Yes	Yes	Yes	No
171					Work Force		No	Yes	Yes	Yes	No	Yes	No	Yes

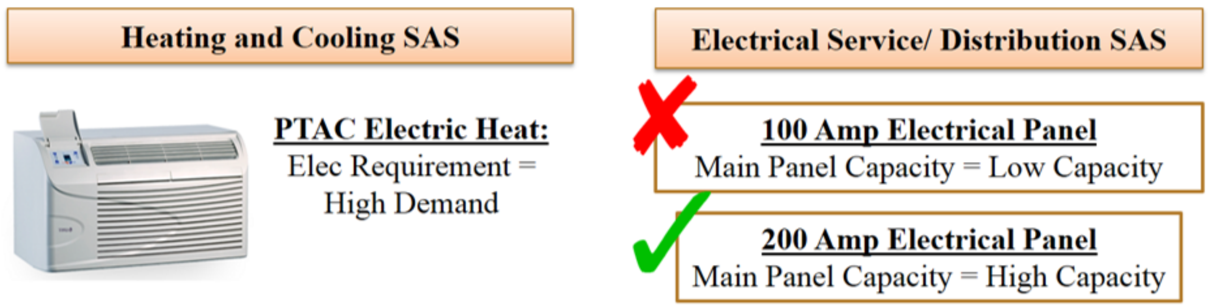


Figure 3-11: Compatibility matrix (electrical, HVAC)

This research focuses on the design-based rules of the offsite project’s compatibility matrix. The project design parameters draw the boundaries of the selection process from the pool of available alternatives and define the acceptable range of alternatives by comparing the project construction factor values with those of available SAS alternatives.

3.1.3. Costing Equations

Mathematical algorithms provide powerful tools that utilize the parametric values of the selection criteria in order to produce the best combination of assemblies based on available unit cost. Traditionally, the design-estimate process is unsupervised; project design and potential performance criteria are used to develop a project cost without a clear indication to the relationship between cost and performance. The unsupervised design-estimate approach lacks a structured framework for the cost distribution, and it significantly depends on PM/estimator experience in the cost breakdown, resulting in the need to manually adjust the costs of the project at various levels.

TCMd follows a structured bottom-up approach, which introduces a dynamic cost unit distribution based on construction, costing, and priority factors. As illustrated in Figure 3-12, costing equations are derived from the offsite project design, estimation, and specification dataset. Costing factors (CF_i) and performance factors represented by SAS value ranking constitute the equation inputs, and the regression analysis technique generates the costing equation coefficients in order to calculate the cost associated with a specific SAS alternative for a desired design.

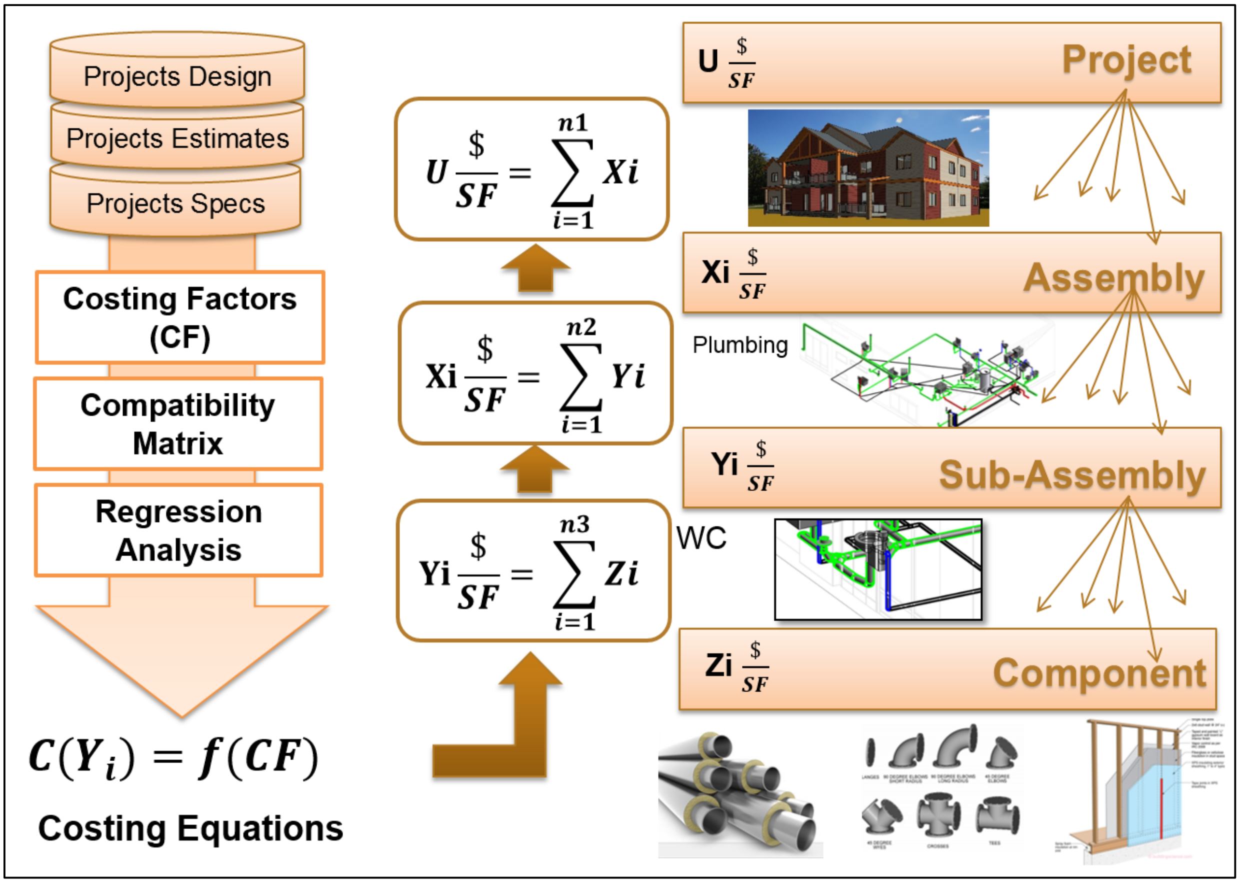


Figure 3-12: Costing equation diagram

3.1.3.1.***Offsite costing factors***

SAS costing factors (CFs) draw the relationship between distinct parameters and the cost associated with each SAS alternative, and they translate PM or estimator expertise into quantifiable factors constituting the key inputs of SAS costing equations. When an estimator develops an estimate for an offsite construction project, a set of vital factors must be calculated or considered for each of the construction systems. Calculations are based on a predefined set of measurement units, whether a unit of time (days, weeks, or months), a unit of length (ft or m), a unit of area (ft^2,

m^2, ac, ha), a unit of volume (ft^3 or m^3), a unit of quantity (each, or piece), or a unit of cost ($) for lump sum items. SAS units of measurement are essential indicators to the type of parameters influencing the associated cost. The variation in estimating methods provides a guideline to the different possible parameters affecting a SAS alternative cost. For instance, when estimating the cost of sub-assembly wall systems, some estimators use linear foot as the measurement unit, while others use square footage area of the wall. Regardless of the unit of measurement, estimators follow general rules to estimate the quantity of studs, insulation, sheathing, and drywall. Moreover, labour productivity is estimated according to standard labour productivity tables, or through the historical knowledge or experience an estimator may have from working with specific framing crews.

The proposed research introduces the concept of costing factors as a set of parameters interacting through mathematical equations in order to depict the link between design parameters and SAS total cost.

CFs cover the material and installation cost, and consider the overall cost of a SAS rather than the mere material used for the construction process. CFs constitute the desired parameters employed to generate costing equations that can control the project unit cost distribution. SAS performance is not considered when developing CF, but it is represented through the incorporation of value ranking in the development process. Value ranking provides an indication to distinguish SAS alternatives, and represents the link between performance and cost. CF values can be extracted from the 3D model of the offsite project. The complete set of CFs influencing an offsite project is found by combining those of the main assembly systems (Eq. 6), which are, correspondingly, composed of each SAS costing factor (Eq. 7).

$$Prj\colon\{\mathrm{Cf}\} = \bigcup_{i=1}^{t}\left[\bigcup_{j=1}^{m_i} AS_i(CF_{ij})\right] \qquad [6]$$

where:

Prj:{Cf}: Costing factors on the offsite construction project level (Prj)

t: Total number of assembly systems

m_i: Number of costing factors of an assembly system (AS_i)

CF_{ij}: Costing factor J of an assembly system (AS_i)

$$As_i: \{\text{Cf}\} = \bigcup_{k=1}^{n_i} [\bigcup_{l=1}^{m_k} SAS_k(CF_{kl})] \quad [7]$$

where:

AS_i: {Cf}: Costing factors for an assembly system (AS_i)

n_i: Total number of sub-assembly systems composing an AS_i

m_k: Number of costing factors of a sub-assembly system (SAS_k)

CF_{kl}: Costing factor l of a sub-assembly system (SAS_k)

For the purpose of this research, these CFs are determined after conducting several focus group discussions with professionals representing the offsite construction industry. The representative expert team includes professionals covering the construction industry various management levels; on the executive level, a chief financial officer CEO, and a vice-president (VP); and on the operational level, four general managers, nine project managers, and twelve site managers. The number of attendee in each meeting is relevant to the experience of each team member to the topic discussed.

Based on the recommendation from the focus group meeting, CFs are divided into three categories based on their financial impact on the overall project: (1) global, affecting all SASs (such as ranking value, year of construction, duration, and total floor area); (2) semi-global, affecting more than one SAS, but not all (such as total footprint); and (3) local, which are associated with only one SAS (such as total perimeter). Table 3-6 illustrates the three CFs categories influencing the site work SASs.

Table 3-6: Site work SASs' costing factors

SAS	**Costing Factors**					
General Conditions	Ranking value	Year	Duration	Tot. Floor Area	Lot Size	Tot. Foot Print
Site	Ranking value	Year	Duration	Tot. Floor Area		
Foundation Systems	Ranking value	Year	Duration	Tot. Floor Area	Tot. Perimeter	Tot. Foot Print

The CFs three categories are expressed in Eqs. 8, 9, and 10, respectively.

$$\text{Glb}: \{\text{Cf}\} = (\text{CF}_1 \cap \text{CF}_2 \ldots \cap \text{CF}_\text{i} \ldots \cap \text{CF}_\text{ncf}) \quad [8]$$

$$\text{SGlb}:\{\text{Cf}\} = \bigcup_{\text{icf}=1}^{\text{n\_i}} [\text{SAS}(\text{CF}_{\text{icf}}) \cap \text{SAS}(\text{CF}_{\text{icf}+1})];\ \text{Cf} \notin \text{Glb}:\{\text{Cf}\} \quad [9]$$

$$\text{Loc}:\{\text{Cf}\} = \complement[\text{CF} \cap (\text{CF}_{Gbl} \cup \text{CF}_{SGbl})] \quad [10]$$

where:

CF_{kl}: Global costing factors

ncf: Total number of all costing factors for all the sub-assembly systems

$\text{SGlb}:\{\text{Cf}\}_i$: Semi-global costing factors

$\text{Loc}:\{\text{Cf}\}_i$: Local costing factors

The influential effect of a costing factor on the overall offsite construction project target cost is proportional to the number of SAS groups it belongs to; therefore, it is the global CFs that require the most attention during the data collection and analysis phase. This research defines four global factors: (1) value ranking, (2) year of construction, (3) project duration, and (4) total floor area. TCMd global costing factors reflect project performance, market effect, and project complexity.

As a representative of SAS performance, value ranking is considered one of the most influential CFs, particularly given the link between the overall project value and cost. Construction year affects the price due to inflation, exchange rates, and market conditions. Although construction year effect may be absorbed by its own factors—for instance, inflation can be offset by higher competition in the market—it is important to study the effect of construction year on each SAS in order to justify any possible increase in construction cost. Floor area reflects the project size, and, in collaboration with project duration, project complexity is defined. Understanding the relationship between project complexity and cost is vital to the accuracy of the target costing model.

3.1.3.2. ***Regression analysis***

Regression analysis is widely used for prediction and forecasting. It is defined as a statistical methodology that utilizes the relationship between two or more quantitative or qualitative variables in order to predict dependent variables based on the independent variables (see Eq. 11).

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{ip-1} + \varepsilon_i \quad [11]$$

where Y_i is the value of the response variable in the i^{th} trial, $\beta 0$ and $\beta 1$ are the regression parameters, X_i is the value of the predictor variable in the i^{th} trial, and ε_i is the random error. The equation can be expected to provide a best-fit curve and to have variation errors given the following assumptions: (1) the errors around a regression line are independent for each value of the predictor variable; (2) the errors around a regression line are assumed to have constant standard deviation for all variable values; and (3) the errors around a regression line are assumed to be normally distributed at each value of X (Levine et al. 2002).

The proposed research introduces SAS costing equations as mathematical functions deploying a set of inputs to yield a desired output. The accuracy of offsite TCMd relies heavily on understanding the relationship between SAS cost, the main output, SAS costing factors, and equation input parameters. Mathematical tools can reveal the hidden links between a CF and its corresponding cost by analyzing a set of collected data. Dataset size and structure play a key role in the tool selection process. Some tools, such as neural network, require a large dataset in order to fit the inputs to a non-linear curve and produce a specific function.

Linear regression analysis is a parametric mathematical tool that clearly identifies the input factors, giving the modeller the ability to influence the modelling process, which makes it the ideal tool for a supervised optimization, i.e., a supervised TCMd, (as opposed to neural network, which does not reveal the relationship among the input and output factors – a black box – using a vector input to give a vector output).

The collected dataset covers 25 projects over a five-year span. Using linear regression analysis, 80% of the data is used to train the model (20 projects), and the remaining 20%, five projects, comprise the testing phase. A stepwise refinement of the linear model is performed at the sub-assembly level, where the P-value gives the significance of CF_i, where a high P-value indicates a CF_i with no significance to the outcome, and which is therefore not statistically influential and can be removed to simplify the model without diminishing its prediction power. The categorization of CFs is essential during the stepwise refinement process. CF with the lowest financial impact (local CFs) are removed first, then the semi-global CFs, and finally the global CF.

The first iterations of all SAS regression models with corresponding dependent variables are illustrated in Appendix A. Tables 3-7, 3-8, and 3-9 illustrate the costing factors categorized under three groups: global, semi-global, and local.

Table 3-7: First iteration SAS dependent variables – global costing factor coefficients

Semi-Global Costing Factors	Sub-Assembly Systems (SASs)																										
	ID	**01-01**	**01-02**	**01-03**	**02-01**	**02-02**	**02-03**	**02-04**	**02-05**	**02-06**	**02-07**	**02-08**	**03-01**	**03-02**	**04-01**	**04-02**	**04-03**	**05-01**	**05-02**	**05-03**	**06-01**	**06-02**	**06-03**	**06-04**	**06-05**	**06-06**	**06-07**
	DESCRIPTION	**General Conditions**	**Site**	**Foundation Systems**	**Exterior Wall Systems**	**Interior Wall Systems**	**Windows**	**Doors**	**Roofing Systems**	**Floor Systems**	**Ceiling Systems**	**Modular Onsite Connections**	**Plumbing Fixtures**	**Plumbing Distribution**	**Heating and Cooling System**	**Ducting**	**Fire Protection Systems**	**Electrical Service/Distribution**	**Lighting and Branch Wiring**	**Other Electrical Systems**	**Exterior Finishes**	**Wall Finishes**	**Floor Finishes**	**Ceiling Finishes**	**Millwork**	**Cabinets & Countertops**	**Furniture and Appliances**
Reliability Ranking		$\beta_{1.1}$	$\beta_{2.1}$	$\beta_{3.1}$	$\beta_{4.1}$	$\beta_{5.1}$	$\beta_{6.1}$	$\beta_{7.1}$	$\beta_{8.1}$	$\beta_{9.1}$	$\beta_{10.1}$	$\beta_{11.1}$	$\beta_{12.1}$	$\beta_{13.1}$	$\beta_{14.1}$	$\beta_{15.1}$	$\beta_{16.1}$	$\beta_{17.1}$	$\beta_{18.1}$	$\beta_{19.1}$	$\beta_{20.1}$	$\beta_{21.1}$	$\beta_{22.1}$	$\beta_{23.1}$	$\beta_{24.1}$	$\beta_{25.1}$	$\beta_{26.1}$
Construction Year		$\beta_{1.2}$	$\beta_{2.2}$	$\beta_{3.2}$	$\beta_{4.2}$	$\beta_{5.2}$	$\beta_{6.2}$	$\beta_{7.2}$	$\beta_{8.2}$	$\beta_{9.2}$	$\beta_{10.2}$	$\beta_{11.2}$	$\beta_{12.2}$	$\beta_{13.2}$	$\beta_{14.2}$	$\beta_{15.2}$	$\beta_{16.2}$	$\beta_{17.2}$	$\beta_{18.2}$	$\beta_{19.2}$	$\beta_{20.2}$	$\beta_{21.2}$	$\beta_{22.2}$	$\beta_{23.2}$	$\beta_{24.2}$	$\beta_{25.2}$	$\beta_{26.2}$
Duration		$\beta_{1.3}$	$\beta_{2.3}$	$\beta_{3.3}$	$\beta_{4.3}$	$\beta_{5.3}$	$\beta_{6.3}$	$\beta_{7.3}$	$\beta_{8.3}$	$\beta_{9.3}$	$\beta_{10.3}$	$\beta_{11.3}$	$\beta_{12.3}$	$\beta_{13.3}$	$\beta_{14.3}$	$\beta_{15.3}$	$\beta_{16.3}$	$\beta_{17.3}$	$\beta_{18.3}$	$\beta_{19.3}$	$\beta_{20.3}$	$\beta_{21.3}$	$\beta_{22.3}$	$\beta_{23.3}$	$\beta_{24.3}$	$\beta_{25.3}$	$\beta_{26.3}$
Total Floor Area		$\beta_{1.4}$	$\beta_{2.4}$	$\beta_{3.4}$	$\beta_{4.4}$	$\beta_{5.4}$	$\beta_{6.4}$	$\beta_{7.4}$	$\beta_{8.4}$	$\beta_{9.4}$	$\beta_{10.4}$	$\beta_{11.4}$	$\beta_{12.4}$	$\beta_{13.4}$	$\beta_{14.4}$	$\beta_{15.4}$	$\beta_{16.4}$	$\beta_{17.4}$	$\beta_{18.4}$	$\beta_{19.4}$	$\beta_{20.4}$	$\beta_{21.4}$	$\beta_{22.4}$	$\beta_{23.4}$	$\beta_{25.4}$	$\beta_{26.4}$	$\beta_{27.4}$

Table 3-8: First iteration SAS dependent variable – semi-global costing factor coefficients

Semi-Global Costing Factors	SAS ID																									
	01-01	**01-02**	**01-03**	**02-01**	**02-02**	**02-03**	**02-04**	**02-05**	**02-06**	**02-07**	**02-08**	**03-01**	**03-02**	**04-01**	**04-02**	**04-03**	**05-01**	**05-02**	**05-03**	**06-01**	**06-02**	**06-03**	**06-04**	**06-05**	**06-06**	**06-07**
Footprint	$\beta_{1.6}$	$\beta_{2.5}$	$\beta_{3.6}$													$\beta_{16.5}$										
Tot. Perimeter			$\beta_{3.5}$																	$\beta_{20.10}$						
No. Mod units									$\beta_{9.5}$	$\beta_{10.5}$	$\beta_{11.5}$		$\beta_{13.9}$							$\beta_{20.7}$						
No. Suites													$\beta_{13.8}$				$\beta_{17.5}$	$\beta_{18.5}$	$\beta_{19.5}$						$\beta_{25.5}$	$\beta_{26.5}$
Avg. Suite Size																	$\beta_{17.6}$	$\beta_{18.6}$								

Continue Table 3-8

Semi-Global Costing Factors	SAS ID																									
	01-01	01-02	01-03	02-01	02-02	02-03	02-04	02-05	02-06	02-07	02-08	03-01	03-02	04-01	04-02	04-03	05-01	05-02	05-03	06-01	06-02	06-03	06-04	06-05	06-06	06-07
No. Floors													$\beta_{13.6}$		$\beta_{15.11}$	$\beta_{16.6}$				$\beta_{20.6}$						
Floor Height													$\beta_{13.7}$		$\beta_{15.9}$					$\beta_{20.5}$						
Avg. Mod Perimeter									$\beta_{9.6}$	$\beta_{10.6}$	$\beta_{11.6}$															
Avg. Mod Area									$\beta_{9.7}$	$\beta_{10.7}$	$\beta_{11.7}$															
Tot. Ex - Wall Area				$\beta_{4.6}$																	$\beta_{21.7}$					
Tot. In - Wall Area					$\beta_{5.6}$																$\beta_{21.8}$					
No. Windows																				$\beta_{20.8}$				$\beta_{24.8}$		
Avg. Window Perimeter																				$\beta_{20.9}$				$\beta_{24.9}$		
No. Doors							$\beta_{7.10}$																	$\beta_{24.10}$		
No. Kitchens												$\beta_{12.5}$			$\beta_{15.5}$										$\beta_{25.6}$	
No. Bathrooms												$\beta_{12.9}$			$\beta_{15.6}$									$\beta_{24.8}$	$\beta_{25.7}$	
No. Washer/Drier												$\beta_{12.10}$			$\beta_{15.7}$											
Tot. Elec Fixtures																$\beta_{16.7}$	$\beta_{17.7}$									
Tot. Wall Length - Suite																					$\beta_{21.5}$			$\beta_{24.5}$		
Tot. Wall Length - Washrooms																					$\beta_{21.6}$			$\beta_{24.6}$		
Tot. Floor Area - Suites																						$\beta_{22.5}$	$\beta_{23.5}$			
Tot. Floor Area - Washroom/Kitchen																						$\beta_{22.6}$	$\beta_{23.6}$			

Table 3-9: First iteration SAS dependent variable – local costing factor coefficients

Local Costing Factors	SAS ID																									
	01-01	**01-02**	**01-03**	**02-01**	**02-02**	**02-03**	**02-04**	**02-05**	**02-06**	**02-07**	**02-08**	**03-01**	**03-02**	**04-01**	**04-02**	**04-03**	**05-01**	**05-02**	**05-03**	**06-01**	**06-02**	**06-03**	**06-04**	**06-05**	**06-06**	**06-07**
Tot. Building Size														$\beta_{14.5}$												
Avg. Room Size														$\beta_{14.8}$												
Lot Size	$\beta_{1.5}$																									
Tot. Ex - Wall length				$\beta_{4.5}$																						
Tot. In - Wall length					$\beta_{5.5}$																					
Tot. Window Size						$\beta_{6.5}$																				
Window Facing South						$\beta_{6.6}$																				
Window Facing North						$\beta_{6.7}$																				
Window Facing East						$\beta_{6.8}$																				
Window Facing West						$\beta_{6.9}$																				
Window Glazing						$\beta_{6.10}$																				
Window Framing						$\beta_{6.11}$																				
Avg. Window Perimeter																				$\beta_{20.9}$						
Exterior Door Facing S							$\beta_{7.6}$																			
Exterior Door Facing N							$\beta_{7.7}$																			
Exterior Door Facing E							$\beta_{7.9}$																			

Continue Table 3-9

Local Costing Factors	SAS ID																									
	01-01	01-02	01-03	02-01	02-02	02-03	02-04	02-05	02-06	02-07	02-08	03-01	03-02	04-01	04-02	04-03	05-01	05-02	05-03	06-01	06-02	06-03	06-04	06-05	06-06	06-07
Exterior Door Facing W							$\beta_{7.9}$																			
Door Material							$\beta_{7.11}$																			
Roof Perimeter								$\beta_{8.5}$																		
Roof Area								$\beta_{8.6}$																		
Roof Type								$\beta_{8.7}$																		
Roof Slope								$\beta_{8.8}$																		
No. Sinks												$\beta_{12.7}$														
No. Tubs												$\beta_{12.8}$														
No. Lavatory												$\beta_{12.9}$														
No. Fixtures												$\beta_{12.10}$														
No. Water Heaters												$\beta_{12.11}$														
No. Hose Bibb												$\beta_{12.12}$														
Tot. Plumbing Fixtures													$\beta_{13.5}$													
Corridor Area														$\beta_{14.6}$												
Common Area														$\beta_{14.7}$												
No. Receptacles																		$\beta_{18.8}$								
No. Switches																		$\beta_{18.10}$								
No. Light Fixtures																		$\beta_{18.11}$								
No. Thermostats																		$\beta_{18.12}$								
No. PTAC units																		$\beta_{18.13}$								

The costing factors categorization is essential during the stepwise refinement, which utilizes the p-value to test each costing factor (coefficient) against the null hypothesis, through which a low p-value (usually less than 0.05) rejects the null hypothesis and shows a meaningful effect of the coefficient on the overall equation; vice versa, a high p-value suggest proves the null hypothesis and indicates that the predictor has no effect on the equation and needs to be removed to improve the overall accuracy. During the stepwise refinement, if a multiple CFs have a large (significant) p-value, CFs with the lowest financial impact (local CFs) are the ones discarded first and the regression analysis is run in an attempt to improve the costing equations accuracy (one step); similarly, semi-global CFs are next, and the global CFs are kept last. Table 3-10 shows the final costing equations.

Table 3-10: SAS Costing equations

SAS ID	Costing Equations
01-01	$\mathrm{GC_i} = 4.658 \times R + 1.609 \times Yr$
01-02	$\mathrm{St_i} = 1.395 \times R + 0.888 \times Yr + 0.480 \times Dur + 0.0002 \times Flr_{Area} + 0.0005 \times Ft_{Print}$
01-03	$Fnd_{\mathrm{i}} = 4.078 \times R$
02-01	$ExW_{\mathrm{i}} = 6.820 \times R + 0.0005 \times ExW_{length}$
02-02	$InW_{\mathrm{i}} = 14.380 - 0.0002 \times Flr_{Area} + 0.0013 \times InW_{length} + 0.0001 \times InW_{Area}$
02-03	$Wnd_{\mathrm{i}} = 4.640 + 1.787 \times R + 2.640 \times Glazing_{Type}$
02-04	$Dr_{\mathrm{i}} = 0.391 \times R$
02-05	$Rf_{\mathrm{i}} = 6.016 - 0.00002 \times Rf_{Area}$
02-06	$Flr_{\mathrm{i}} = 9.289 - 0.00004 \times Flr_{Area}$
02-07	$Clng_{\mathrm{i}} = 4.279 \times R - 0.853 \times Yr - 0.00001 \times Flr_{Area}$
02-08	$Mod.Cn_{\mathrm{i}} = 0.860 \times R$
03-01	$Plm.Fix_{\mathrm{i}} = 0.341 \times R + 0.213 \times Yr + \beta_{i3} \times Dur + 0.00001 \times Flr_{Area} - 0.006 \times No.Snk$
03-02	$Plm.Dis_{\mathrm{i}} = 11.103 + 0.00006 \times Flr_{Area} - 0.0097 \times No.Fxtr - 0.5547 \times No.Flr - 0.0157 \times No.Mods$
04-01	$HVAC_{\mathrm{i}} = 1.514 \times R - 0.00002 \times Flr_{Area} - 0.0000005 \times Tot.Bldng_{Size} + 0.00004 \times Cmn_{Area} + 0.00167 \times Avg.Rm_{Size}$

Continue Table 3-10

SAS ID	Costing Equations
04-02	$Dct_{\mathrm{i}} = 1.985 + 1.075 \times R - 0.610 \times No.Flr +$
04-03	$FRS_{\mathrm{i}} = 0.332 \times R - 0.00001\beta_{i4} \times Flr_{Area} + 0.00004 \times Tot.Ft_{print}$
05-01	$Elec.Dis_{\mathrm{i}} = 5.985 + 0.0217 \times No.Suites - 0.0019 \times Tot.Elec_{Fixtures}$
05-02	$Elec.Wrng_{\mathrm{i}} = 6.474 + 0.733 \times R - 0.0001 \times Flr_{Area} - 0.0009 \times Avg.Suite_{Size} + 0.0019 \times Tot.Elec_{Fixtures}$
05-03	$Elec.Othr_{\mathrm{i}} = 0.742 \times R - 0.00001 \times Flr_{Area} + 0.0034 \times No.Suites$
06-01	$Ex.Fnsh_{\mathrm{i}} = 1.563 \times R$
06-02	$W.Fnsh_{\mathrm{i}} = 2.557 \times R - 0.0000004 \times Tot.Wall_{Area}$
06-03	$Flr.Fnsh_{\mathrm{i}} = 1.022 \times R - 0.122 \times Yr - 0.000003 \times Flr_{Area}$
06-04	$Clng.Fnsh_{\mathrm{i}} = 1.101 \times R - 0.000002 \times Flr_{Area}$
06-05	$Mlwrk_{\mathrm{i}} = 1.785 \times R + 0.789 \times Yr$
06-06	$Cbnt_{\mathrm{i}} = 2.145Yr + 1.290 \times Dur - 0.0003 \times Flr_{Area} + 0.0670 \times No.Suites$
06-07	$Frn_{\mathrm{i}} = 0.190 \times Dur - 0.0570 \times No.Suites$

The regression analysis is performed on each SAS function and associated CF_i, and the quality of the fit is evaluated using the F-Test, R^2, and residual test in order to evaluate the impact of CF_i on the costing equation accuracy. An F-test utilizes significance-F for each model to measure the accuracy level. The significance-F value is derived from the P-value and should be close to zero, with values equal to or less than 0.05 (Significance-F $\leq$ 0.05) considered acceptable. CFi with high P-value are taken out separately, and the analysis is run until acceptable significance-F is realized.

Table 3-11 illustrates the significance-F (see Figure 3-13) and R^2 (Figure 3-14) of the SAS models. Significance-F is near zero, and R^2 ranges around 0.95 in most of the costing equations, which indicates a strong linear relationship between the dependent variable and the result. While the accuracy of all costing equations is considered acceptable, the two figures (3-13 and 3-14) show a clear deviation in three costing equations; (1)03-02: Plumbing distribution, (2) 04-02: HVAC ducting, and (3) 05-01: Electrical service/distribution. The lower accuracy level in those costing equations is contributed to the lack of well-detailed mechanical and electrical design covering the main service distributions within the walls, floors, and ceiling; concurrently. The onsite crew counts on their experience in order to fill in the missing details, which results in an increased inconsistency in the cost and quality of the work performed.

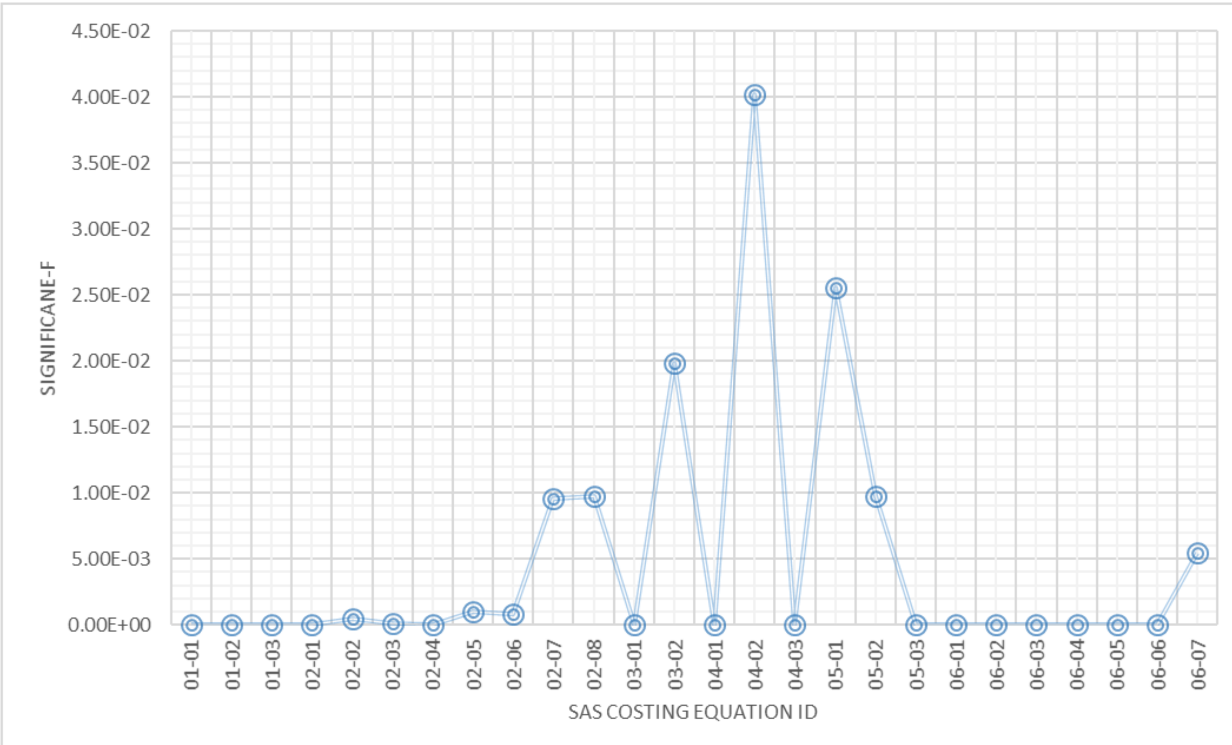


Figure 3-13: SAS costing equations – significance-F

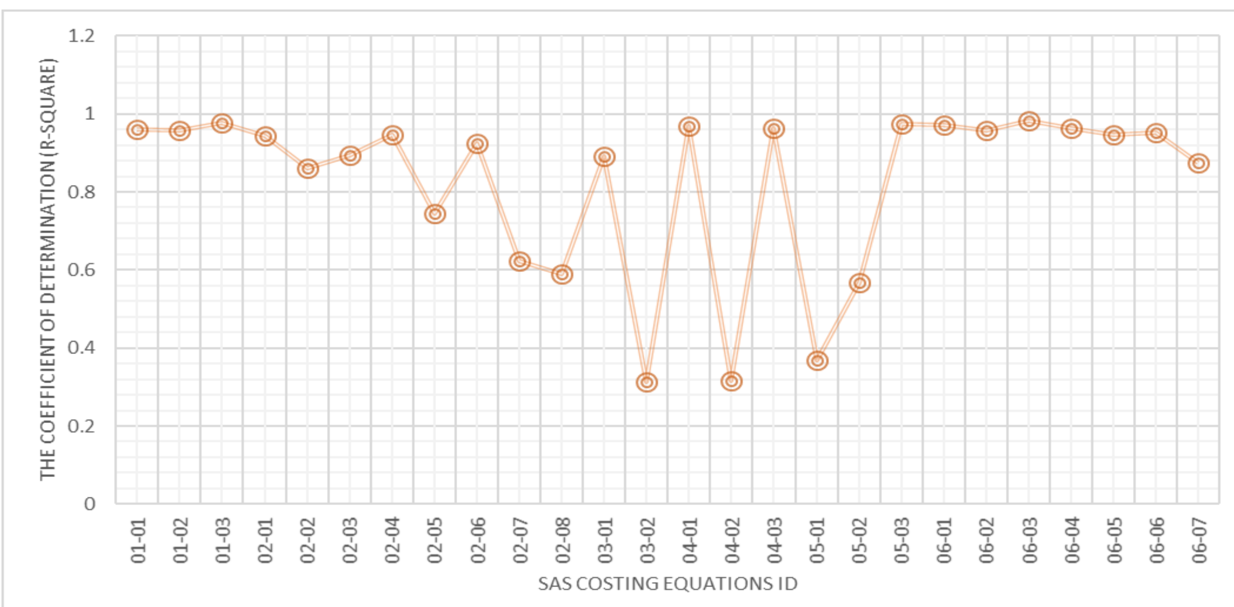


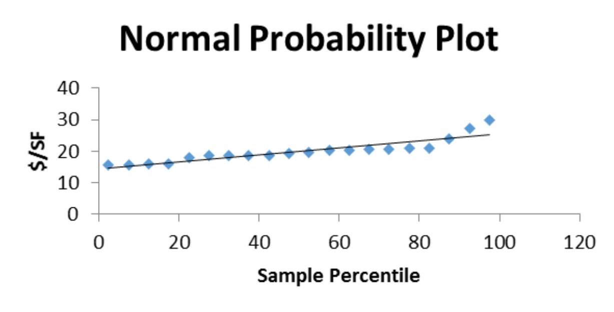
Figure 3-14: SAS costing equations – R-square

Table 3-11: SAS significance-F

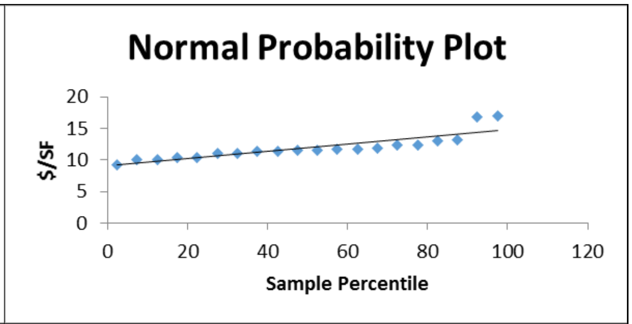
	Site work	Building Structure	Plumbing Systems	HVAC Systems	Electrical Work	Finishes
1	General Conditions	Exterior Walls	Plumbing Fixtures	Heating and Cooling System	Electrical Service/Distribution	Exterior Finishes
F R^2	6.28497E-13 0.961239123	1.5397E-11 0.943585102	2.82234E-07 0.892013355	3.69824E-09 0.967925576	0.025525383 0.3684071	1.06124E-15 0.972471548
2	Site	Interior Walls	Plumbing Distribution	Ducting	Lighting and Branch Wiring	Wall Finishes
F R^2	3.17808E-09 0.956403	0.00050092 0.659732855	0.019800004 0.314385844	0.040200131 0.314840842	0.009731477 0.56784609	1.23189E-12 0.958052983
3	Foundations	Windows		Fire Protection Systems	Other Electrical Systems	Floor Finishes
F R^2	1.84679E-16 0.977321329	0.000139394 0.895111055		9.10945E-12 0.96191719	4.49879E-13 0.97385099	3.16933E-14 0.981230323
4		Doors				Ceiling Finishes
F R^2		3.6485E-13 0.947460661				3.07303E-13 0.964362112
5		Roofing Systems				Millwork
F R^2		0.000976689 0.744981559				9.06413E-12 0.946984307
6		Floor Systems				Cabinets & Countertops
F R^2		0.000790524 0.924022192				6.61012E-10 0.952006501
7		Ceiling Systems				Furniture and Appliances
F R^2		0.009583775 0.624381559				0.005423775 0.875962413
8		Modular Onsite Connections				
F R^2		0.009717895 0.591121559				

The residual check is a visual check based on the fact that diagnostic checks, which are used to verify the linear regression assumptions, include the normality error, the homoscedasticity, and the independence of error. The normal probability and frequency plots of residuals for the developed models are checked visually. The models are run multiple times to filter out CF_i yielding high P-value.

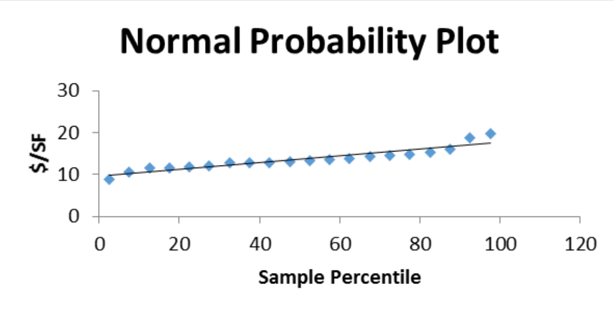
The visual check of the normal probability plot as illustrated in Figure 3-15 shows that the error terms are close to normality with a relatively small departure from the line, which gives a fairly accurate result.



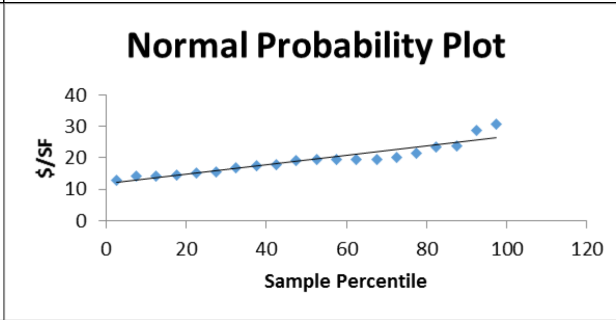
A- General conditions



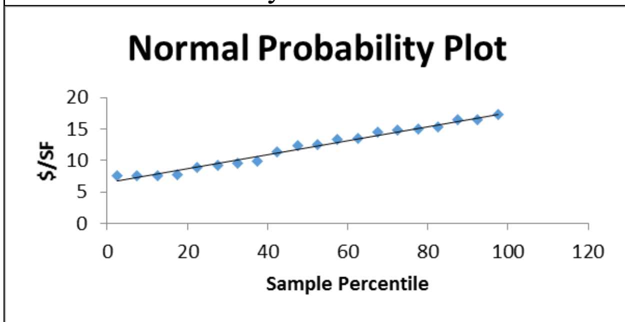
B- Site



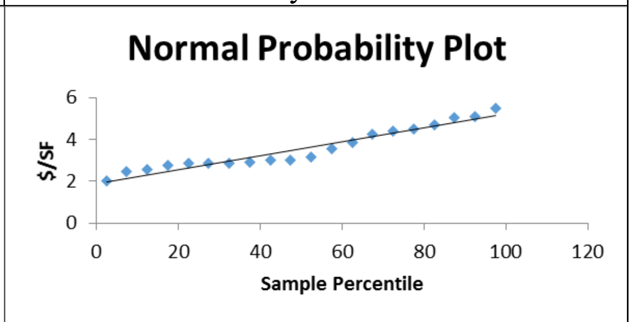
C- Foundation systems



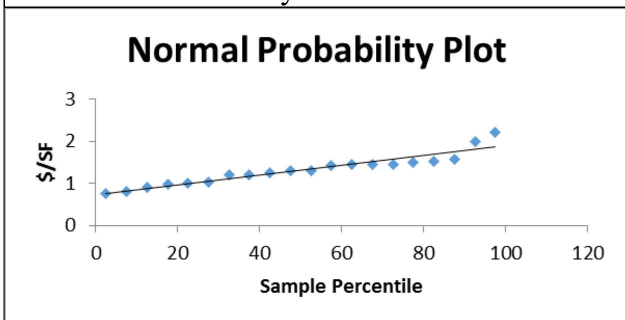
D- Exterior wall systems



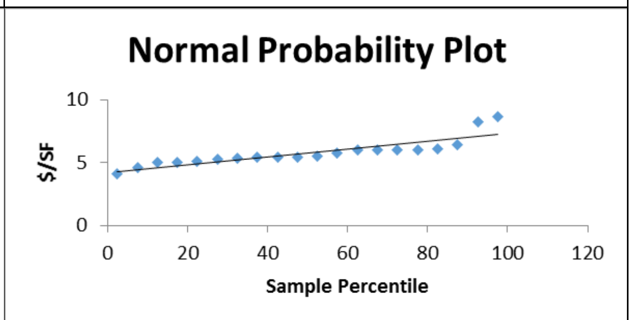
E- Interior wall systems



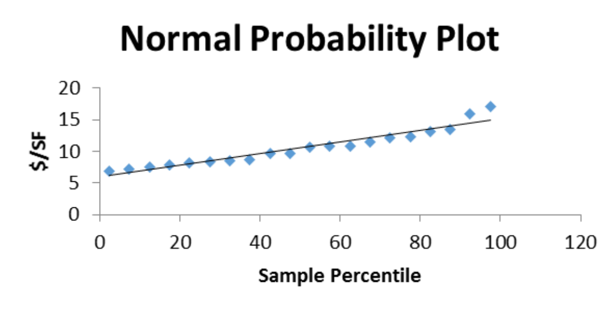
F- Windows



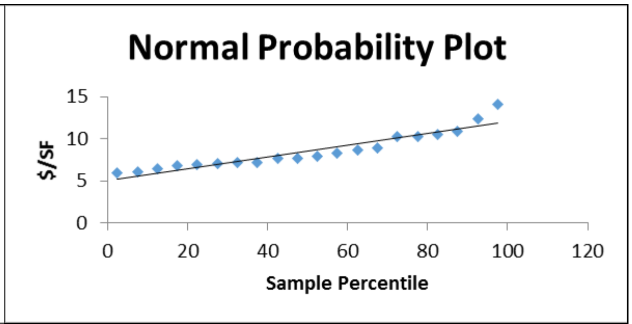
G- Doors



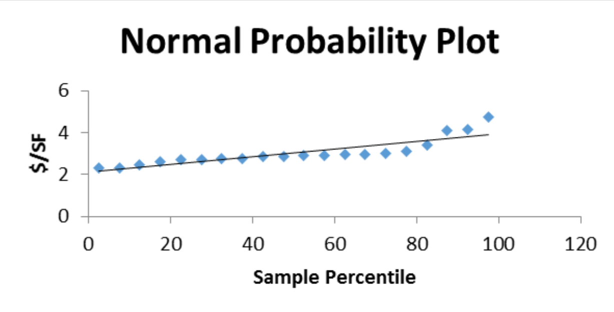
H- Roofing systems



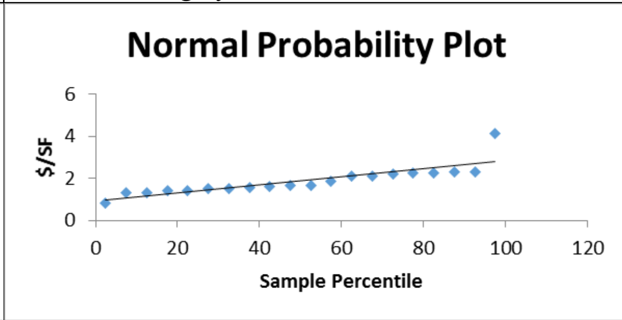
I- Floor systems



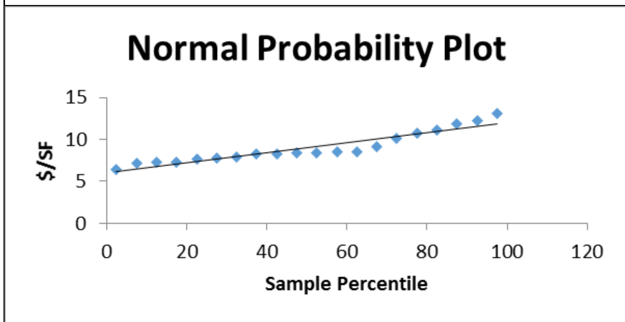
J- Ceiling systems



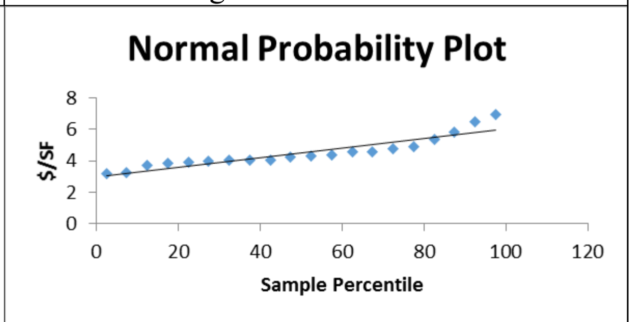
K- Modular onsite connections



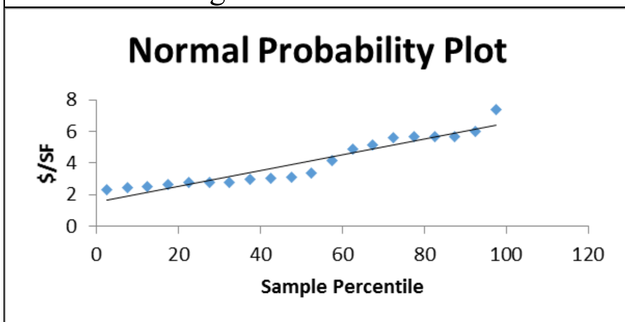
L- Plumbing fixtures



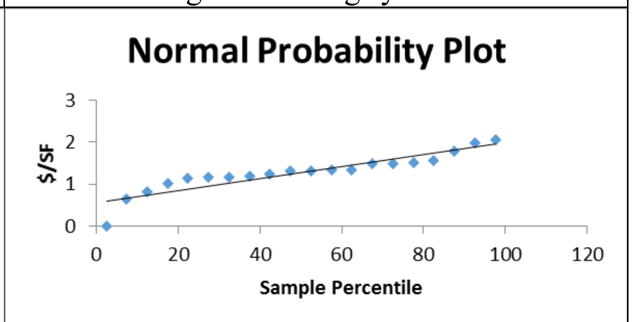
M- Plumbing distribution



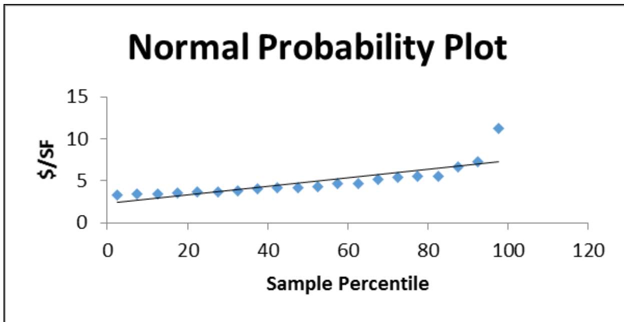
N- Heating and cooling systems



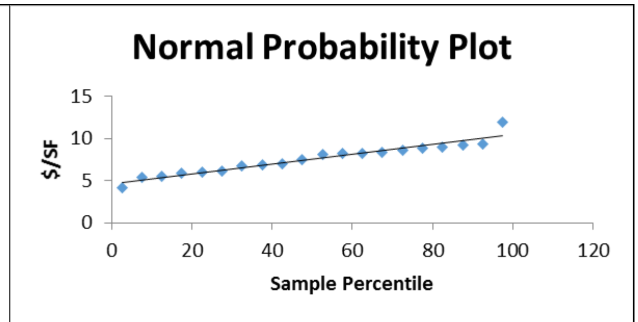
O- Ducting



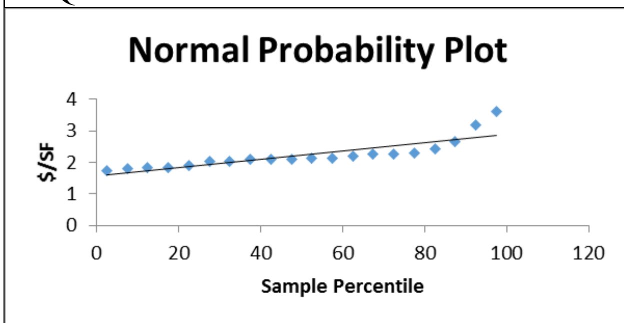
P- Fire protection systems



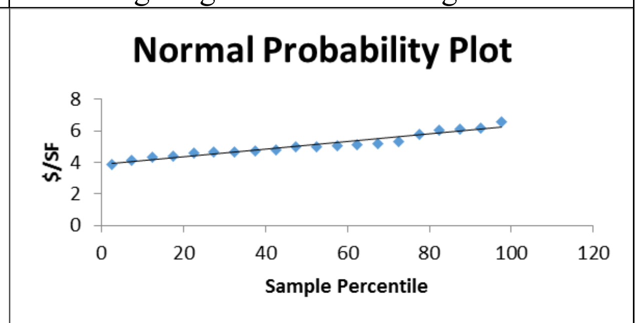
Q- Electrical service/distribution



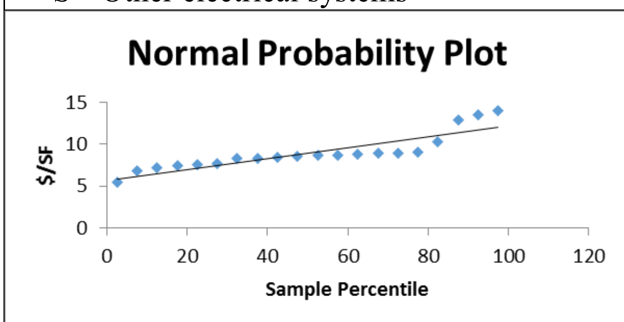
R- Lighting and branch wiring



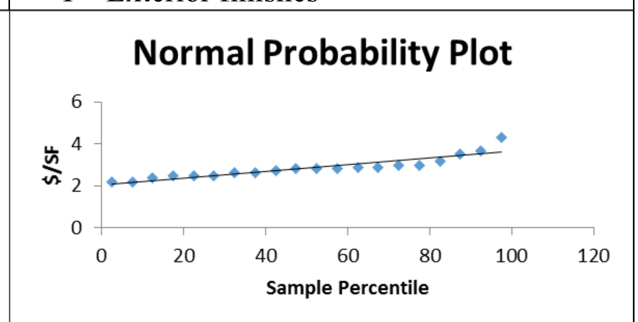
S- Other electrical systems



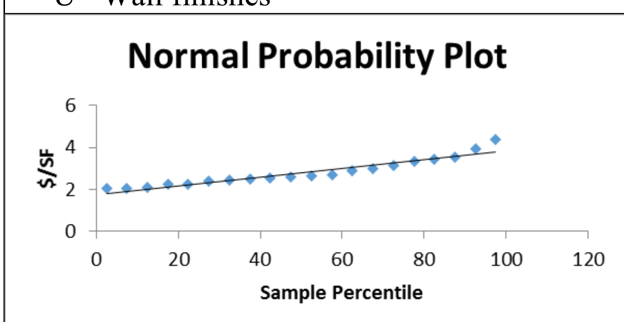
T- Exterior finishes



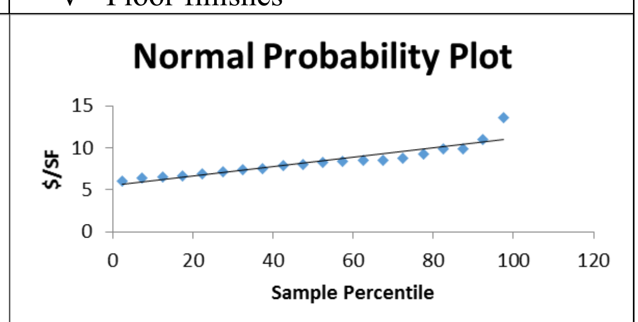
U- Wall finishes



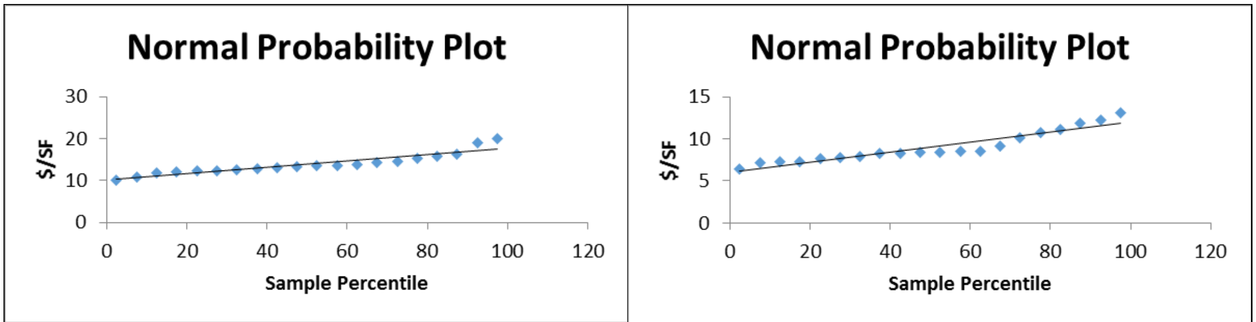
V- Floor finishes



W- Ceiling finishes



X- Millwork



Y- Cabinets & countertops	Z- Furniture and appliances

Figure 3-15: SAS normal probability plots

The Shapiro–Wilk test, an analytical test of the normality of probability outcomes, shows that the SAS costing equations follow a normal distribution, as the P-values in all the equations are greater than a significance level – alpha-value – of 5% (see Figure 3-16); therefore, the predicted results are considered acceptable.

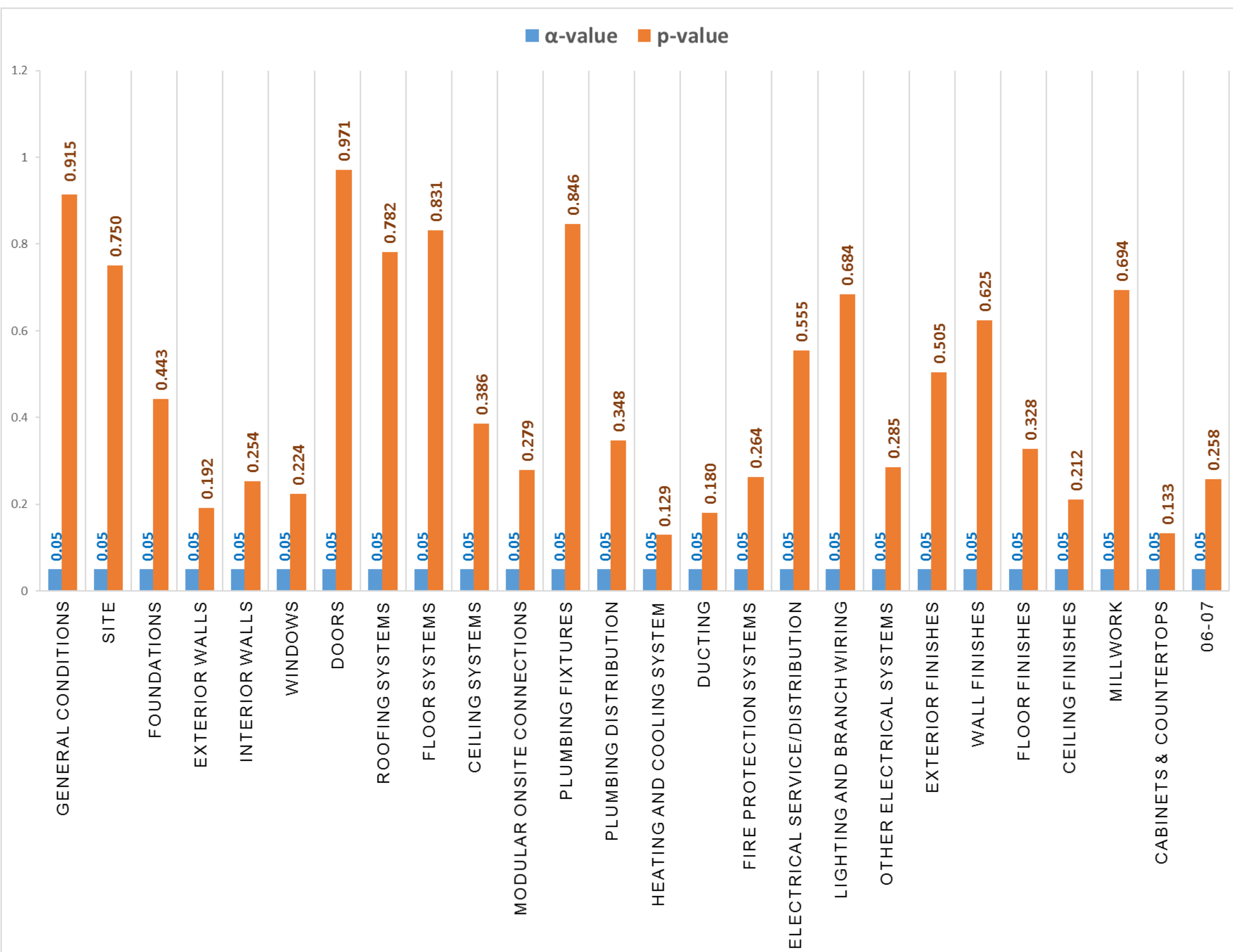


Figure 3-16 Shapiro–Wilk test

Having trained the equations, the developed models are validated using the 20% validation dataset, which has not been exposed to the models during their development. The performance of the model is validated with respect to certain mathematical validation diagnostics as recommended in the literature (Zayed & Halpin 2005; Al-Barqawi & Zayed 2006). Eqs. 12 and 13 show the average validity/invalidity percentages (i.e., AVP and AIP) needed in order to predict the error. Eq. 14, Eq. 15, and Eq. 16 validate the accuracy of the regression analysis.

$$\mathrm{AIP} = \left\{\sum_{1=1}^{n} \left|1 - \frac{\mathrm{E_i}}{\mathrm{C_i}}\right|\right\} \times \frac{100}{\mathrm{n}} \quad [12]$$

$$\mathrm{AVP} = 100 - \mathrm{AIP} \quad [13]$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(C_i - E_i)^2}{n}} \quad [14]$$

$$\mathrm{MAC} = \frac{\sum_{i=1}^{n} |C_i - E_i|}{n} \quad [15]$$

$$f_i = \frac{1000}{1 + \mathrm{MAE}} \quad [16]$$

where AIP = average invalidity percent; AVP = average validity percent; RMSE = root mean square error; MAE = mean absolute error; fi = fitness function; Ei = estimated value; Ci = actual value; and n = number of events. (The model validation results are listed in Appendix B.) Figure 3-17 shows that the developed models yield an average AVP of 86.80%, which is acceptable for cost estimating during the pre-construction phase; collecting more data can result in higher AVP.

Value ranking (Rn) costing factor is the most influential CF due to its significant coefficient value in the developed costing equations. Figure 3-18 shows the relationship between value Rn and the proposed SASs. The overall project cost yields an average accuracy of 86.38% (AVP for R; average validity percentage), which exceeds the accuracy obtained from construction costing research studies that have utilized neural network without sufficient analysis of the project structure and influencing factors. The higher accuracy level is due to the variation in Rn coefficient value, which implies a dynamic relationship between costing factors and the overall project cost, and compensates for the linear regression analysis representation of costing equation. The accuracy level can be increased by obtaining more data.

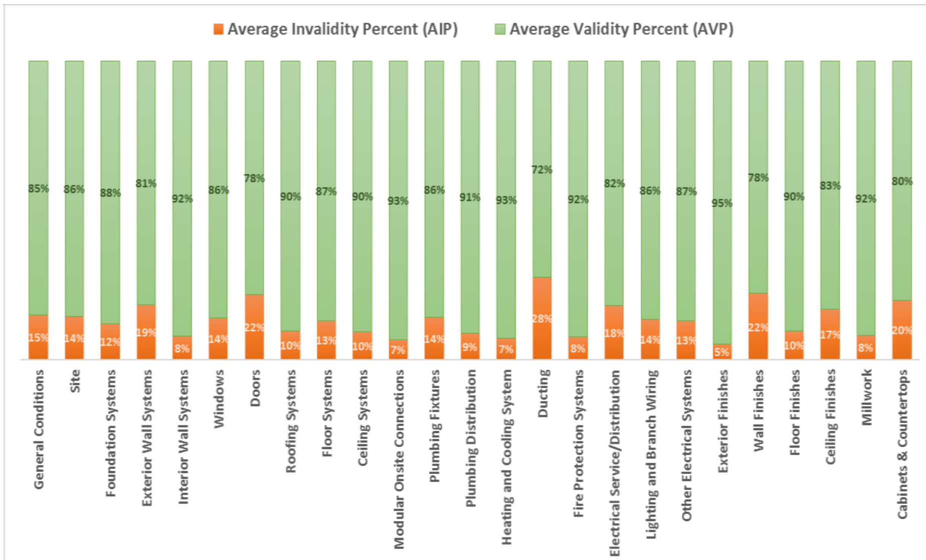


Figure 3-17: SAS model validation results

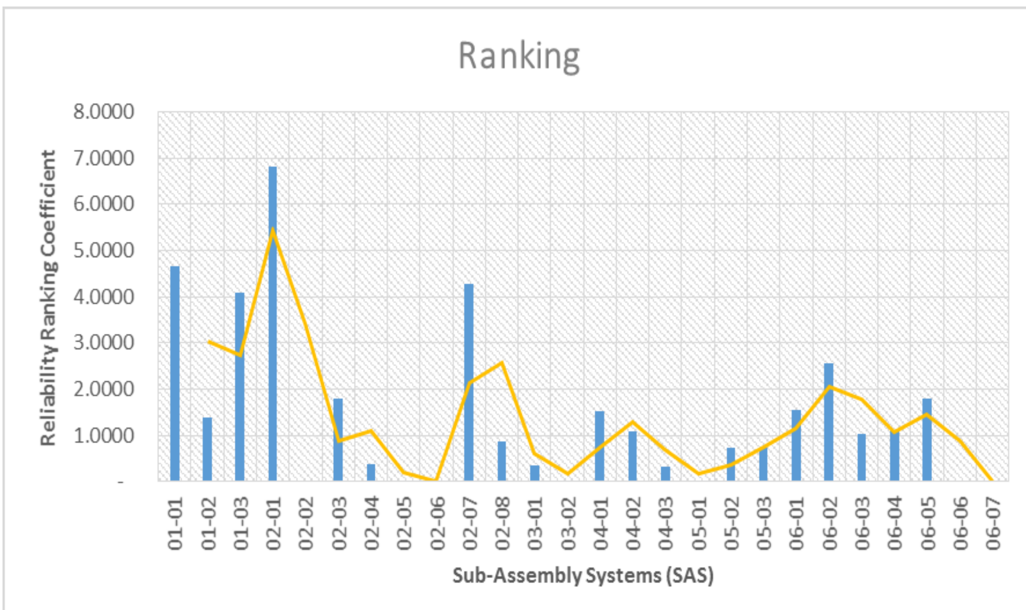


Figure 3-18: Value ranking AVP for SAS regression models

3.1.4. Value Ranking Rule-based Analysis

The value ranking rule-based analysis (RBA) mimics the project manager experience during the evaluation process of different alternative systems through the incorporation of ranking values (Rn) of each SAS alternative as the deciding factors. The proposed TCMd is an iterative rule-based analysis that explores all the compatible SASs for a specific design in order to improve the performance while retaining a targeted project cost. Figure 3-19 shows the overall RBA process.

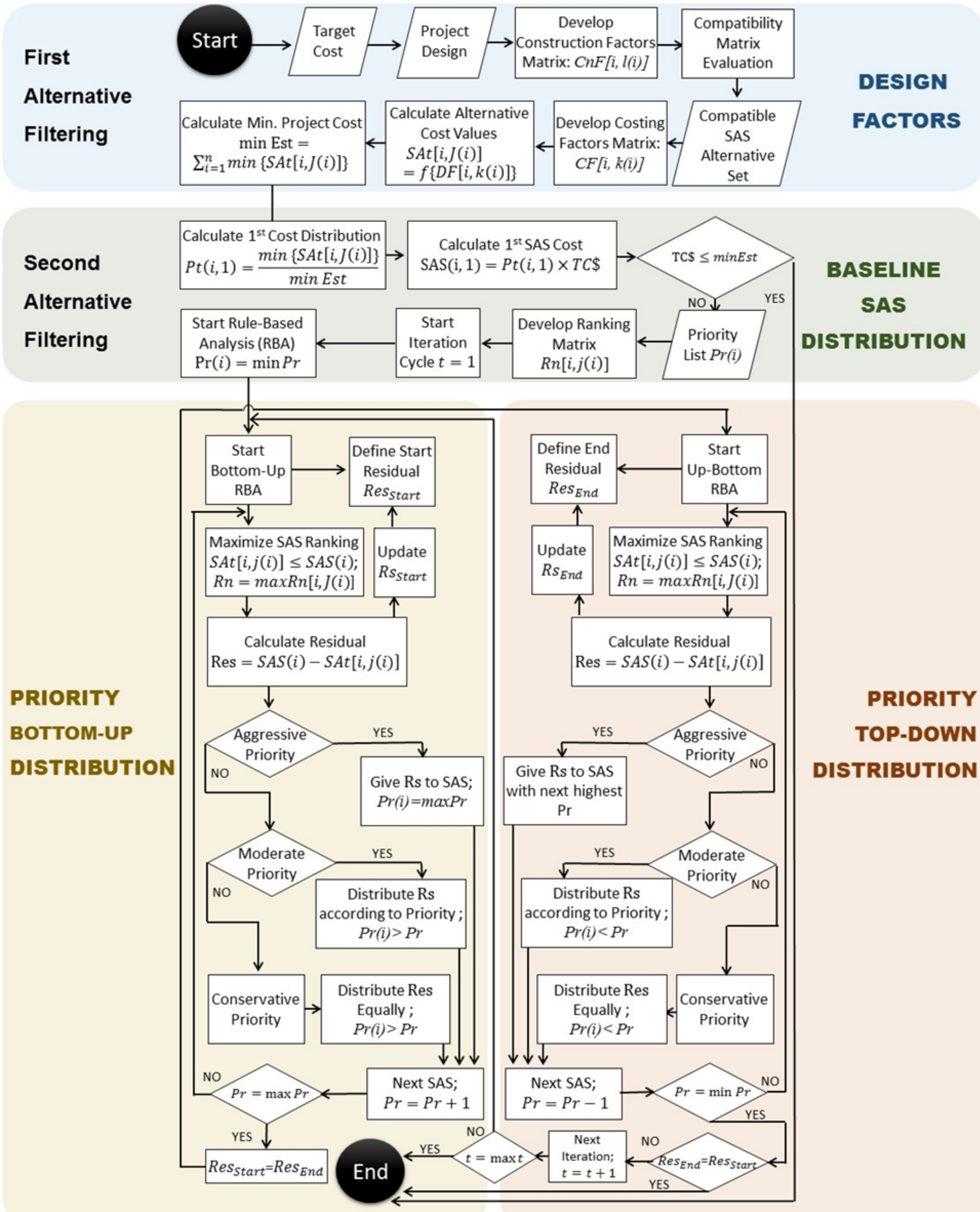


Figure 3-19: Rule-based analysis process map

As illustrated in figure 3-19, the following steps are taken in order to perform TCMd analysis:

3.1.4.1. *First alternative filtering (design factors)*

Project design and client requirement establish an adequate range of values for the construction factors, after which the model selects the matching alternative for those satisfying the design criteria. Consequently, a design-based SAS selection process is performed, and a set of acceptable SAS alternatives from the available pool is generated. For instance, for a residential apartment project, alternatives include: medium in size, landscaping is included, paved, flat roof, high-end exterior, etc. Based on the compatibility matrix, a SAS alternative does not belong to the acceptable alternative set when the construction factors associated with it are incompatible with the values from those listed for the studied project. TCMd rejects incompatible SAS alternatives by assigning a larger cost value, which prevents the model from considering them during the value evaluation process.

3.1.4.2. *Second alternative filtering (baseline SAS distribution)*

SAS cost distribution is performed using the priority factors assigned to each SAS; the cost is distributed as a percentage from the project total target cost and refined through a number of iterations until an acceptable defined delta between the target cost distribution and actual cost is reached.

The pool of available SAS alternatives compatible with the project design having been identified, SAS cost is calculated for each alternative using the costing equations, thereby creating a SAS costing matrix for all SAS with their respective compatible alternatives (Eq. 17).

$$SAt[i,\ J(i)] = f\{CF[i,\ k(i)]\} \qquad [17]$$

where:

$SAt[i,\ J(i)]$: Cost value of alternative *J(i)* of a SAS_i

J(i): Index of the number of available alternatives for a SAS_i

$CF[i,\ k(i)]$: Costing factor *k(i)* of a SAS_i

k(i): Index of the number of costing factors associated with a SAS_i

The first SAS distribution is established using the costing equations in order to calculate the minimum cost of each SAS, thus determining the SAS alternative that yields the lowest cost for the specified design (Eq. 18).

$$\min \text{Est} = \sum_{i=1}^{n} min\,\{SAt[i,\ J(i)]\} \quad [18]$$

where:

min Est: Minimum project cost

The baseline SAS unit cost percentage distribution is carried out by calculating the lowest cost of the project from available SASs and finding a percentage (Pt) of total target cost for each SAS (Eq. 19).

$$Pt(i,1) = \frac{min\,\{SAt[i,\ J(i)]\}}{min\ Est} \quad [19]$$

where:

$Pt(i,1)$: Unit cost percentage distribution for SAS_i in the first iteration t = 1

The first unit cost percentage distribution is used to develop the baseline SAS unit cost distribution by multiplying the percentage value derived from the minimum cost by the target cost (TC$) (Eq. 20). The SASs with the lowest priority factors are analyzed first, and SAS alternative values that exceed the baseline SAS distribution cost are excluded from the evaluated pool in the specified iteration (Eq. 21).

$$\text{SAS}(\text{i},1) = Pt(i,1) \times TC\$ \quad [20]$$

$$SAt[i,j(i)] \leq SAS(i)\ ;\ Rn = maxRn[i,J(i)] \quad [21]$$

where:

Rn: Ranking value associated with $SAt[i,\ J(i)]$

3.1.4.3. ***Priority bottom-up distribution process***

SAS residual value (Rs), the delta cost between SAS available alternative values and baseline unit cost distribution, is stored under (Rs_{Start}) (Eq. 22).

$$Res = SAt[i,j(i)] - SAS(i);\ SAt[i,j(i)] \leq SAS(i)\ AND\ Rn(i) = maxRn[i,J(i)] \quad [22]$$

Res_{Start} is distributed over the remaining SAS in one of three manners: (1) aggressive priority distribution (APD), where SAS residual value is given in full to the SAS with the highest priority number, which allows for the maximum available cost to be given to the SAS with the highest priority; (2) moderate priority distribution (MPD), which takes priority factors into account during the distribution of residual cost, where Res is distributed to SASs with higher ranking values in proportion to the associated Pr(i) (Eq. 23); and (3) conservative priority distribution (CPD), which allocates Res to SASs with higher priority uniformly (Eq. 24).

$$Res(i) = Res_{Start} \times \frac{\Pr(i)}{\sum_{i=1}^{n} \Pr(i)}; Rn(i) > Rn \qquad [23]$$

$$Res(i) = Res_{Start} \times \frac{1}{n_i}; Rn(i) > Rn \qquad [24]$$

As a result, a new cost distribution is generated and the second set of cost distributions is calculated. Following the same methods, the SASs with the second lowest priority ranking are evaluated against the available SAS alternatives, and Res is distributed among the other SASs. The bottom-up distribution process continues until the SAS with highest priority is reached, signalling the start of top-down distribution.

3.1.4.4. *Priority top-down distribution process*

This process begins with the highest priority SAS and ends when the lowest priority SAS is reached, indicating the end of a complete iteration. During this phase, Rs is stored under Rs_{End} and distributed to the SASs with the next highest priority factor (APD), or to SASs with lower P(i) according to their P(i) value (MPD), or equally over the remaining SASs with lower P(i) (CPD). This iteration cycle is repeated until all SASs have achieved their improved performance within the targeted cost. The iteration stops if the maximum iteration number (max t) is reached, or if the end residual from the top-down analysis is equal to the start residual from the bottom-up analysis ($Rs_{End} = Rs_{Start}$), concluding that the same residuals have gone through all SASs and no further improvement can be achieved.

Programming TCMd rules into an appropriate programming environment (e.g., Excel Macro) facilitates the automation of TCMd. The final result of TCMd for a given design and a specified TC$ includes a list of SASs with maximized Ranking value (see Figure 3-20).

	A	B	C	D	E	F	G	H	I	J	K
1	ID	Project Components	Ranking	Description	TC $	TC $/SF	TC %	Est $	Est $/SF	Est %	Residual $/SF
2		Site work									
3	1.1.3.0	General Conditions	4.192	GC 3	$ 719,780.19	$ 24.35	8.23%	$ 946,127.69	$ 24.35	8.33%	$ 2.61
51	1.2.3.0	Site	4.625	SW 3	$ 515,102.66	$ 14.96	5.89%	$ 581,287.75	$ 14.96	5.96%	$ -
75	1.3.6.0	Foundations	4.175	Fnd 6	$ 535,026.50	$ 17.02	6.12%	$ 661,391.19	$ 17.02	6.19%	$ -
94		Building Structure									
95	2.1.2.0	Exterior Walls	3.381	Ex W 1.2	$ 692,338.56	$ 19.42	7.92%	$ 754,575.75	$ 19.42	8.01%	$ -
108	2.2.4.0	Interior Walls	2.793	In W 1.4	$ 820,794.00	$ 15.95	9.39%	$ 619,727.13	$ 15.95	9.50%	$ -
118	2.3.9.0	Windows	4.450	W 2.3	$ 422,682.16	$ 12.59	4.84%	$ 489,253.16	$ 12.59	4.89%	$ -
122	2.4.2.0	Doors	4.110	Dr 2	$ 49,099.54	$ 1.61	0.56%	$ 62,449.41	$ 1.61	0.57%	$ -
127	2.5.1.0	Roofing Systems	2.090	Rf 1.1	$ 306,802.66	$ 5.96	3.51%	$ 231,646.39	$ 5.96	3.55%	$ -
154	2.6.3.0	Floor Systems	3.800	Flr 3	$ 469,450.72	$ 9.12	5.37%	$ 354,451.13	$ 9.12	5.43%	$ -
172	2.7.2.0	Ceiling Systems	3.163	Clng 2	$ 412,056.44	$ 10.47	4.71%	$ 406,709.91	$ 10.47	4.77%	$ -
185	2.8.4.0	Modular Onsite Connections	4.167	M Cn 2.3	$ 137,928.45	$ 3.58	1.58%	$ 139,223.27	$ 3.58	1.60%	$ -
204		Plumbing Systems									
205	3.1.5.0	Plumbing Fixtures	3.850	Plmbng Fix 5	$ 61,392.44	$ 1.81	0.70%	$ 70,215.77	$ 1.81	0.71%	$ -
222	.2.8.0	Plumbing Distribution	4.250	Plmbng Dis 8	$ 692,796.56	$ 13.46	7.93%	$ 523,084.78	$ 13.46	8.02%	$ -
230		HVAC Systems									
231	4.1.2.0	Heating and Cooling System	3.700	HVAC Sys 1.2	$ 138,767.19	$ 4.44	1.59%	$ 172,417.73	$ 4.44	1.61%	$ -
236	4.2.3.0	Ducting	4.250	HVAC Dct 3	$ 148,996.69	$ 4.72	1.70%	$ 183,494.22	$ 4.72	1.72%	$ -
243	4.3.2.0	Fire Protection Systems	4.158	HVAC FPS 2	$ 65,014.96	$ 1.37	0.74%	$ 53,035.77	$ 1.37	0.75%	$ -
247		Electrical Work									
248	5.1.3.0	Electrical Service/Distribution	4.500	Elec Srvc 3	$ 233,914.92	$ 4.55	2.68%	$ 176,613.66	$ 4.55	2.71%	$ -
254	5.2.3.0	Lighting and Branch Wiring	4.750	Elec Wrng 3	$ 342,261.19	$ 8.04	3.92%	$ 312,534.59	$ 8.04	3.96%	$ -
263	5.3.3.0	Other Electrical Systems	3.500	Elec Othr 3	$ 81,681.63	$ 2.18	0.93%	$ 84,750.01	$ 2.18	0.95%	$ -
274		Finishes									
275	6.1.4.0	Exterior Finishes	4.250	Ex Fnsh 3.1	$ 229,186.11	$ 6.64	2.62%	$ 258,045.78	$ 6.64	2.65%	$ -
293	6.2.1.0	Wall Finishes	3.675	W Fnsh 1.1	$ 304,842.22	$ 9.38	3.49%	$ 364,299.91	$ 9.38	3.53%	$ -
297	6.3.8.0	Floor Finishes	3.917	Flr Fnsh 8	$ 132,695.34	$ 3.52	1.52%	$ 136,581.39	$ 3.52	1.54%	$ -
298	6.4.2.0	Ceiling Finishes	2.850	Clng Fnsh 2	$ 130,194.58	$ 3.03	1.49%	$ 117,555.96	$ 3.03	1.51%	$ -
302	6.5.6.0	MilWork	3.725	Mlwrk 6	$ 316,898.41	$ 9.01	3.63%	$ 350,196.94	$ 9.01	3.67%	$ -
322	6.6.5.0	Cabinets & Countertops	4.625	Cbnt 5	$ 781,815.81	$ 15.19	8.94%	$ 590,297.38	$ 15.19	9.05%	$ -
332	6.7.1.0	Furniture & Appliances	3.000	Furniture & Appliances	$ -	$ -	0.00%	$ -	$ -	0.00%	$ -
334											
335		**Total**	**99.945**	-------------	**$ 8,741,519.00**	**$ 225.00**	**100.00%**	**$ 8,639,967.00**	**$ 222.39**	**100.00%**	**$ 2.61**

Figure 3-20: TCMd results

3.2. Energy-Based Performance Analysis

The energy evaluation process is measured against the desired project energy performance. The process starts with modelling and collecting project data from the pool of available historical projects organized under well-structured data forms. Given that energy is the chosen performance criteria, data related to building envelope and Heating, Ventilation, and Air Conditioning (HVAC) systems is extracted from two main datasets, project design and project specifications. The available datasets contain a number of alternatives for each of building envelope and HVAC sub-assemblies, (n) and (m) respectively. The two sets of alternatives are crossed over in order to develop the pool of all available energy models $(m \times n)$ in preparation for the energy modelling step, during which energy simulation tools are utilized to accurately evaluate the alternative models. The energy simulation having been run on all the models, the energy consumption results are stored in a structured dataset, which contains two groups of parameters; (1) input parameters—the energy factors which represent quantifiable factors that lay down the foundation for standardization of energy analysis of SASs, and which govern project cost, design, and specifications. (2) Output parameter—energy use intensity (EUI), which is defined by Natural

Resources Canada (NRCan) as: "*the measurement used to size up a building's energy performance. EUI represents the energy consumed by a building relative to its size and is expressed in GJ/m²/yr.*" A building's EUI is calculated as follows:

$$\text{EUI } (\text{GJ/m}^2/\text{yr}) = \frac{\text{Total energy consumed in one year (GJ)}}{\text{Total floor space of the building } (m^2)} \quad [25]$$

The relationship between the energy factors and EUI is drawn through the utilization of artificial neural network (ANN), which results in the development of the proposed energy equations. Energy equations are then embedded in a rule-based analysis (RBA) that optimizes the project performance and energy consumption within a target cost. Figure 3-21 illustrates the main methodology of the proposed energy-based target cost modelling.

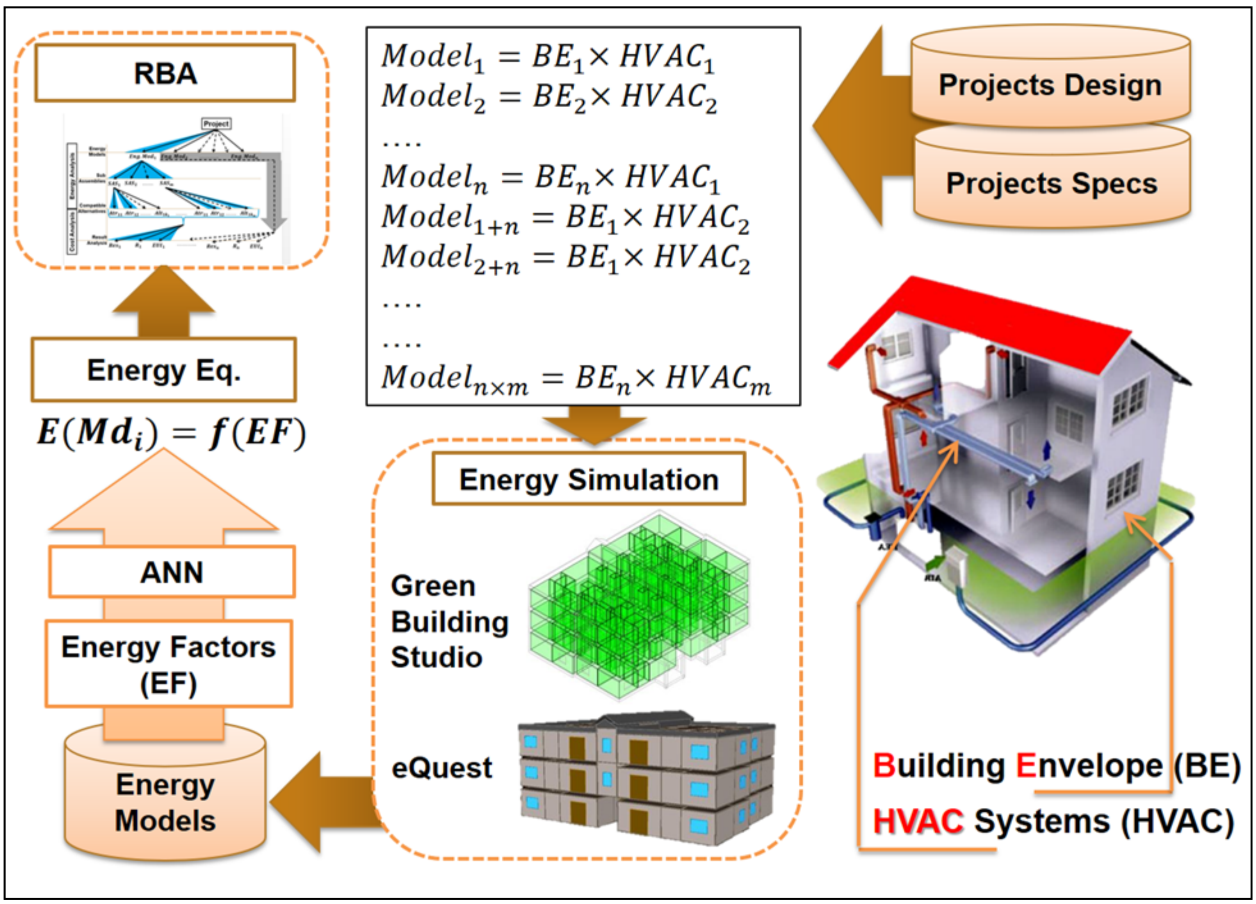


Figure 3-21: Energy modelling main methodology

This research introduces a novel solution for energy efficiency improvement by incorporating energy studies with target costing (TC) techniques. The energy evaluation process is based on the direct energy impact of TCMd systems—the three level hierarchical systems; assembly systems, sub-assembly systems (SASs), and construction components (CCs)—and their indirect impact due to the interchangeable interactions among those systems. Consequently, an internal comparative-based energy evaluation of all possible energy models that satisfy client's requirements and target cost is established, and an improved energy design along with detailed project estimate breakdown and full list of project specifications is generated.

To remain congruent with the research objectives, energy-based TCMd requires the achievement of four main tasks as follows:

1- Construction energy factor development
2- Energy dataset development
3- Energy equation development
4- Energy-based rule-based analysis

3.2.1. Construction Energy Factor Development

TCMd project breakdown provides the well-detailed framework necessary in order to establish the link between cost and energy studies throughout the design-estimate process. The proposed energy-based TCMd follows the same structure as the previous value ranking TCMd; it focuses on transforming energy related design criteria into quantifiable factors suitable for the evaluation of the impact of SAS alternatives on the overall project energy consumption measured by means of EUI. Energy factors allow for the standardization of energy design, which lays the foundation for an automated comprehensive decision support system (DSS).

The collected pool of offsite construction projects contains information about various performance aspects, including cost, specifications, and energy. These aspects are discussed and analyzed through a series of focus group meetings with a group of experts in the construction industry (one chief financial officer, one vice-president, four general managers, nine project managers, and twelve site managers), resulting in the definition of a set of factors that can adequately capture the key energy characteristics that influence the decision making process during the early design stages. The proposed energy factors are clustered into two main groups: global and local factors (See Figure 3-22).

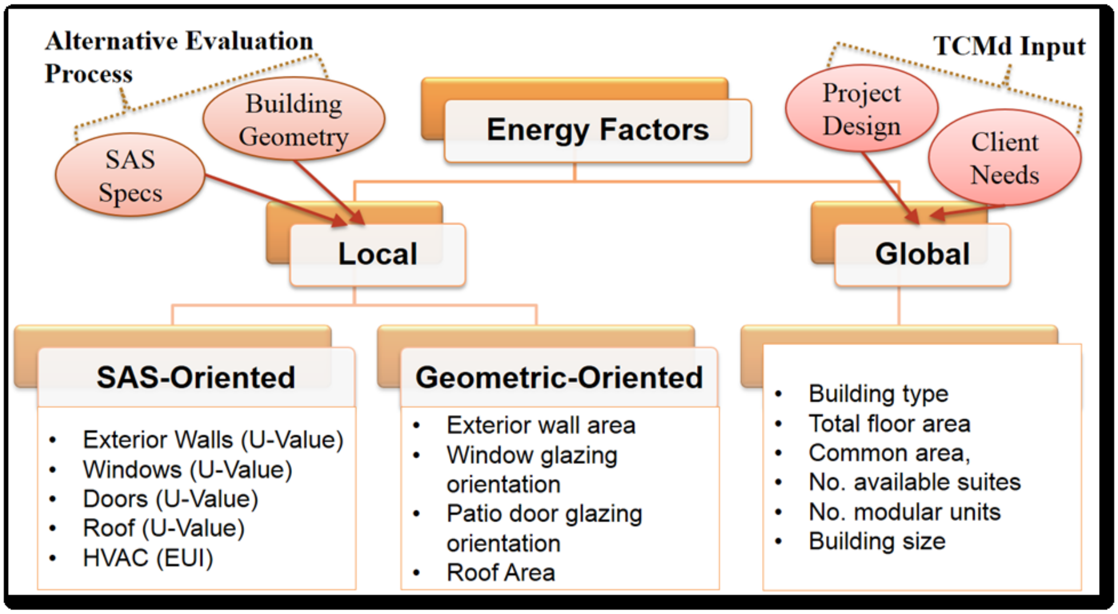


Figure 3-22: TCMd energy factors

Building type, total floor area, common area, number of available suites, number of required modular units, and overall building size are considered the energy global factors, as a result of the fact that the values these factors hold rely on a high-level project design that satisfies specific client requirements. Energy analysis considers global energy factors as constant values during the energy improvement process; for instance, the size of the building is calculated using two constant design parameters, a building's floor area and the corresponding floor height, which results in a constant value for the volume of air confined within the building. Along with the building type, which determines the building occupancy type and pattern, building size governs the air exchange requirements, and, subsequently, the necessary heating and cooling loads. Although global energy factors are independent of the alternative energy evaluation process, they have a significant influence on the building energy consumption, which makes them an essential part of the analysis.

Local energy factors are dependent on alternative energy evaluation; their values are linked directly to SAS specifications and building geometry, which results in a further categorization of the local energy factors into two sub-groups: (1) geometric-oriented local energy factors depend on the design criteria and the directional orientation of the building. Design criteria governs the total required areas of the exterior walls, window glazing, patio doors, and roof, and the orientation of the building determines the distribution of windows and patio doors over the four façades of the building, which in turn significantly influences the overall energy consumption (Morrissey et al. 2011; Barrett 2014; Abanda & Byers 2016). Similar to global energy factors, geometric-oriented energy factors are considered constant during the energy alternative analysis; however, they are significant during the customization of project design—i.e., scope change—that the client may perform since they inform efforts to study the impact design changes have on energy consumption. (2) SAS-oriented local energy factors are related to the building envelope and HVAC system, the two main assembly systems responsible for the energy performance of the building; consequently, the corresponding SASs under building envelope and HVAC assembly systems have a direct influence on the alternative evaluation during the energy analysis. In the present research, supported by the knowledge acquired during the focus group meeting, exterior wall, windows, doors, roof and HVAC SASs are selected as the key influential local energy factors. This decision is based on a comparative analysis of the impact of the available SAS alternatives on the overall energy efficiency. Table 3-12 lists the values of SAS-oriented local energy factors, which have been obtained from the selected pool of offsite construction projects.

Table 3-12: SAS-oriented energy factors

SAS	**Value 1**		**Value 2**		**Value 3**		**Value 4**	
Exterior Walls	**Low Insulation**		**Medium Insulation**		**High Insulation**		**Very High Insulation**	
	U-Value	0.061	U-Value	0.054	U-Value	0.049	U-Value	0.047
	R-Value	19	R-Value	20	R-Value	22	R-Value	24
Windows	**Double-Glazed**		**Triple-Glazed**					
	U-Value	0.348	U-Value	0.270				
Doors	**Double-Glazed**		**Triple-Glazed**					
	U-Value	0.348	U-Value	0.270				
Roof	**Medium Insulation**		**High Insulation**					
	U-Value	0.024	U-Value	0.020				
	R-Value	38	R-Value	49				

SAS	**Value 1**	**Value 2**	**Value 3**	**Value 4**	**Value 5**
HVAC	**Separate Furnace - Forced Air 1**	**Separate Furnace - Forced Air 2**	**PTAC Units W/ Supplemental Heat 1**	**PTAC Units W/ Supplemental Heat 2**	**PTAC Units W/ Supplemental Heat 3**
EUI	0.190	0.197	0.174	0.178	0.183
kWh ×1,000	124.8	143.0	231.0	239.1	255.8
Btu ×1,000,000	1,243.5	1,243.5	738.8	747.1	738.8
Main Heating	High Eff. Package System	High Eff. Package System	PTAC Electric Heat	PTAC Electric Heat	PTAC Electric Heat
Cooling System	No	Electric	Yes	Yes	Yes
Supplementary System	No	No	Baseboard	Electric Furnace	Electric Heat

Continue Table 3-12

SAS	Value 6	Value 7	Value 8	Value 9
HVAC	**Separate Furnace - Forced Air W/ Supplemental Heat**	**Separate Furnace - Forced Air W/ Supplemental PTAC**	**Centralized Furnace - Forced Air**	**Centralized Hydronic Heating System**
EUI	0.1896	0.1896	0.194	0.214
kWh ×1,000	124.85	124.85	127.7	112.7
Btu ×1,000,000	1,243	1,243	1,273	1,498
Main Heating	High Eff. Package System	High Eff. Package System	Central - Furnace	Gas Hydronic
Cooling System	No	No	No	No
Supplementary System	Electric Heat	PTAC	No	Furnace

As illustrated in Table 3-12, exterior wall SASs are classified according to the heat resistance value (R-value) of the insulation layer into four classes: low, medium, high, and very high insulation; window and exterior door classification is based on the number of panes in the glazing layer, based on which the available SAS alternatives are divided into two classes—double- and triple-pane; and roof SAS classification is connected to the insulation layer R-value, which, according to the historical data, groups the available roof SAS alternatives into two sets—medium insulated with an R-value of 38, and highly insulated with an R-value of 49.

The classifications of the SAS-oriented local energy factors result in thirty-two building envelope alternative models, as illustrated in Eq. 26.

$$n_{BE} = n_{ExW} \times n_W \times n_{Dr} \times n_{Rf} = 4 \times 2 \times 2 \times 2 = 32 \qquad [26]$$

where:

n_{BE}: Number of building envelope models

n_{ExW}: Number of exterior wall SAS classifications

n_W: Number of window SAS classifications

n_{Dr}: Number of door SAS classifications

n_{Rf}: Number of roof SAS classifications

The energy factors related to building envelope having been defined, the available HVAC systems are analyzed and classified according to three criteria: main heating systems, cooling systems, and other supplementary heating systems. High efficiency package system, packaged terminal air conditioner (PTAC), centralized forced air furnaces, and centralized hydronic heater are the four main heating systems; cooling systems are either included or not; and the necessity for supplementary heating is determined by the project design, where a multiple-zone occupancy project may require a supplementary system to cover the common areas, such as corridor area, reception area, and any other shared facilities. Table 3-13 illustrates a sample of HVAC SAS.

Table 3-13: PTAC units with supplemental heat

HVAC Sys 2.1	**PTAC Units W/ Supplemental Heat 1**
Centralized System	N/A
Separate System	PTAC IN ROOMS - AMANA WS900E ship on floor, Low voltage (18/5) wire run from PTAC to T-Stat location, strip 2 wires on thermostat wire each end, Install Thermostat - install remote sensor on suite entry door, Install Thermostat harness in PTAC in 2 wires in R & C ports
Supplemental Heat	300 watt Baseboard Heat in Suite Bathrooms c/w thermostats on heater, Install baseboard heaters 4 1/2" above floor - to clear 4" rubber baseboard,

Consequently, nine HVAC SAS alternatives are chosen for the energy analysis as follows: (a) separate furnace - forced air type 1, (b) separate furnace - forced air type 2, (c) PTAC units with supplemental heat type 1, (d) units with supplemental heat type 2, (e) units with supplemental heat type 3, (f) separate furnace - forced air with supplemental heat, (g) separate furnace - forced air with supplemental PTAC, (h) centralized furnace - forced air, and (i) centralized hydronic heating system. The nine HVAC SAS alternative models and the thirty-two building envelope alternative models result in a total of 288 possible energy alternative models, as illustrated in Eq. 27.

$$n\_Eng_{Alt} = n_{BE} \times n_{HVAC} = 32 \times 9 = 288 \quad [27]$$

where:

n_Eng_{Alt}: The number of energy alternative models

n_{HVAC}: the number of HVAC systems

In the context of the proposed research, the total available energy models (EngAlt) is defined as: *the set of energy models generated to explore all the possible configurations for the building envelope and HVAC systems of a project by crossing-over the developed set of SAS-oriented energy factors among each other.*

Each energy model evaluates the energy impact one SAS-oriented energy factor has on the overall project energy performance by choosing one of the developed values of that energy factor while keeping the rest of the factors constant. Eq. 28 illustrates the formation of EngAlt.

$$Eng_{Alt_i} = \bigcup_{i=1}^{n_{ExW}} \left\{ \bigcup_{j=1}^{n_W} \left\{ \bigcup_{k=1}^{n_{Dr}} \left\{ \bigcup_{l=1}^{n_{Rf}} \left\{ \bigcup_{m=1}^{n_{HVAC}} \left[f\left(ExW_i, W_j, Dr_k, Rf_l, HVAC_m \right) \right] \right\} \right\} \right\} \right\} \quad [28]$$

where:

ExW_j : Exterior walls heat transfer coefficient value [BTU/(h.ft2.F)]; $ExW_i \in [ExW_1, ExW_2, ExW_3, ExW_4]$

W_k : Heat transfer coefficient value of windows [BTU/(h.ft2.F)]; $W_k \in [\mathrm{W}_1, \mathrm{W}_2]$

Dr_l : Heat transfer coefficient value of patio doors [BTU/(h.ft2.F)]; $Dr_l \in [Dr_1, Dr_2]$

Rf_m : Roof heat transfer coefficient value [BTU/(h.ft2.F)]; $Rf_m \in [Rf_1, Rf_2]$

$HVAC_n$: Energy use intensity for a 20,000 ft^3 standard building ($GJ/m^2/Yr$); $HVAC_n \in [HVAC_1, HVAC_2, HVAC_3, HVAC_4, HVAC_5, HVAC_6, HVAC_7, HVAC_8, HVAC_9]$

3.2.2. Energy dataset development

Data modelling is carried out on four major types of buildings: multi-family, housing, work force camp, and hotel. These types constitute a representative set of the available pool of offsite construction projects; Figure 3-23 illustrates the four project designs modelled in Autodesk Revit.

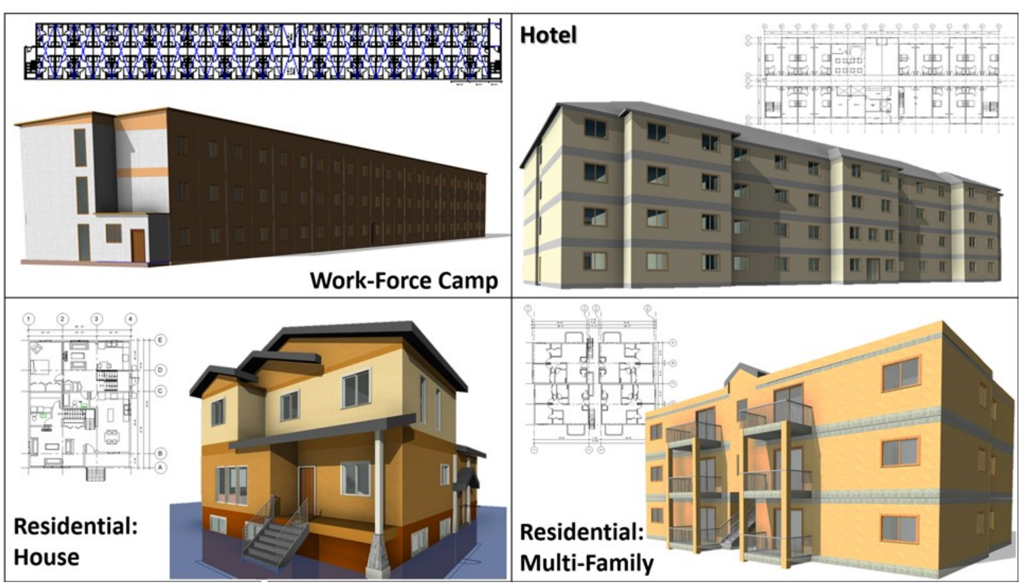


Figure 3-23: Offsite construction energy modelling projects

Design layouts and specifications of the four representative projects provide the values of the global and local geometric-oriented energy factors; Table 3-14 lists the corresponding values of the energy factors derived from a building information modelling (BIM) modelled after the four representative projects.

Table 3-14: Modelling project energy factors values

Energy Factors			**Projects**			
			Apartment	**House**	**Camp**	**Hotel**
Global	Building Type	BT	1.0	2.0	3.0	4.0
	Floor Area	FA	10,224.0	3,987.0	29,254.5	50,454.0
	Common Area	CA	656.8	-	5,070.0	10,103.5
	No. Suites	NS	12.0	2.0	123.0	83.0
	No. Mods	NM	12.0	9.0	18.0	56.0
	Building Size	BS	03,944.0	1,066.1	95,470.5	521,356.3
Geometric-Oriented	Exterior Wall Area	ExWA	6,575.9	4,222.0	17,582.0	19,272.0
	Window Glazing Facing (S)	WA_S	96.0	67.0	64.0	896.0
	Window Glazing Facing (N)	WA_N	96.0	143.0	48.0	896.0
	Window Glazing Facing (E)	WA_E	96.0	52.0	1,008.0	48.0
	Window Glazing Facing (W)	WA_W	96.0	16.0	1,008.0	48.0
	Patio Door Facing South	PA_S	-	-	-	-
	Patio Door Facing North	PA_N	-	-	-	-
	Patio Door Facing East	PA_E	120.1	-	-	-
	Patio Door Facing West	PA_W	120.1	-	-	-
	Roof Area	RA	3,408.0	1,926.0	9,735.0	15,342.0

Driven by the fact that global and geometric-oriented energy factors hold constant values during the energy evaluation process, each representative project reflects only one data point. SAS-oriented local energy factors, on the other hand, are bound to the collected pool of historical projects, resulting in the 288 available energy alternative models (Eng_{Alt}). The crossover of the four project types, along with the total number of energy simulation models, generates the number of total records—i.e., data points—of the proposed energy dataset (see Eq. 29).

$$Eng_{DS} = n_{prj} \times Eng_{Alt} = 4 \times 288 = 1{,}152 \; data\, points \quad [29]$$

where:

Eng_{DS}: Number of energy dataset records

n_{prj}: Number of representative projects

The structure of the proposed energy dataset is divided into two distinct sets of parameters, input and output parameters, in order to facilitate the formation of energy equations capable of automatically generating energy outcomes of a set of alternative models during the energy analysis process. The energy factors of the total number of energy alternative models that are derived from the historical data constitute the main input data, and energy consumption outputs are modelled using appropriate simulation tools.

The selection of appropriate energy simulation tools is vital to the accuracy of the energy consumption outcome. Green Building Studio (GBS) by Autodesk has proven to be an effective tool capable of modelling complex construction project designs and incorporating any required changes to the design with ease. Figure 3-24 shows a sample representation of complex geometries of a 12-suite residential project as a suitable set of spaces and occupancy zones.

GBS is preloaded with a set of alternatives that covers a wide range of building systems, and gives a detailed report of various outcomes that may significantly influence the design process. Wind loads, CO_2 emissions, heating and cooling loads, and analysis of potential energy consumption savings are included in the GBS report. An example of the reports provided by GBS for a 12-suite residential modular building is illustrated in Appendix C. Although GBS provides a quick energy simulation tool, it does not allow the end-user to customize energy inputs in order to precisely represent a specific set of building system details in accordance with a special client requirement. This major limitation of GBS warrants the utilization of powerful energy simulation tools able to define and customize each of the energy elements, ranging from walls, to roofs, doors, windows, and HVAC systems.

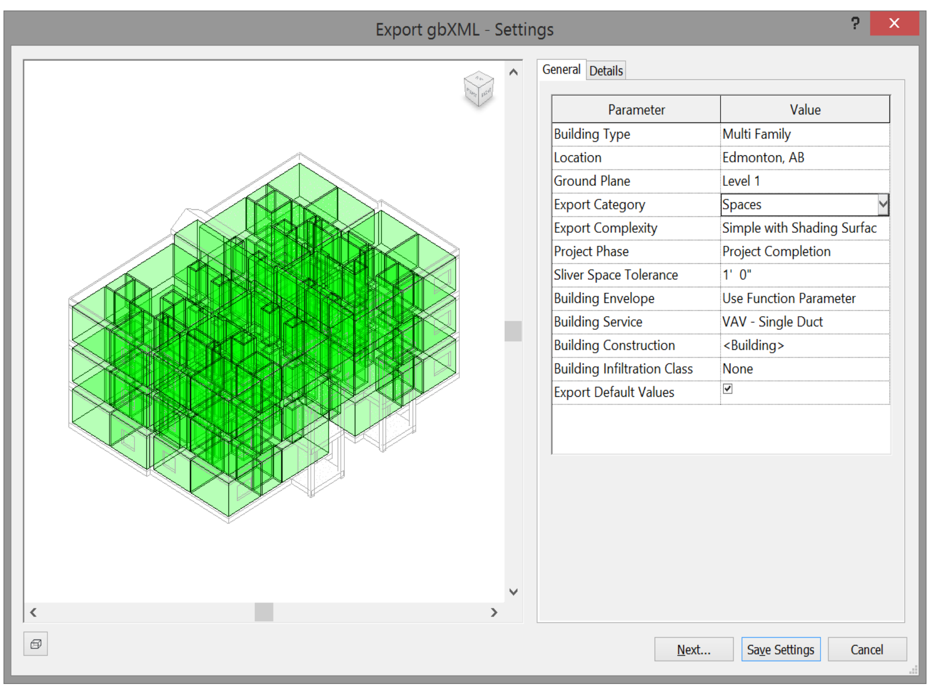


Figure 3-24: GBS space modelling

eQUEST, a well-known energy simulation tool that supports the full customization of energy models, is the ideal tool when dealing with unique structures similar to the ones encountered in offsite construction. Through a well-structured set of dialog boxes, eQUEST can customize the energy model according to the developed set of SAS-oriented local energy factors including exterior walls, roof, windows, doors. eQUEST provides a report showing the annual electrical and gas consumption. An example of the reports provided by eQUEST for a 12-suite residential modular building is illustrated in Appendix D.

The combination of the two tools enhances the energy simulation accuracy both modelling-wise and energy-wise, and reduces the gap between actual and modelled energy performance as illustrated in figure 3-25 (Azhar and Brown 2009; Kim et al. 2011; Wong and Fan 2013; Mostafavi et al. 2015).

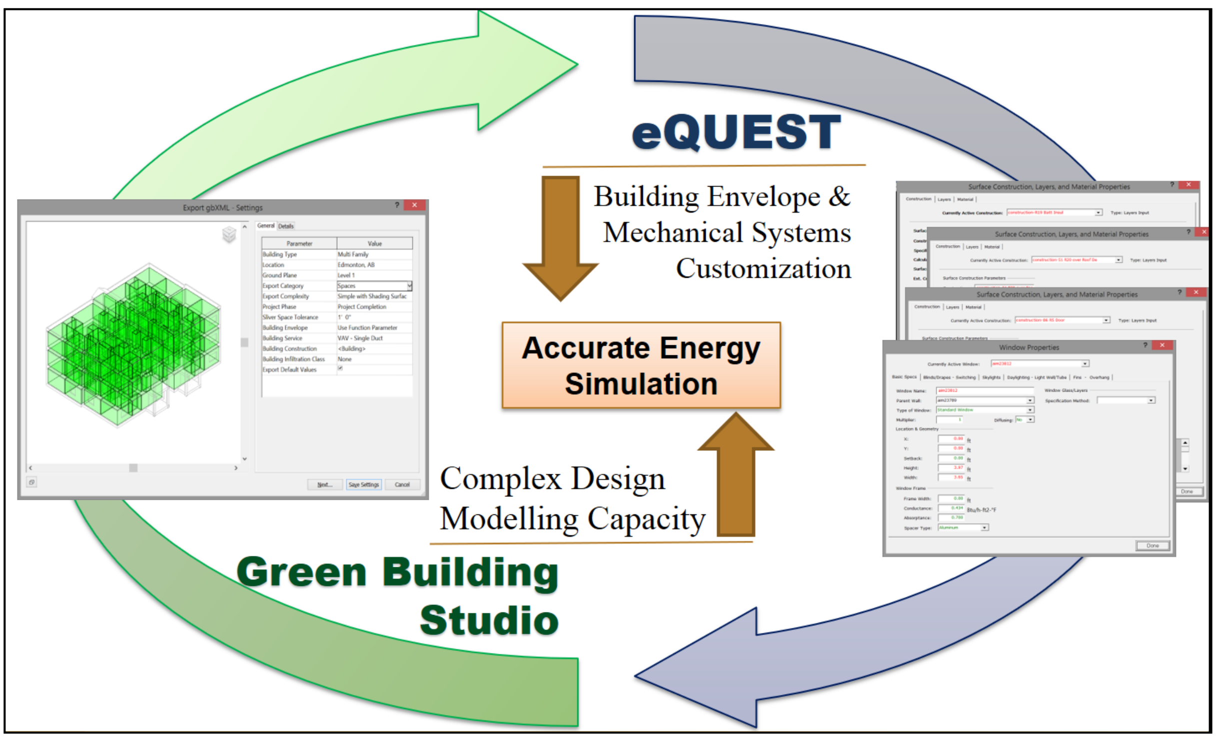


Figure 3-25: Energy simulation tools

A comparison between the two modelling tools – GBS and eQUEST – performed on a work force camp project with a separate furnace unit for heating and cooling purposes, shows that the two tools give comparable results, with a delta of 7.20% in gas consumption and 4.57% in electricity consumption. The small difference in modelled energy outcome proves that the representation of actual data is adequate, given that each energy simulation tool has a unique energy algorithm to transfer a set of input parameters related to project design and specifications into an annual energy consumption. Table 3-15 shows the comparison results between GBS and eQUEST when modelling the same 12-suite apartment building.

Table 3-15: GBS and eQUEST energy simulation comparison

	Gas Consumption (US Therm)			Electricity (kWh ×000)			
	HVAC	Hot Water	Tot.	HVAC	Lighting	Misc. Elec	Tot.
GBS	6,312.000	1,551.000	7,863.000	27.937	13.529	14.988	56.454
eQUEST	6,867.500	1,605.400	8,472.900	30.640	13.530	14.990	59.160
Detla (Δ)	555.500	54.400	609.900	2.703	0.001	0.002	2.706
Δ %	8.09%	3.39%	7.20%	8.82%	0.01%	0.01%	4.57%

Upon selection of appropriate simulation energy tools, the energy modelling begins with GBS, the first energy simulation that transfers the 3D-model of the four representative projects into a set of energy spaces categorized into a number of zones according to the building occupancy type. Subsequently, eQUEST, which allows for the customization of energy models through its powerful construction sub-assemblies parameter tools, receives the models from GBS as (DOE-2), a file format compatible with eQUEST, and performs advanced energy analysis. Figure 3-26 shows the four representative projects after being exported to eQuest.

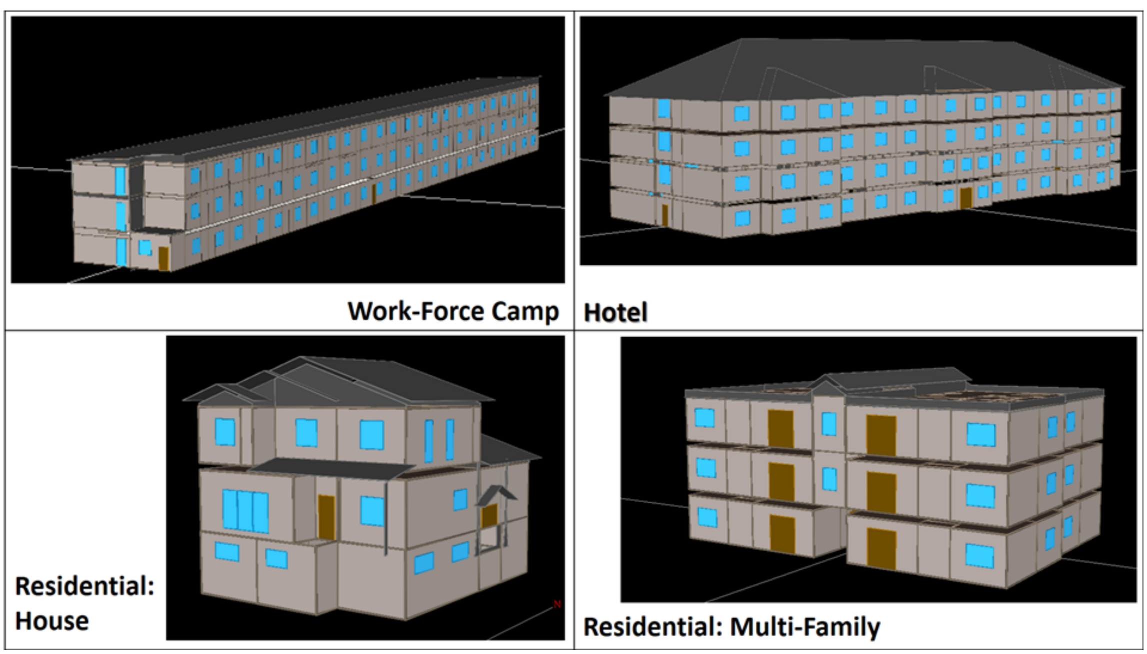


Figure 3-26: eQUEST offsite construction project modelling

Energy models are analyzed through the utilization of the proposed energy factors in order to measure the effect SAS-oriented local energy factors have on the overall energy output, represented by energy use intensity (EUI). The EUI graphical representation of one of the four representative projects, residential multi-family building, illustrates a clear pattern clustering the data into nine groups according to the corresponding HVAC SAS alternatives (see Figure 3-27).

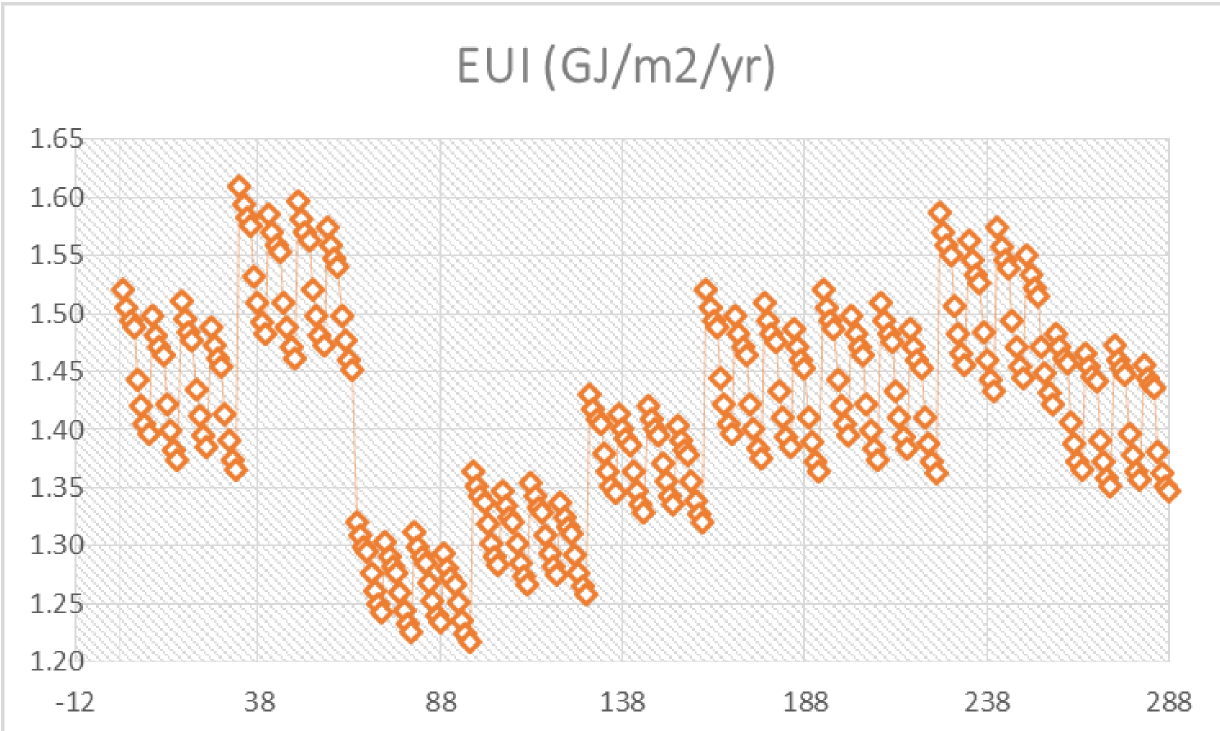
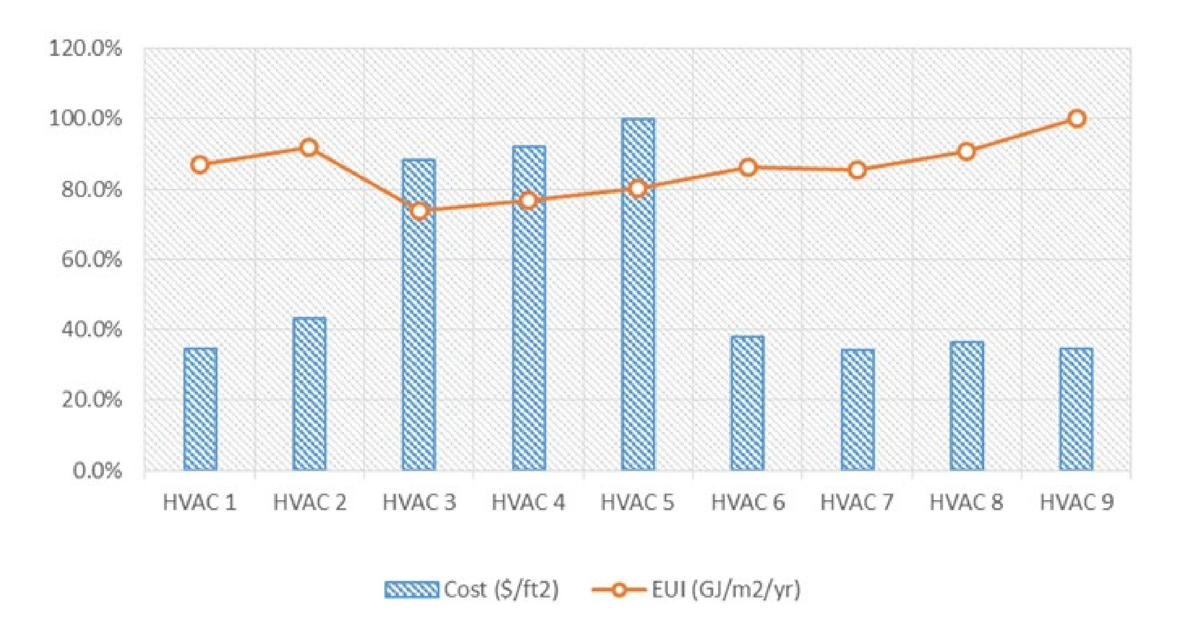
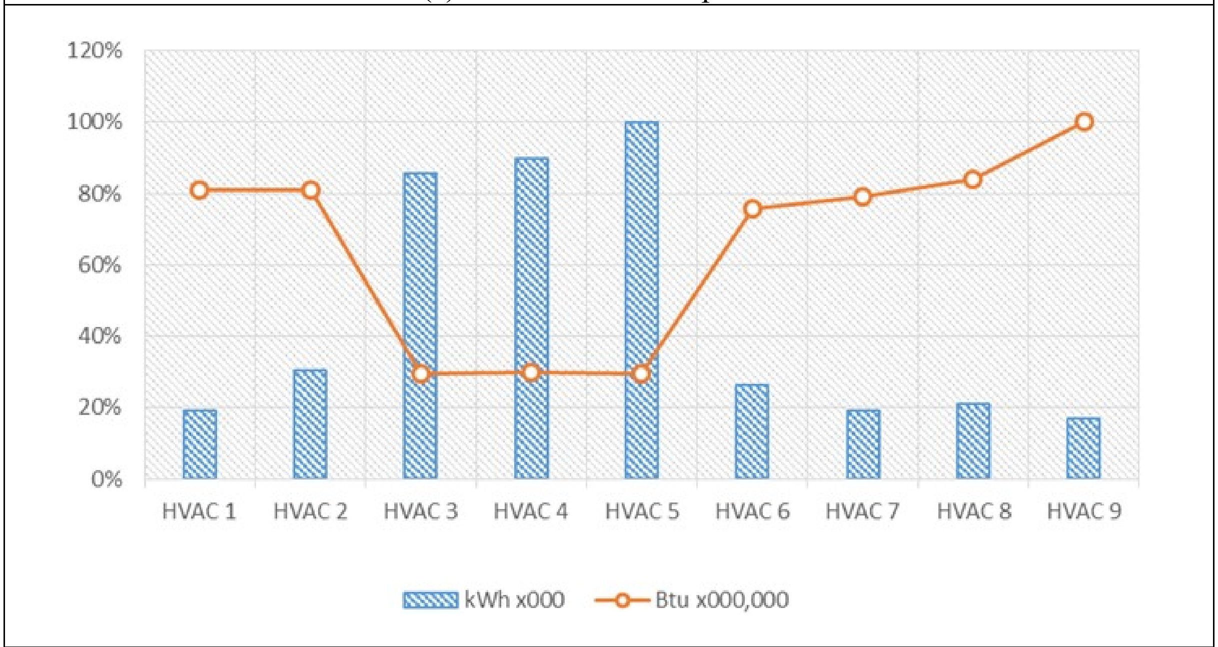


Figure 3-27: Residential multi-family modelled EUI

This observation proves that the influence of HVAC SAS alternative selections on the overall energy efficiency surpasses those realized through the explorations of building envelope alternative SASs. As a result, a further study with a focus on the impact of HVAC systems on the operational cost (measured by $\$/ft^2$) and energy consumption (measured by $GJ/m^2/yr$) is performed. The HVAC SAS-based sensitivity analysis shows a significant increase in operational cost in three of the HVAC systems—HVAC3, HVAC4, and HVAC5, with an inversely correlated result with respect to EUI (see Figure 3-28a and Table 3-16). These three HVAC SAS alternatives have electric PTAC, which consumes a higher amount of electricity than other systems, as the main heating and cooling system. (The PTAC average required electrical load is 408,394 kWh, compared to an average of 98,887 kWh for non-PTAC systems.) On the other hand, the average fuel-based energy consumption of PTAC systems is 788.7 MBtu, with a reduction of 1,433.5 MBtu compared to the other HVAC systems (see Figure 3-28b and Table 3-17). While the use of PTAC systems has proven to reduce the overall EUI, its high electrical usage along with the high cost of electricity (in Edmonton, \$0.0522/kWh, \$0.1787/Therm; 1 Therm = 100,000 Btu) results in a negative effect on the operational cost. This analysis demonstrates that utility cost is a key influential factor during the early design stages.



(a) Cost and EUI comparison



(b) Fuel and electricity comparison

Figure 3-28: HVAC-based sensitivity analysis

Table 3-16: HVAC-based cost and EUI sensitivity analysis

	Cost ($/ft^2)					EUI (GJ/m^2/yr)				
Buildings	**Avg.%**	**Bldg 1**	**Bldg 2**	**Bldg 3**	**Bldg 4**	**Avg.%**	**Bldg 1**	**Bldg 2**	**Bldg 3**	**Bldg 4**
HVAC 1	**34.6%**	$0.39	$0.36	$0.41	$0.31	**86.9%**	1.44	0.97	1.51	0.96
HVAC 2	**43.1%**	$0.51	$0.37	$0.56	$0.41	**91.8%**	1.53	0.97	1.62	1.03
HVAC 3	**88.3%**	$1.07	$0.92	$0.96	$0.84	**73.7%**	1.27	0.73	1.38	0.76
HVAC 4	**92.0%**	$1.11	$0.94	$1.01	$0.88	**76.8%**	1.31	0.79	1.42	0.80
HVAC 5	**100.0%**	$1.21	$0.98	$1.13	$0.97	**80.4%**	1.37	0.77	1.51	0.86
HVAC 6	**38.1%**	$0.40	$0.36	$0.51	$0.37	**86.2%**	1.44	0.97	1.49	0.95
HVAC 7	**34.2%**	$0.39	$0.36	$0.40	$0.31	**85.7%**	1.44	0.97	1.47	0.93
HVAC 8	**36.5%**	$0.42	$0.37	$0.44	$0.34	**90.7%**	1.50	1.01	1.57	1.01
HVAC 9	**34.7%**	$0.36	$0.36	$0.44	$0.33	**100.0%**	1.41	1.22	1.75	1.23

Table 3-17: HVAC-based fuel and electricity sensitivity analysis

	kWh ×1,000					Btu x1,000,000				
Buildings	**Avg.%**	**Bldg 1**	**Bldg 2**	**Bldg 3**	**Bldg 4**	**Avg.%**	**Bldg 1**	**Bldg 2**	**Bldg 3**	**Bldg 4**
HVAC 1	**19%**	36.3	18.4	111.0	179.3	**81%**	1,175.1	275.9	3,518.5	3,655.3
HVAC 2	**30%**	58.9	19.2	195.1	269.4	**81%**	1,176.6	275.9	3,518.5	3,655.3
HVAC 3	**86%**	193.0	69.7	471.1	788.0	**29%**	483.3	18.5	1,935.0	702.9
HVAC 4	**90%**	201.4	71.0	500.8	826.3	**30%**	492.7	34.8	1,944.0	713.7
HVAC 5	**100%**	221.1	74.0	569.4	914.6	**29%**	483.3	18.5	1,935.0	702.9
HVAC 6	**26%**	37.4	18.4	175.4	237.4	**76%**	1,171.1	275.9	3,235.1	3,395.2
HVAC 7	**19%**	36.2	18.4	108.8	178.7	**79%**	1,174.9	275.9	3,414.2	3,537.9
HVAC 8	**21%**	39.8	18.5	124.1	193.3	**84%**	1,218.3	290.9	3,617.4	3,831.1
HVAC 9	**17%**	31.6	14.1	104.8	148.8	**100%**	1,164.5	381.5	4,153.5	4,945.3

3.2.3. Energy Equations

Within a well-defined framework, mathematical tools such as artificial neural network (ANN) can depict the relationship between the energy input and the output parameters—in this case the energy factors and energy consumption represented by EUI. The accuracy of predicted results is dependent on the adequate selection of energy factors, which guides the process of evaluating energy alternatives in order to achieve an acceptable error margin. The objective of this task is to develop energy equations through the utilization of energy factors, a dataset, and an adequate ANN method.

The generalized regression neural network (GRNN) has proven its effectiveness in predicting a numerical output (i.e., independent parameter) linked to a set of numerical inputs (i.e., dependent parameters) when a sufficient dataset is present. It has been used in a wide range of applications including gas emission predictions, system sizing, structural analysis, epidemic prediction, and weather forecasting (Sun et al. 2008; Khatib & Elmenreich 2014; Liu et al. 2015, Lu et al. 2015; Wei et al. 2016). GRNN is closely related to probabilistic neural networks; it is derived from the nonlinearity regression theory, which can depict the relationship between input and output vectors with speed and stability through the utilization of small training samples compared to the other backpropagation neural networks, such as multilayer perceptron feedforward (MLF) network (Specht 1991). Aside from the training and testing input-output dataset, GRNN does not require any addition inputs, which makes it an ideal tool to predict system performance with a practical data size. GRNN calculates the most probable output *y* according to a set of training inputs *x* through the utilization of an appropriate density function$f(x,y)$, which is usually sampled from historical data or a sample of available observations, when $f(x,y)$ is unknown. The regression of the expected output value *y* of a given input vector *x* is illustrated in Eq. 30.

$$E[y|x] = \frac{\int_{-\infty}^{+\infty} yf(x,y)dy}{\int_{-\infty}^{+\infty} f(x,y)dy} \qquad [30]$$

GRNN utilizes Euclidian distance during the training process to measure the goodness of a training sample compared to the position of the prediction *x*. The smaller the distance between the point of prediction and training sample D_i (Eq. 31), the better the prediction is, and the best point of evaluation is achieved when $D_i = 0$.

$$D_i^2 = (X - X^i)^T(X - X^i) \qquad [31]$$

The network output for numerical matters is calculated using Eq. 32.

$$f^\wedge = \frac{\sum_{i=1}^{n} y^i \times exp\left(\frac{D_i^2}{2\sigma^2}\right)}{\sum_{i=1}^{n} exp\left(\frac{D_i^2}{2\sigma^2}\right)} \qquad [32]$$

where:

n = Number of sample observations

σ = Smoothing factor

T= Value of the explained variable on *n* observations

The training and testing process of MLF is dependent on the appropriate selection of the number of hidden layers, activation – transfer – functions, and the weight effects, which in turn influence the output prediction accuracy. Unlike MLF, the performance GRNN is influenced by one key parameter, the smoothing factor σ; the larger the value σ takes, the smoother it gets, until a specific limit where it turns into a multivariate Gaussian with covariance σ^2; on the other hand, a smaller value of σ may result in non-Gaussian shapes with wild points, which affects the modelling process (Specht 1991). The utilized tool for energy equation modelling, PALISADE NeuralTool, automatically selects the optimum smoothing factor in order to improve the output prediction accuracy.

GRNN has a four layers: an input layer, pattern layer (hidden layer), summation layer, and an output layer. Figure 3-29 illustrates the architecture of the developed network, and input layer consists of the three energy factor sets (global, geometry-oriented, and SAS-oriented); the pattern layer contains a number of neurons equal to the number of training cases.

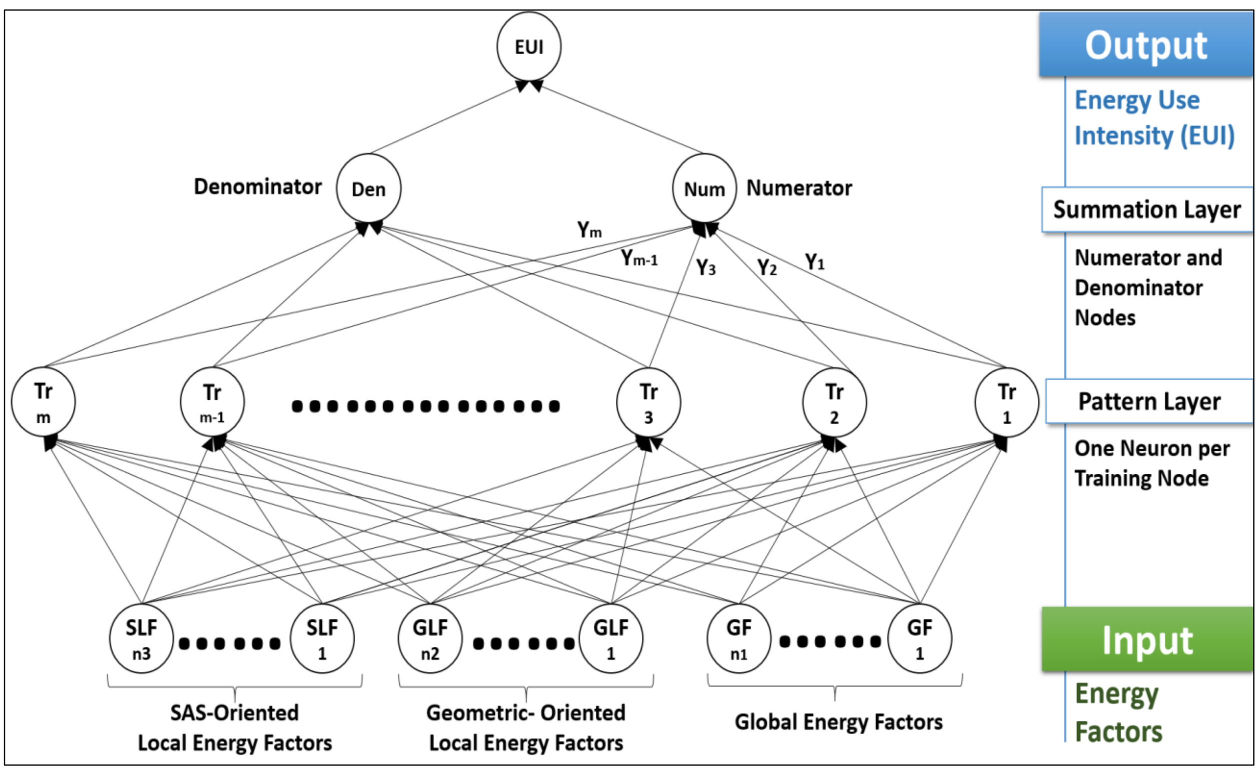


Figure 3-29: GRNN block diagram

Neuraltool utilizes root mean square error (RMSE), mean absolute error (MAE), and standard deviation of absolute error (R^2) as the key indicators to describe the goodness of fit (see Eqs. 33, 34, and 35)

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(T_i - A_i)^2}{n}} \quad [33]$$

$$\text{MAE} = \frac{\sum_{i=1}^{n} |T_i - A_i|}{n} \quad [34]$$

$$\text{R}^2 = \sum_{i=1}^{n} \frac{(T_i - MAE)^2}{n} \quad [35]$$

where:

T_i = observed value

Ai = Predicted value

n = number of observations

Table 3-18 shows the training results of the developed energy dataset, a total of 1,152 data points. Eighty percent of the dataset (922 data points) is utilized for training the network, and the remaining 20% (230 data points) is used for testing purposes, with a 5% tolerance level. The illustrated results reflect a high accuracy prediction, with 6.96% bad prediction (error is greater than the 5% tolerance) for testing, 6.18% bad predictions for training, and less than 0.05 for both RMSE and MAE. Figure 3-30 provides a visual representation of the network analysis results.

Table 3-18: Artificial neural network training results

Training		Testing	
Number of Cases	922	Number of Cases	230
Number of Trials	64	% Bad Predictions (5% Tolerance)	6.9565%
% Bad Predictions (5% Tolerance)	6.1822%	Root Mean Square Error	0.03759
Root Mean Square Error	0.03103	Mean Absolute Error	0.02295
Mean Absolute Error	0.01935	Std. Deviation of Abs. Error	0.02978
Std. Deviation of Abs. Error	0.02426		

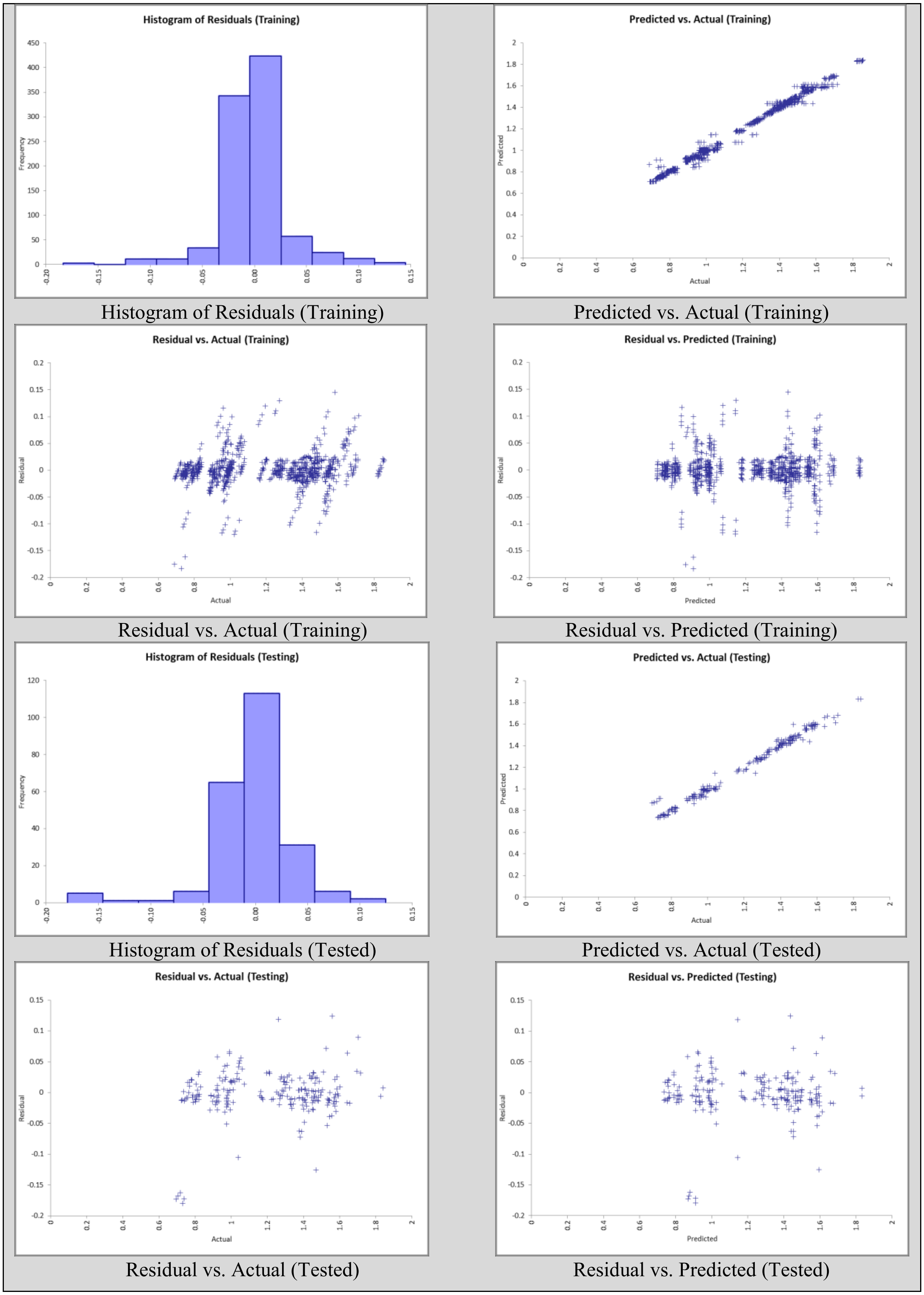
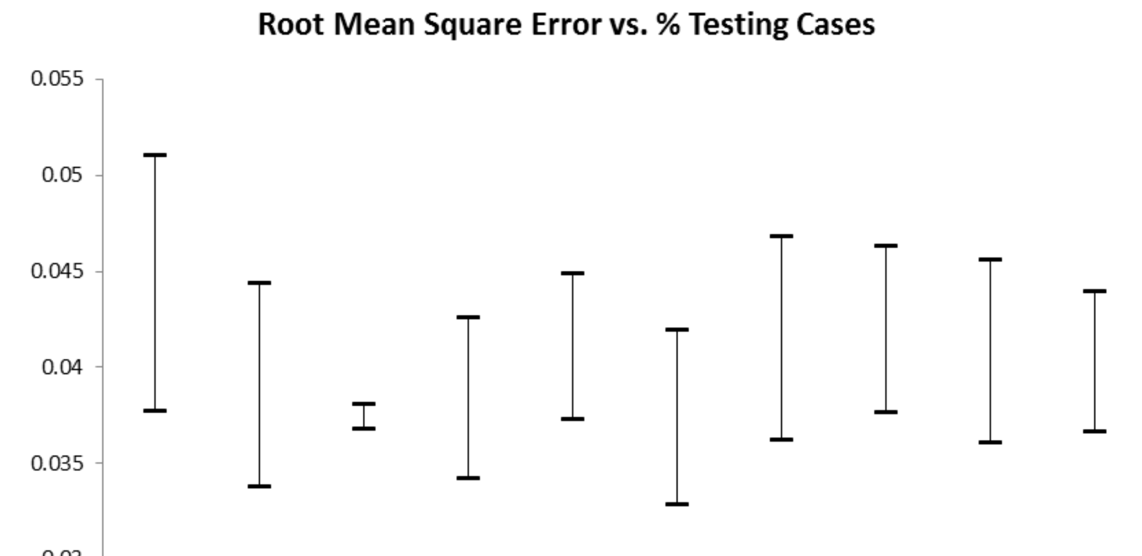


Figure 3-30 GRNN results

A sensitivity analysis for the size of training sample provides a clear indication of the stability of the dataset and the analysis process. Figure 3-31 includes a detailed analysis of the training sample size, where the size has been tested on 10 scenarios with a start point (testing sample equal to 5% of the dataset), end point (testing size equal to 50%), and incremental increase equal to 5%. The represented results reflect a stable network with RMSE less than 0.05 in the majority of the cases.



	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Series1	0.03768	0.03371	0.03672	0.03415	0.03720	0.03277	0.03614	0.03756	0.03604	0.03660
Series2	0.03821	0.03403	0.03677	0.03451	0.03741	0.03546	0.03703	0.03873	0.03713	0.03741
Series3	0.03975	0.03741	0.03714	0.03615	0.04107	0.03825	0.04165	0.03923	0.04011	0.04125
Series4	0.04290	0.03993	0.03780	0.03626	0.04361	0.04085	0.04379	0.04207	0.04026	0.04191
Series5	0.05100	0.04434	0.03804	0.04257	0.04480	0.04188	0.04679	0.04625	0.04552	0.04385

% Testing Cases

Figure 3-31: Test size sensitivity analysis

3.2.4. Energy-Based Rule-based Analysis

Deterministic rule-based analysis (RBA) is utilized for the purpose of developing the energy-based version of the target cost modelling tool (TCMd), based on a specific target cost that satisfies a set of design constraints. RBA is developed to enable the automation of energy-based TCMd process, to eliminate tedious estimation tasks, and to minimize human error. The proposed energy-based TCMd is an iterative RBA that explores all the compatible SASs for a specific design in order to improve the energy performance while maintaining a target cost. Programming tools such as Excel Macro, VBA, and VB.NET allow for the automation of the analysis according to a well-structured set of rules mimicking human logical reasoning.

The energy-based TCMd process is divided into two main streams: energy analysis and cost analysis. During the energy analysis, TCMd explores the available energy alternative models as proposed in the energy dataset, it begins with identifying the available set of energy models that satisfy the required project design, as expressed in Eq. 36. As a result, the energy analysis constraints the set of compatible SAS alternatives studied during the cost analysis.

$$\mathrm{EUI_i} = \mathrm{f}\left[\mathrm{SAS_j(Eng_i)}\right]; \left[\mathrm{SAS_j(Eng_i)}\right] = \bigcup_{k=1}^{n_k}\left[\mathrm{SAS_j(Eng_k)}\right]; \mathrm{SAS_j(Eng_k)} = \mathrm{SAS_j(Eng_i)} \quad [36]$$

where:

$\mathrm{EUI_i}$: Energy use intensity of an energy model i

$\mathrm{Eng_i}$: Specified SAS-oriented energy factor for an energy model i

$\mathrm{SAS_j(Eng_i)}$: SAS alternative group with energy factor equal to $\mathrm{Eng_i}$

$\mathrm{SAS_j(Eng_k)}$: All available SAS alternatives

n_k: Total number of $\mathrm{SAS_j(Eng_k)}$ alternatives

For instance, if the project design specifies double-glazed windows as the required window type, the SAS alternatives corresponding to triple-glazed SAS-oriented local energy factors windows type are excluded from the TCMd analysis for the studied energy model.

Cost analysis generates the project residual, ranking value, and energy consumption of each model by following the same four-step procedure illustrated in the value ranking TCMd as follows: first alternative filtering (design factors), second alternative filtering (baseline SAS distribution), priority bottom-up distribution process, and priority top-down distribution process. Project Residual (Res) is defined as the difference between target cost (TC$) and the cost associated with a certain energy model, project ranking is composed of the individual SAS value rankings, and energy consumption is represented by a unit of EUI (see Figure 3-32).

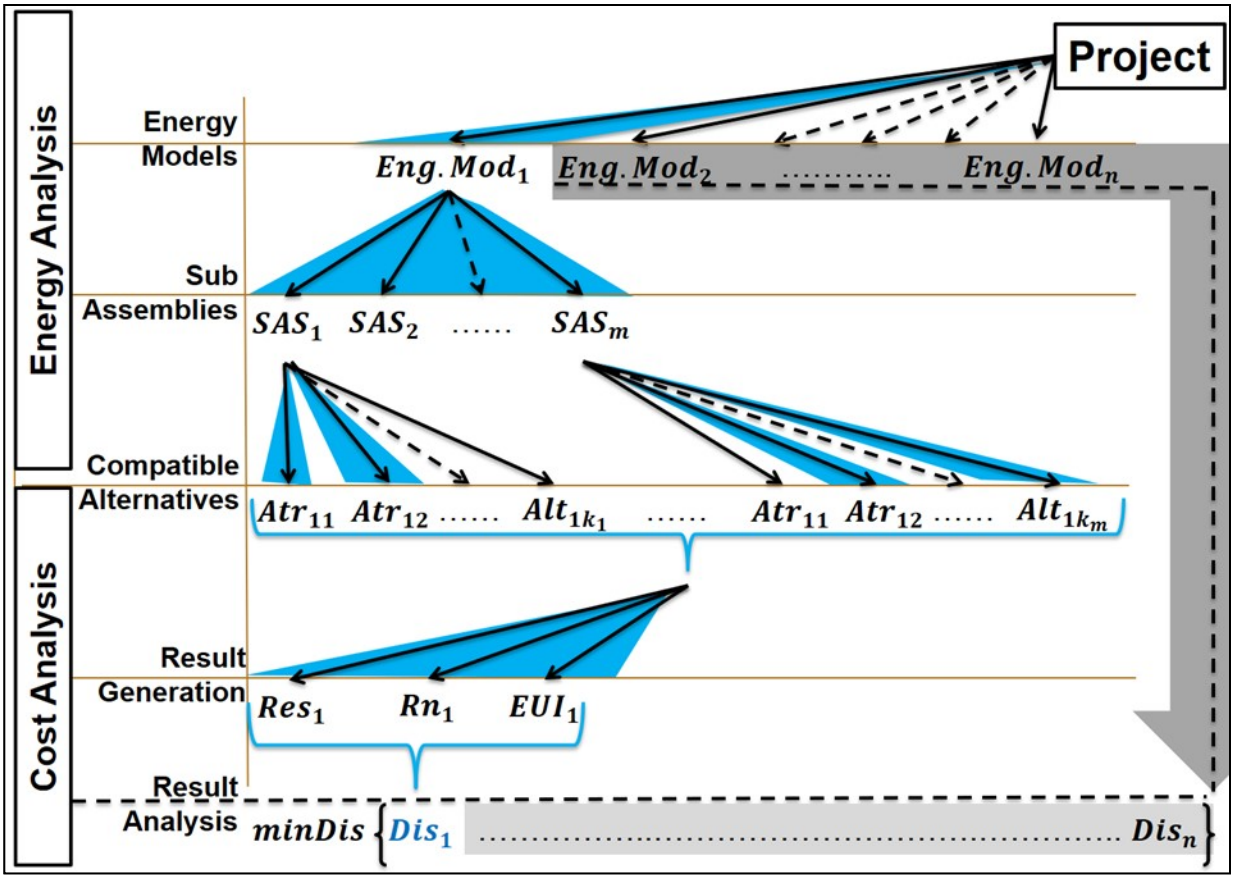
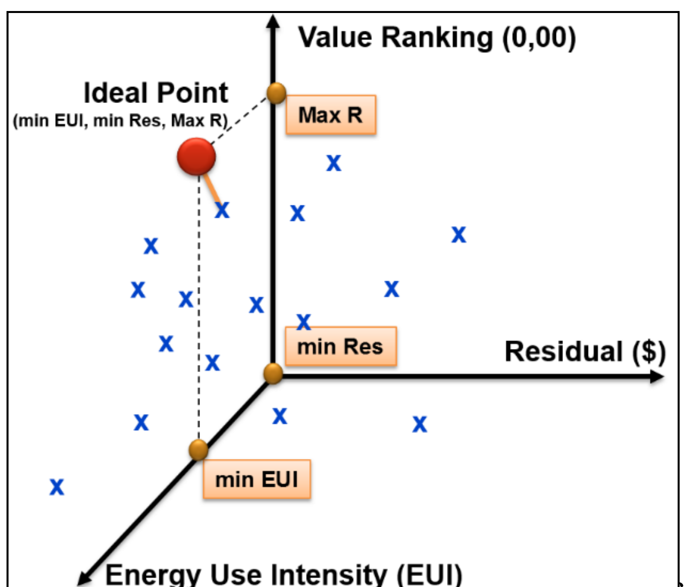


Figure 3-32: Energy-based TCMd rule-based analysis

Each iteration of TCMd generates a three-coordinate solution with three distinct objective values (Res_i, Rn_i, EUI_i); the weighted objective values determine the model with optimum energy consumption satisfying a specific TC$. The Euclidean distance between a theoretical optimum solution and the current solution provides an objective weighting method (see Figure 3-33).



Theoretically, the optimal solution is represented by a three-coordinate point: (1) minimum residual value, indicating that the developed estimate matches the target cost (see Eq. 37); (2) maximum SAS value ranking, where each selected

SAS alternative holds the highest ranking value among the available SAS alternatives (see Eq. 38); and (3) minimum EUI, which represents the optimum building envelope and HVAC system of the analyzed project (see Eq. 39).

$$\text{min. Res} = 0 \, ; \text{TC\$} = \text{Prj}_{\text{Est}} \qquad [37]$$

$$\text{max. Prj}_{\text{Rn}} = \sum_{i=1}^{i=26} \left[\text{max.} SAS_i\left(Rn_j\right)\right] ; \text{max.} SAS_i\left(Rn_j\right) = \max\{SAS_i(Rn_1), SAS_i(Rn_2) \ldots \ldots SAS_i(Rn_{ni})\} \qquad [38]$$

$$\text{min. EUI} = \min\left\{\text{EUI}_1, \text{EUI}_2 \ldots \ldots \text{EUI}_{Eng_{Alt}}\right\} \qquad [39]$$

where:

Res: Project residual value

TC$: Target cost

$\text{Prj}_{\text{.Est}}$: Developed project estimate

Rn: Project ranking value

$SAS\left(Rn_{ij}\right)$: Ranking value associated with a SAS

Eng_{Alt}: The number of energy alternative models

The Euclidean distance concept dictates that the squared length of a vector X = [x_1,x_2] is equal to the sum squares of its coordinates; similarly, the distance between a solution $Sol_i(Res_i, Prj_{Rni}, EUI_i)$ and the optimum solution Sol_{Opt} (*min.Res, max.*Prj_{Rn}*, min.EUI*) is calculated as illustrated in Eq. 40. Consequently, the solution with the shortest distance represents the optimum solution according to a user-defined priority ranking of the SASs, which is close to the optimum solution.

$$\text{Dis}_{\text{i}} = \sqrt[2]{[(Res_i - min.Res)^2 + (Rn - max.Prj_{Rn})^2 + (EUI_I - min.EUI)^2} \qquad [40]$$

3.3. Target Cost Modelling (TCMd) Optimization Analysis

The proposed TCMd is based on a set of rules governing the selection of optimum solution which yields the closest estimate to the target cost, i.e., lowest residual value, with the highest value ranking and lowest energy consumption. The supervised rule-based analysis (RBA) is closely related to the priority index given to each of the SASs in order to reflect the client's preferences; the cost distribution is affected by the assigned priority value as well, where the SAS with the highest priority (given value 1) has the highest chance of reaching the maximum ranking value. For instance, if the window SAS is given the highest priority index, the proposed RBA prioritizes the possibility of improving the selection of the window SAS among the available window alternatives on the expense of the remaining SASs. This deterministic approach yields a priority-oriented optimal solution by exploring all available solutions through the deterministic supervised RBA.

Unsupervised optimization methods are independent of the proposed priority list; they can provide an optimal solution through the utilization of probabilistic evolutionary algorithm methods to assist decision makers to reach objective goals (Machairas et al. 2014). The present research deals with offsite construction projects where the developed SAS dataset lists all the available alternatives, and the proper selection of SASs directly influences the project performance outcomes in term of cost, quality, and energy efficiency. The alternative values of each SAS constrain the selection process. For instance, a window SAS can only take one of twelve distinct alternative values, each with an individual set of properties that influences the overall project outcome. Table 3-19 lists the available alternatives of a window, each with their description and respective ranking value.

Table 3-19: Window SAS alternative values

ID	Window SAS	Description	Ranking Value
1	W 1.1	PVC Slider 1	2.000
2	W 1.2	PVC Slider 2	2.225
3	W 1.3	PVC Slider 3	2.288
4	W 1.4	PVC Slider 4	2.513
5	W 1.5	PVC Slider 5	2.325
6	W 1.6	PVC Slider 6	3.250
7	W 2.1	PVC Awing 1	2.725
8	W 2.2	PVC Awing 2	2.850
9	W 2.3	PVC Awing 3	4.450
10	W 2.4	PVC Awing 4	3.925
11	W 2.5	PVC Awing 5	3.088
12	W 2.6	PVC Awing 6	3.413

The distinct nature of available SAS alternatives makes the optimization method discrete in nature. Simulated annealing (SA) optimization method is a good fit for discrete optimization problems due to its ability to escape local optima in the search for the global optima (Henderson et al. 2003). SA is a local meta-heuristic search algorithm that simulates the thermodynamic behaviour of cooling a solid object through a slow cooling process. At each iteration of SA, the objective function generates two values, the current state (ω) and the new state (ω'), where the new state is selected from a set of neighbouring solution sets $N(\omega)$ that can be reached from the current state by one step. If the new state is better (cooler) than the current state, the algorithm accepts the new state and updates the current state accordingly; however, if the new state is inferior to the current state (warmer), the new solution may be accepted in the hope of escaping a local optima and eventually reaching the global optima. Accepting an inferior state is dependent on a non-increasing probabilistic parameter, temperature parameter t_k, whose value decreases during each iteration until reaching a zero value, theoretically. Eq. 41 illustrates the new state acceptance process.

$$\mathrm{P}\,(\omega') = \begin{cases} 1, & f(\omega') < f(\omega) \\ \exp\left\{\dfrac{-\ [f(\omega') - f(\omega)]}{t_k}\right\}, & f(\omega') \geq f(\omega) \end{cases} \qquad [41]$$

where:

P (ω'): Probability of accepting the new solution ω'

$f(\omega)$: Objective function value of the current solution ω

$f\ (\omega')$: Objective function value of the new solutionω'

t_k : Temperature parameter; $t_k > 0\ , \lim_{k\to\infty}(t_k) = 0$

The proper selection of t_k and the size of neighbouring solution set $N(\omega)$ are the two main elements for the search mechanism of SA, as the slow reduction of t_k and the proper size of $N(\omega)$ allow for reaching an equilibrium (steady state) for each iteration *k*. As the solution gets closer to the optimality, i.e., the temperature parameter gets closer to a zero value, the probability of selecting an inferior state solution decreases.

SA follows the Markov chain, through which the algorithm converges to a state where all the probability is focused on the set of globally optimal solutions. SA is utilized in the present research for the two developed TCMd—the value ranking and energy-based—as follows:

3.3.1. Value Ranking Optimization Model

The objective of value ranking TCMd is to maximize the quality of the selected set of SASs by finding the solution with the highest project ranking value Prj_{Rn} that satisfies a target cost, as illustrated in Eq. 42.

$$\max.\mathrm{Prj_{Rn}} = \sum_{i=1}^{i=26}\left[max.SAS_i(Rn_j)\right]; Prj_{Est} = \sum_{i=1}^{n=26} SAS_i(Cst) \le TC\$ \qquad [42]$$

where:

TC$: Target cost

SAS_i: Sub-assembly system

$SAS_i(Rn_j)$: Chosen SAS_i value ranking

$SAS_i(Cst)$: Chosen SAS_i cost value

Prj_{Rn}: Overall project value ranking

Prj_{Est}: Project estimate

Figure 3-34 illustrates the overall optimization methodology.

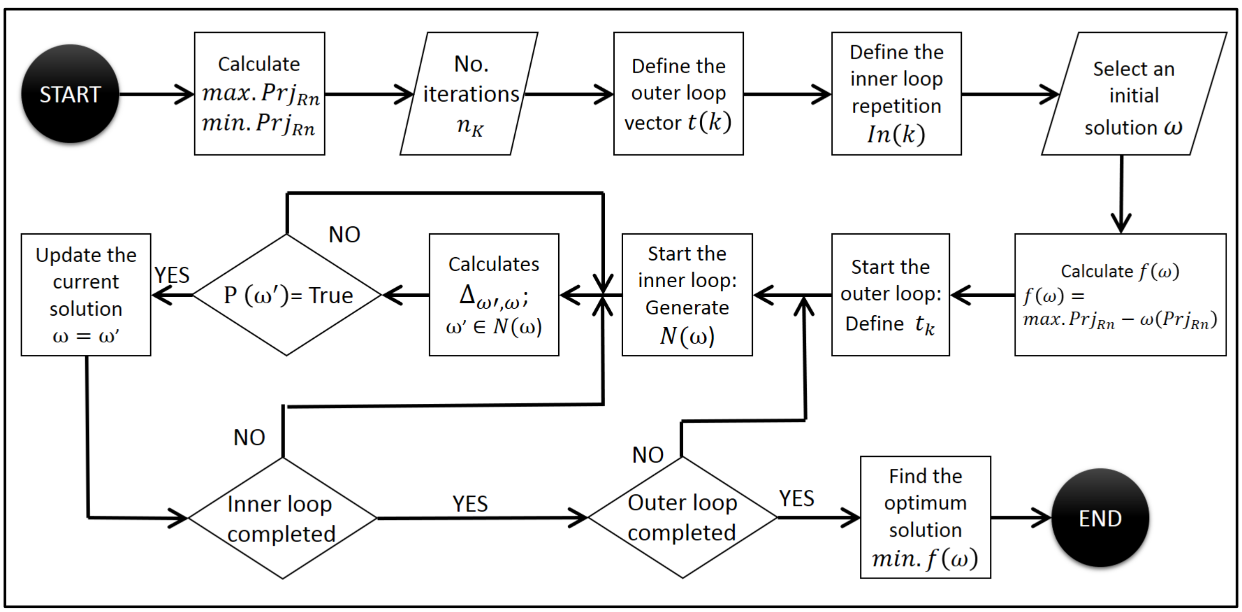


Figure 3-34: Value-ranking simulated annealing process map

The SA optimization method begins by identifying the lowest possible project ranking (Prj_{Rn}), which represents the warmest state, and the highest possible project ranking ($max.Prj_{Rn}$), which represents the coolest state. The distance between the boundary states, along with the number of iteration k, controls the t_k value for each iteration (see Eq. 43).

$$t(k) = \bigcup_{k=1}^{n_k}\left[\frac{(max.Prj_{Rn} - min.Prj_{Rn})}{k}\right] \qquad [43]$$

where $t(k)$ vector constitutes the temperature cooling schedule during each iteration of the outer loop in the algorithm. The value of t_k decreases in every iteration; on the contrary, the size of the neighbouring solution set $N(\omega)$, which represents the number of repetitions during each iteration, i.e., the inner loop, should increase during each iteration in order to allow a sufficient search set for each temperature t_k. The proposed structure for the inner loop vector In_k is illustrated in Eq. 44.

$$In(k) = \bigcup_{k=1}^{n_k} (n_{SAS} \times k) \quad [44]$$

where:

In(k) : Size of inner loop during an iteration k

Upon having identified the outer loop and inner loop structure, the SA optimization method selects an initial solution (ω) with a project ranking $\omega(Prj_{Rn})$, and establishes the distance between the initial solution ω and the optimum solution with $max.Prj_{Rn}$ as the main objective optimization function (see Eq. 45)

$$f(\omega) = max.Prj_{Rn} - \omega(Prj_{Rn}); Prj_{Est} \leq TC \quad [45]$$

The outer loop is initiated by defining the cooling temperature t_k from the outer loop vector $t(k)$, after which the algorithm generates a neighbouring solution set $N(\omega)$ with a size equal to *In(k)*. During the inner loop, solution ω is compared to the new solution ω' (see Eq. 46), where the acceptance of the new solution follows the probabilistic distribution expressed in Eq. 47.

$$\Delta_{\omega',\omega} = f(\omega') - f(\omega) \quad [46]$$

$$P(\omega') = \begin{cases} 1, & \Delta_{\omega',\omega} < 0 \\ \exp\left(\frac{-\Delta_{\omega',\omega}}{t_k}\right), & \Delta_{\omega',\omega} \geq 0 \end{cases} \quad [47]$$

SA algorithm goes through inner and outer loops as per the defined $t(k)$ and $In(k)$, and after having a sufficient number of iterations, SA algorithm selects an optimum solution with the shortest distance from the global optimum solution with the ultimate maximum project ranking value.

3.3.2. Energy-Based Optimization Model

Energy-based TCMd is a multi-objective optimization problem, where the optimum solution is the one that minimizes the difference project estimate and target cost, maximizes the value ranking of the project, and minimizes the energy consumption represented by the energy use intensity (EUI). The proposed optimization structure includes:

1- **Objective functions** as per Eq. 48, 49, and 50.

a. minimize $Res\,; Res = TC\$ - \sum_{i=1}^{n=26} SAS_i(Cst)\,; Res \geq 0$ [48]

b. maximize Prj_{Rn}; Prj_Rn $= \sum_{i=1}^{i=26} SAS_i(Rn)$ [49]

c. mininimize $Prj_{EUI}\,; Prj_{EUI} \in$ [EUI]; $Prj_{EUI} = f(ExW_i, W_j, Dr_k\,, Rf_l, HVAC_m)$ [50]

where:

SAS_i(Cst): Chosen SAS_i unit Cost

TC$: Project target cost

Res: Cost residual from the target cost

Prj_{Rn}: Project ranking value

Prj_{EUI}: Energy use intensity of the project GJ/m^2/yr)

2- **Subject to**: EUI energy functions as listed in Appendix E.

3- Constraints:

a. Discrete alternative values for the project's SASs, as listed in Appendix F

b. SAS-oriented energy factor values, expressed as follows:

i. ExW_i: Exterior wall heat transfer coefficient value [BTU/(h.ft2.F)]

$$ExW_i \in \{(ExW_1 = 0.0613), (ExW_2 = 0.0540), (ExW_3 = 0.0491), (ExW_{14} = 0.0468)\}$$

ii. W_j: Window heat transfer coefficient value [BTU/(h.ft2.F)]

$$W_j \in \{(W_1 = 0.3482), (W_2 = 0.2700)\}$$

iii. Dr_k: Patio door heat transfer coefficient value [BTU/(h.ft2.F)]

$$Dr_k \in \{(Dr_1 = 0.3482), (Dr_2 = 0.2700)\}$$

iv. Rf_l: Roof heat transfer coefficient value [BTU/(h.ft2.F)]

$$Rf_l \in \{(Rf_1 = 0.0235), (Rf_2 = 0.0200)\}$$

v. $HVAC_m$: Energy use intensity for HVAC system in a 20,000 ft^3 standard building (GJ/m^2/Yr)

$$HVAC_m \in \{(HVAC_1 = 0.1896), (HVAC_2 = 0.1966), (HVAC_2 = 0.1966), (HVAC_3 = 0.1738), (HVAC_4 = 0.1175), (HVAC_5 = 0.1830), (HVAC_6 = 0.1904), (HVAC_7 = 0.1896), (HVAC_8 = 0.1941), (HVAC_9 = 0.2138)\}$$

Theoretically, the optimum solution reaches the point $Opt_{Sol}(min.Res, max.Prj_{Rn}, min.EUI)$, and the least optimum solution reaches the point $Wst_{Sol}(max.Res, min.Prj_{Rn}, max.EUI)$ (as illustrated in Eqs. 51, 52, 53, and 54)

$$\text{min. Res} = 0\ ;\ \text{TC\$} = \text{Prj}_{\text{Est}} \quad [51]$$

$$\text{max. Res} = \text{TC\$} - \text{min. Prj}_{\text{Est}} \quad [52]$$

$$\text{min. Prj}_{\text{Rn}} = \sum_{i=1}^{i=26} (min.SAS.Rn_{ij})\ ;\ \text{min. SAS. Rn}_{\text{ij}} = \min\{\text{SAS. Rn}_{\text{i1}}, \text{SAS. Rn}_{\text{i2}} \ldots \ldots \text{SAS. Rn}_{\text{in}}\} \quad [53]$$

$$\text{max.} EUI\ ;\ EUI \in \langle EUI_i \rangle;\ EUI_i = f(ExW_j, W_k, Dr_l, Rf_m, HVAC_n) \quad [54]$$

The SA optimization begins by defining the maximum Euclidean distance (max. Dis) between the theoretical optimal and least optimal solution (see Eq. 55), which, along with the outer iteration number (k), governs the outer loop cooling temperature t_k and generates the cooling temperature vector $Eng_t(k)$ (see Eq. 56).

$$\text{max. Dis} = \sqrt[2]{[(max.Res - min.Res)^2 + (max.Prj_{Rn} - min.Prj_{Rn})^2 + (max.EUI_I - min.EUI)^2} \quad [55]$$

$$Eng_t(k) = \bigcup_{k=1}^{n_k} \left(\frac{Dis}{k}\right) \quad [56]$$

The size of inner loop repetition vector $Eng_{in}(k)$ is proportional to the outer iteration cycle (see Eq. 57), and the multi-objective function is then defined as the distance between the analyzed solution and the optimum solution (see Eq. 58)

$$Eng_{in}(k) = \bigcup_{k=1}^{n_k} (n_{SAS} \times k) \quad [57]$$

$$f(\omega) = \sqrt[2]{[(min.Res - Prj_{Res})^2 + (max.Prj_{Rn} - Prj_{Rn})^2 + (min.EUI - Prj_{EUI})^2} \quad [58]$$

Upon having identified the optimization boundaries, the inner and outer loop vectors, and the optimization function $f(\omega)$, SA selects an initial solution, generates a neighbouring set $N(\omega)$, and evaluates the current state with neighbouring solutions until finishing the chosen outer iterations and inner repetition, as illustrated in Figure 3-35. Finally, the optimization selects the solution with the lowest distance value, closest to optimality.

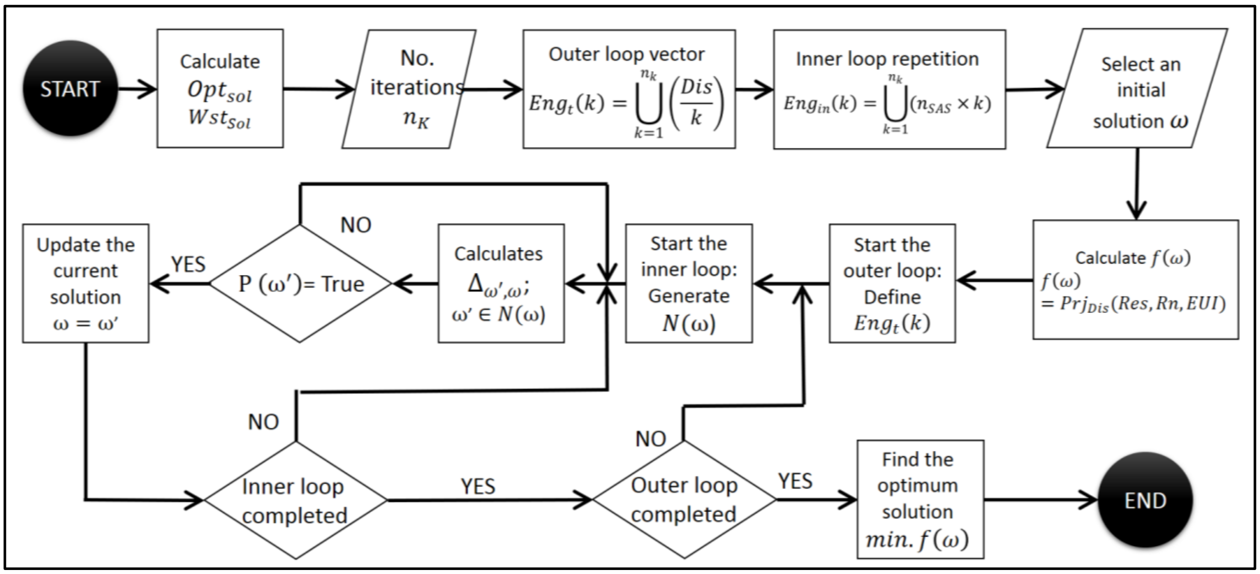


Figure 3-35 Energy-based simulated annealing process map

Chapter 4: Implementation and Application—Case Study

4.1.Project Description and Design

The proposed target cost modelling (TCMd) is validated using a 3-storey offsite construction apartment building project with 48 suites, located in Edmonton, Alberta, Canada. The multidisciplinary design aspects of the project, including architectural, structural, mechanical, and electrical layouts, define the project sub-assembly systems (SASs), which in turn allow for the actual ranking value of the project to be calculated based on the individual ranking value of its composing SASs. Project ranking value (Prj_{Rn} = 74.75), along with project actual cost (Prj_{Est} = \$164.78/ft^2), are utilized to validate the value ranking TCMd. The development of the case study SASs entails a detailed analysis of the project design; Table 4-1 lists the complete set of SASs, along with the influencing project design.

Table 4-1: Case study construction systems

ID	Project Systems	Influencing Design
1.0.	**Site work**	
1.1.	General Conditions	Architectural
1.2.	Site	Architectural
1.3.	Foundations	Structural
2.0.	**Building Structure**	
2.1.	Exterior Walls	Structural
2.2.	Interior Walls	Structural
2.3.	Windows	Architectural
2.4.	Doors	Architectural
2.5.	Roofing Systems	Structural
2.6.	Floor Systems	Structural
2.7.	Ceiling Systems	Structural
2.8.	Modular Onsite Connections	Structural
3.0.	**Plumbing Systems**	
3.1.	Plumbing Fixtures	Mechanical
3.2.	Plumbing Distribution	Mechanical
4.0.	**HVAC Systems**	
4.1.	Heating and Cooling System	Mechanical
4.2.	Ducting	Mechanical
4.3.	Fire Protection Systems	Mechanical

Continue Table 4-1

ID	Project Systems	Influencing Design
5.0.	**Electrical Work**	
5.1.	Electrical Service/Distribution	Electrical
5.2.	Lighting and Branch Wiring	Electrical
5.3.	Other Electrical Systems	Electrical
6.0.	**Finishes**	
6.1.	Exterior Finishes	Architectural
6.2.	Wall Finishes	Architectural
6.3.	Floor Finishes	Architectural
6.4.	Ceiling Finishes	Architectural
6.5.	Millwork	Architectural
6.6.	Cabinets & Countertops	Architectural
6.7.	Furniture & Appliances	Architectural

4.1.1. Architectural design

As is typical for offsite construction, the project proceeds through three distinct phases: pre-construction, offsite manufacturing, and onsite assembly. Project design, specification, and estimation are developed during the pre-construction phase. Figure 4-1 illustrates the project design and specifications.

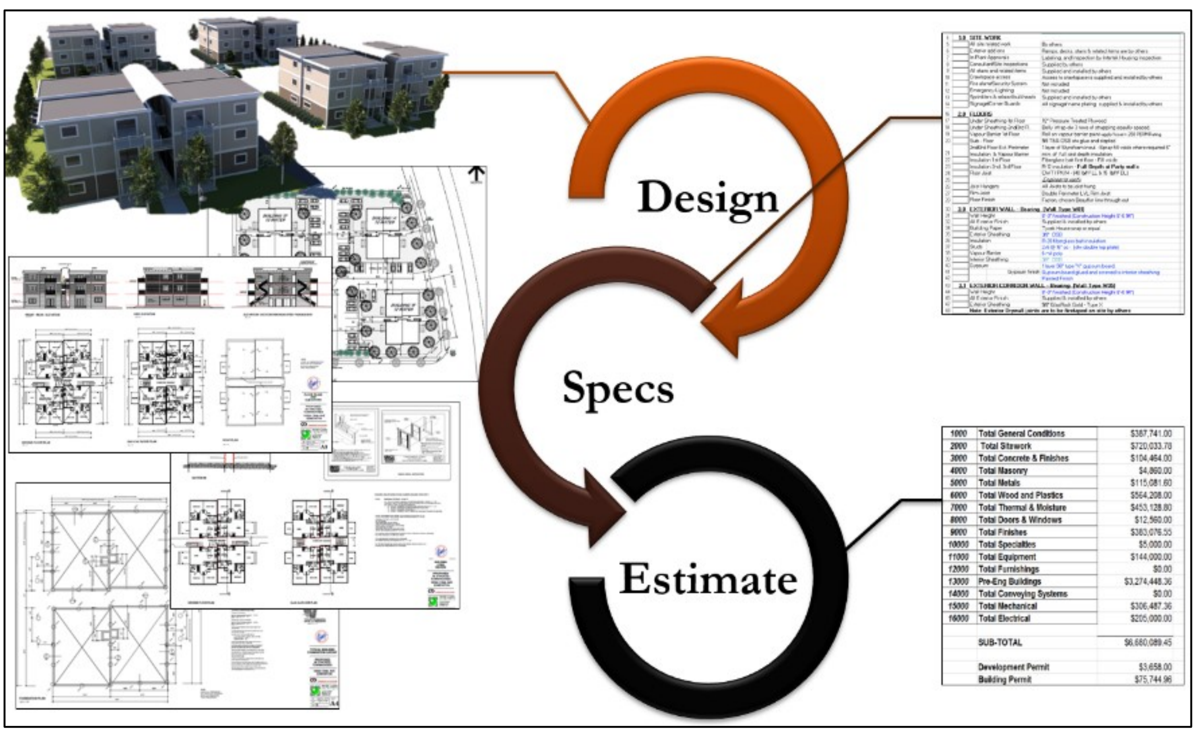


Figure 4-1: Modular pre-construction phase

The project's architectural design defines the values of the corresponding SASs from the developed offsite construction dataset as illustrated in Table 4-2.

Table 4-2: Case study architectural systems

ID	Project Systems	Description
1.0.	**Site work**	
1.1.	General Conditions	General Conditions 4
1.2.	Site	Site Work 2
2.0.	**Building Structure**	
2.3.	Windows	PVC Slider Type 1
2.4.	Doors	Door Group 3
6.0.	**Finishes**	
6.1.	Exterior Finishes	Vinyl Siding System 1
6.2.	Wall Finishes	Painted Walls
6.3.	Floor Finishes	Beauflor lino & Duradeck
6.4.	Ceiling Finishes	Textured Ceiling Throughout
6.5.	Millwork	Millwork System 1
6.6.	Cabinets & Countertops	Cabinet System 1
6.7.	Furniture & Appliances	Included

4.1.2. Mechanical and Electrical design

Understanding the mechanical and electrical details is essential for the selection of prospective SASs, as well as for setting the rules of compatibility analysis. The offsite construction mechanical and electrical design begin by laying the location of the connection points and surfaces between the modular units horizontally—on the same floor, and vertically—from one floor to another. On the same floor, the mechanical design must consider tie-in locations within each suite in order to ensure continuity in the flow of the mechanical rough-ins from one modular unit to another. Potable and sewer water piping lines run through the floor systems, and tie-in locations are specified at the joining line between two modular units. The tie-ins for HVAC ducts are located in both floor and ceiling systems. The tie-in locations are usually kept exposed in the modular units, and, after the onsite assembly is complete, the subfloor is fastened to cover them. Figure 4-2a depicts an exposed floor tie-in location prior to any connection work. Ducts and pipe links are illustrated in 4-2b, and 4-2c indicates the location after installing the subfloor.

(a) Exposed tie-in location (disconnected lines)	(b) Line connection	(c) Subfloor covering

Figure 4-2: Progression of mechanical horizontal tie-in

The vertical connection of mechanical work is carried out by means of vertical chasers to connect the different floors. Suite chasers are located within the suite as illustrated in Figure 4-3a and b, where the chaser is located next to the kitchen within a residential apartment. The building corridor is another possible location for the mechanical chasers.

(a) Suite chaser	(b) Suite chaser connected

Figure 4-3: Mechanical chasers

Electrical design for modular projects requires a distinct focus during the flow analysis. There are two electrical distribution systems: horizontal and vertical. A central electrical room is located on the main floor, and electrical feeders extend to the unit's panel box. This system is ideal for an apartment building with a short corridor, as it eliminates the need to run a sub feeder on each floor. Figure 4-4a shows the panel connection in an apartment building, and the main electrical room for the 12-plexes is illustrated in Figure 4-4b.

(a) Suite switch panel | (b) Main electrical room

Figure 4-4: Horizontal and vertical electrical distribution

The horizontal and vertical tie-ins, along with the offsite modular unit's mechanical and electrical design, determine the values assigned to the SASs as listed in Table 4-3.

Table 4-3: Case study mechanical and electrical systems

ID	Project Systems	Description
3.0.	**Plumbing Systems**	
3.1.	Plumbing Fixtures	Fixture Group 2
3.2.	Plumbing Distribution	Plumbing Distribution System 1
4.0.	**HVAC Systems**	
4.1.	Heating and Cooling System	Separate Furnace - Forced Air Type 3
4.2.	Ducting	Ducting System 5
4.3.	Fire Protection Systems	FPS 2
5.0.	**Electrical Work**	
5.1.	Electrical Service/Distribution	Electrical Services System 5
5.2.	Lighting and Branch Wiring	Electrical Wiring System 2
5.3.	Other Electrical Systems	Electrical Complimentary System 1

4.1.3. Structural Design

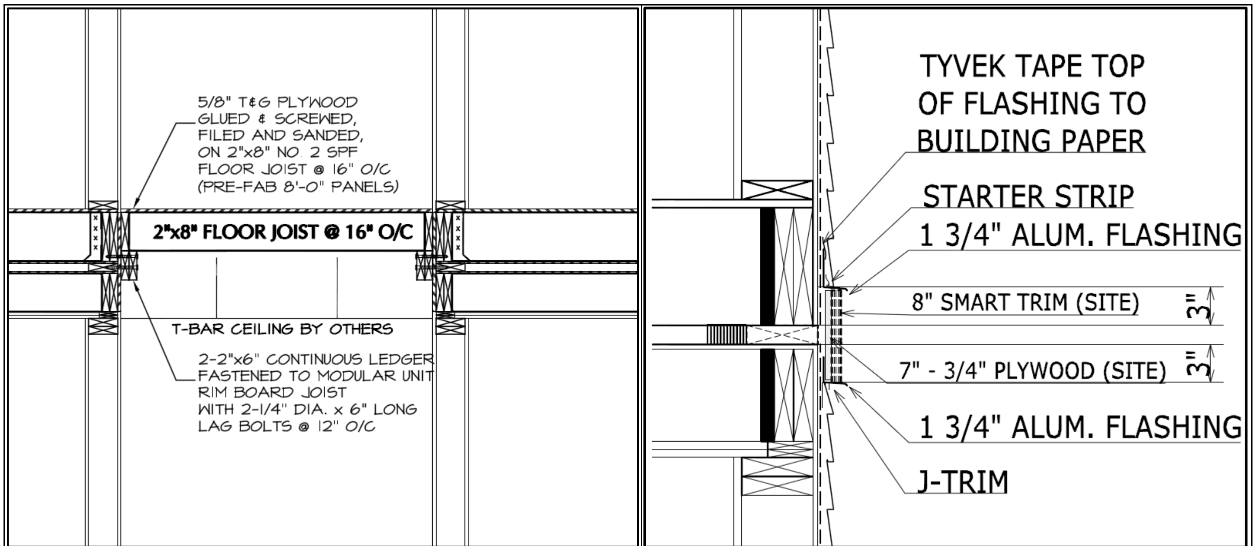
Structurally, modular units are built as load bearing components, and the utilized foundation system comprises grade beams combined with steel piles, as illustrated in Figure 4-5.

Figure 4-5: Modular project foundation - Grade beams with steel piles

Modular unit bracing is carried out through the internal and external joints. Figure 4-6 shows the structural detail for the internal and external joints of a modular project where the corridor acts as the core connection of the two rows of modular units on either side. On each floor, three types of interior joints are present: (1) *V Mod-To-Mod*: vertical joints between the modular units, (2) *H Mod-To-Mod*: horizontal joints between the modular units, and (3) *H Floor-To-Mod*: horizontal joints between the floor sections and the modular units. While the vertical joints require only a fire-rating that can be simply achieved by caulking the joint, drywall boarding, and taping, the horizontal joints are made of structural joints that must allow the load to be transferred through the building from the top to the ground.

A *T ledger* plays a dual role in supporting the two horizontal joint types. The Ts are nailed to the interior perimeter of the modular units prior to the lifting process (see Figure 4-7a, b). Once lifted, 2×12 joists are nailed on top of and between each set of two modular units to provide continuous supporting points for the modular units of the next floor, which will be stacked on top of the current units (see Figure 4-7c). The next floor hallway sections are then placed on the T ledgers (Figure 4-7d), then the T ledgers are bolted to the top of the modular units (Figure 4-7e).

Finally, the floor sections are bolted to the bottom of the modular units of the next floor (Figure 4-7f, g, and h), and the subfloor is then nailed back to the top of the floor joists (Figure 4-7i, j).



(a) Internal joint structural detail	(b) External joint structural detail

Figure 4-6: Structural details of modular joints

(a) Ledge nailed to the modular unit	(b) Ledge (not yet bolted)	(c) 2×12 joists	(d) Second-floor modular units	(e) Ledge bolted to modular unit ceiling

(f) Ledge bolted to the modular unit floor	(g) Ledge bolted to the modular unit floor	(h) Ledge bolted to the modular unit floor	(i) Floor section insulation	(j) Sub-floor nailed to the joist

Figure 4-7: Internal joints

The exterior joints are insulated using spray foam to fill in the vertical gaps between each of the modular units (see Figure 4-8a). These joints are then covered with strips of plywood that serve as a base for the final siding as well as a structural bracing system for the building. The plywood is nailed to the modular units based on the structural engineer’s directions (Figure 4-8b and Figure 4-8c).

(a) Foam insulation	(b) Bracing plywood	(c) Bracing plywood

Figure 4-8: Exterior joints

The modular connection details, along with the offsite construction foundation system, contribute to the development of foundations and modular onsite connections SASs. The remaining structurally related SASs are obtained from the shop drawings and details of the offsite manufacturing facility. Table 4-4 lists the SASs affected by the structural design.

Table 4-4: Case study structural systems

ID	Project Systems	Description
1.0.	**Site work**	
1.3.	Foundations	Foundation System 2
2.0.	**Building Structure**	
2.1.	Exterior Walls	Exterior Walls System - Load Bearing Type 4
2.2.	Interior Walls	Interior Walls System - Non-Load Bearing Type1
2.5.	Roofing Systems	Flat Roof with Parapet Type 3
2.6.	Floor Systems	Open Web Floor Truss (OWT) / PKI14
2.7.	Ceiling Systems	Solid Lumber Type 2
2.8.	Modular Onsite Connections	Modular Connection System without Crawler Space Type 1

4.1.4. Offsite Manufacturing

While a full description of the production line with the required full list of shop drawings and details for each station goes beyond the scope of the present research, understanding the unique nature of modular manufacturing is essential for the proposed TCMd process, given that these details, along with the modular-related design aspects, govern the proper identification and selection of construction and costing factors.

Modular units are built on a production line and are shipped to site to be installed. The production line consists of a number of stations:

1) Material storage: This is where construction materials are stored, after which materials are fed through a production line from one station to another until the final modular unit is completed.
2) Panel stations: The production line begins with the wall framing station, where wood studs pass through cutting machines and are arranged and nailed in order to establish wall frames. Sheathing is cut and nailed to the wall panels, and windows are installed before the wall framing is transported to the next station. Floor and ceiling framing stations follow the wall stations. Floor joists are attached to rim joists through joist hangers (also known as Simpson ties), and HVAC and plumbing locations are marked on the joists during this process. There are three types of floor joists: solid lumber, open web truss (OWT), and pre-engineered. OWT is the preferred joist in cases when plumbing pipes and HVAC ducts must run through the joist, perpendicular to the joist span.
3) Boxing station: The modular unit's framed walls, floors, and ceilings are then transferred after having been framed in their respective stations, at which floor panels are attached to wall panels and are enclosed by ceiling panels. The end result of the boxing station is a modular box containing all of its structural components.
4) Rough-in Station: HVAC ducts, sewer line, potable line, electrical Loomex boxes and connectors, and electrical wiring are installed in the walls, floors, and ceiling. Once all the rough-in components have been installed, the modular box is transferred to the finishing station.
5) Finishing station: Internal and external finishes are performed concurrently. Internally, the work begins with insulating floor and ceiling panels, where applicable, nailing subfloor sheets, and installing ceiling drywall. Wall insulation, vapour barrier, and drywall are also installed. Paint and wall and ceiling coverings are applied, millwork and cabinets are mounted, electrical and plumbing fixtures are installed, and floor finishes and door frames are completed. Externally, exterior finishing is installed on the

exterior walls, and modular units are wrapped with temporary weather proofing (Tyvek) on all the exterior walls of the modular units. This temporary weather proofing protects modular unit walls during the storage and transportation process, and it must be removed during the onsite assembly before craning the modular boxes into their designated locations.

Figure 4-9 illustrates the discussed workstations on a modular factory production line.

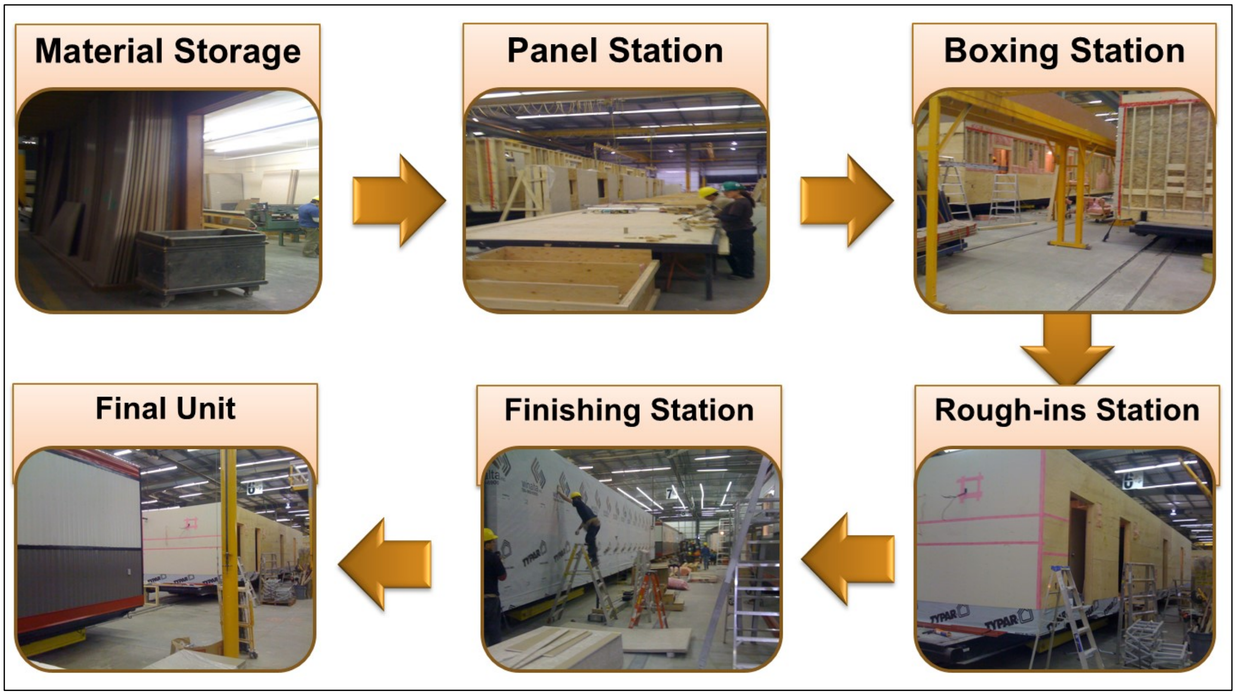


Figure 4-9: Offsite manufacturing stations

4.1.5. Onsite Assembly

Onsite assembly affects the project cost, making it an essential part of the TCMd process. The onsite assembly phase begins with site preparation, which is initiated simultaneously with the offsite manufacturing of the modular units. The selected foundation system is put in place, whether steel cap plate piles, grade beams with steel piles, or footing and foundation walls. Water, sewer, gas, and electrical site services are prepared and extended to the connection points of the modular units, and a staging yard is usually prepared with cribbing blocks to store the modular units until such time that they are lifted and placed by a crane on site. Once the modular units are craned into place, structural connections link the modular units through a set of interior and exterior joints in order to give the building a structural frame sufficient to withstand the vertical and horizontal load.

Additionally, mechanical and electrical tie-ins connect the units with the site services and with one another, as per the selected design. Interior and exterior finishing tasks vary based on the degree to which the modular box has been finished in the manufacturing process. In a blue-skin modular finish, the interior finish does not include paint, and no exterior finish is included. However, fully finished units include any type of exterior finish, siding, stucco, Hardie-Board, even stone and block, and internally, the unit comes fully painted with flooring installed. In the latter case, onsite finishing tasks are limited to covering the modular joints and some minor cosmetic repairs. Where fully finished units are involved, special consideration must be given to the unit rigidity, as any deformation during the transportation or craning tasks could damage the finishing, resulting in costly and time-consuming repairs. Figure 4-10 illustrates the onsite assembly tasks for a modular construction project.

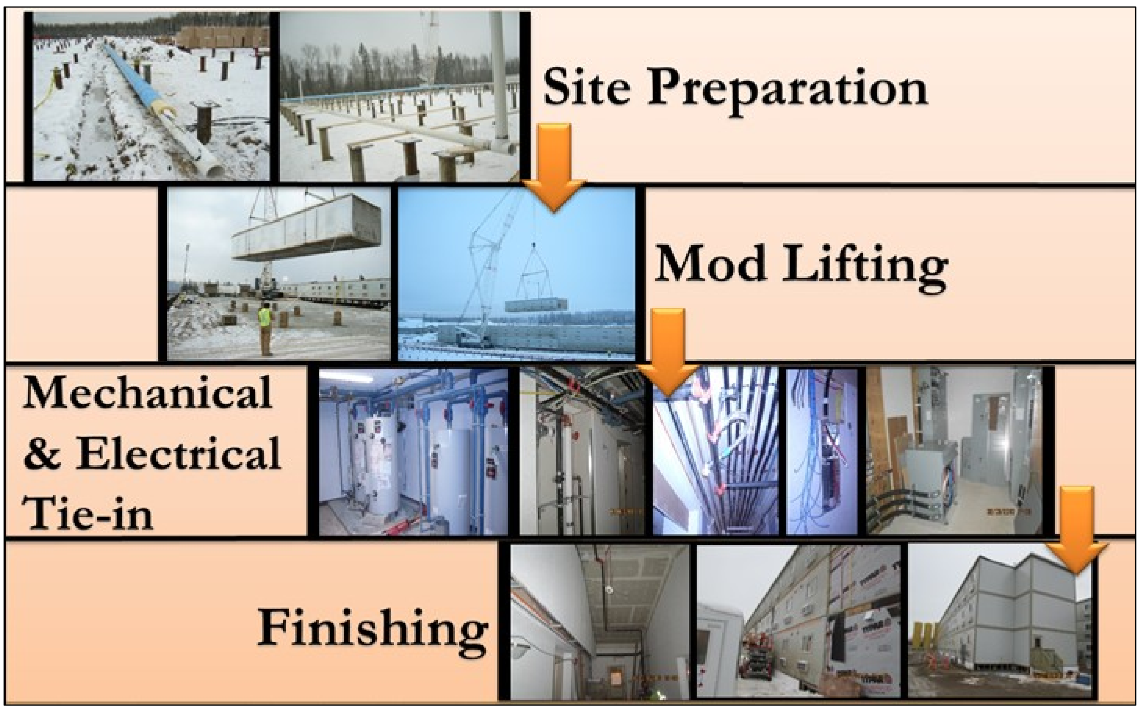


Figure 4-10: Onsite assembly tasks

4.2.Case Study Implementation

4.2.1. Value Ranking TCMd

The case study architectural, mechanical, electrical, and structural design are incorporated into a 3D model using Autodesk Revit, and the main project design input data are filled from predefined schedules lists associated with the 3D model, as listed in Table 4-5.

Table 4-5: Case study design input data

Design Item	Value	Unit	Design Item	Value	Unit
Total Floor Area	40,896	ft^2	**Roof Perimeter**	238.00	ft
No. Stories	3	Storey	**Roof Area**	3,408.00	ft^2
Tot. Footprint	13,632.00	ft^2	**Roof Type**	Flat Roof W/ Parapet 1	-
Tot. Perimeter	952.00	ft	**Roof Slope**	-	1/12
Tot. Building Size	1,717,632.00	ft^3	**Floor System**	OWT / PKI14	-
No. Mod units	96.00	ea.	**Floor Support**	PLY	-
No. Suites	48.00	ea.	**Ceiling System**	Solid Lumber 1	-
Avg. Suite Size	768.00	ft^2	**No. Kitchens**	48.00	ea.
Floor Height	10.21	ft	**No. Bathrooms**	48.00	ea.
Avg. Mod Perimeter	88.00	ft	**No. Sinks**	96.00	ea.
Avg. Mod Area	384.00	ft^2	**No. Tubs**	48.00	ea.
Avg. Room Size	92.00	ft^2	**No. Lavatory**	48.00	ea.
Lot Size	68,160.00	ft^2	**No. Fixtures**	192.00	ea.
Tot. Ex - Wall length	8,448.00	ft	**No. Washer/Drier**	96.00	ea.
Tot. Ex - Wall Area	82,967.62	ft^2	**No. Water Heaters**	48.00	ea.
Tot. In - Wall length	6,336.00	ft	**No. Hose Bibb**	8.00	ea.
Tot. In - Wall Area	55,969.71	ft^2	**Corridor Area**	4,128.19	ft^2
Window Size Facing South	274.67	ft^2	**Common Area**	3,120.00	ft^2
Window Size Facing North	274.67	ft^2	**No. Receptacles**	576.00	ea.
Window Size Facing East	426.67	ft^2	**No. Switches**	336.00	ea.
Window Size Facing West	426.67	ft^2	**No. Light Fixtures**	432.00	ea.
Tot. Window Size	1,402.67	ft^2	**No. Thermostats**	48.00	ea.
Window Glazing	Double	-	**No. PTAC units**	-	ea.
Window Framing	PVC Slider 1	-	**Avg. Window Perimeter**	15.72	ea.
Exterior Door Size Facing South	-	ft^2	**Tot. Wall Length - Suite**	11,660.62	ea.
Exterior Door Size Facing North	-	ft^2	**Tot. Wall Length - Washrooms**	3,123.38	ea.
Exterior Door Size Facing East	960.00	ft^2	**Tot. Floor Area - Suites**	32,256.00	ft^2
Exterior Door Size Facing West	960.00	ft^2	**Tot. Floor Area - Washroom/Kitchen**	8,640.00	ft^2
Door Count	432.00	ea.			
Door Material	Wood	-			

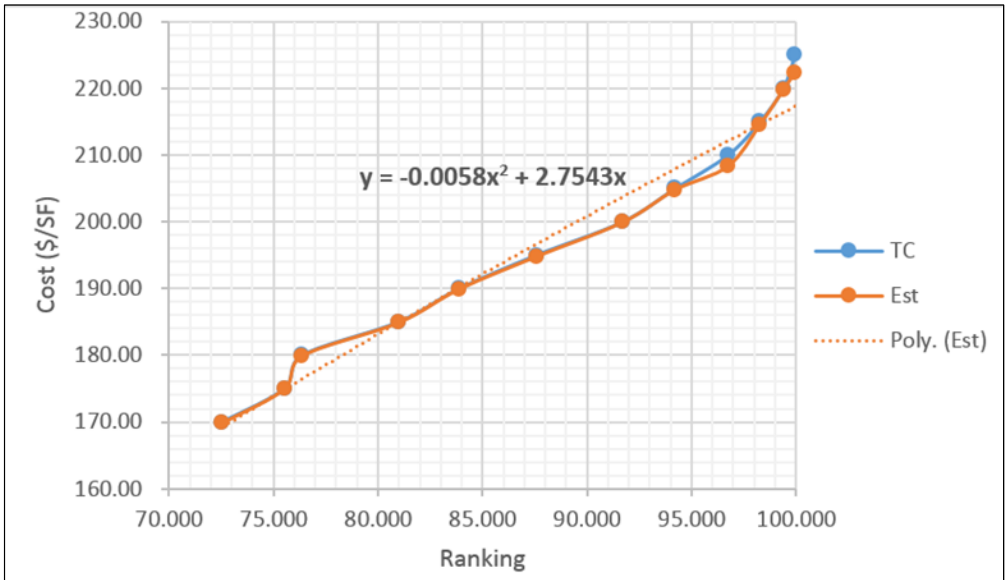
The deterministic value ranking, TCMd, calculates the costs of SAS alternatives using the linear regression analysis equations. These equations utilize the costing factors as the key inputs. With the value ranking for each of the compatible SAS alternatives calculated through the value ranking

(Rn), TCMd is equipped to provide the cost breakdown and specification list for a given target cost. Figure 4-11 displays the estimate breakdown, along with a full detailed specification list generated by TCMd for a target cost equal to $210/ft^2.

The project minimum cost and maximum cost are calculated by assigning very small and very large TC$ values to the project and running TCMd (max EST = $222.39/ ft2, max R = 99.94, min EST = $169.9/ ft^2, min R = 72.55). To calculate the accuracy of the model, the plot between cost and ranking is developed by running the model 12 times with a $5/ft^2 incremental increase. Using the developed curve, the estimated cost that yields a ranking value equal to the actual project is $173.47/ ft^2, with a delta of $8.69/ ft2 and an accuracy level of 94.99%, as illustrated in Figure 4-12.

1	ID	Project Components	Ranking	Description	TC $	TC $/SF	TC %	Est $	Est $/SF	Est %	Residual $/SF
2		Site work									
3	1.1.4.0	General Conditions	2.508	GC 4	$ 671,794.88	$ 16.51	8.23%	$ 641,487.69	$ 16.51	8.30%	$ 1.67
51	1.2.3.0	Site	4.625	SW 3	$ 480,762.50	$ 14.96	5.89%	$ 581,287.75	$ 14.96	5.94%	$ -
75	1.3.4.0	Foundations	2.650	Fnd 4	$ 499,358.13	$ 10.81	6.12%	$ 419,806.63	$ 10.81	6.17%	$ -
94		Building Structure									
95	2.1.2.0	Exterior Walls	3.381	Ex W 1.2	$ 646,182.69	$ 19.42	7.92%	$ 754,575.75	$ 19.42	7.98%	$ -
108	2.2.4.0	Interior Walls	2.793	In W 1.4	$ 766,074.31	$ 15.95	9.39%	$ 619,727.13	$ 15.95	9.47%	$ -
118	2.3.9.0	Windows	4.450	W 2.3	$ 394,503.31	$ 12.59	4.84%	$ 489,253.16	$ 12.59	4.87%	$ -
122	2.4.2.0	Doors	4.110	Dr 2	$ 45,826.24	$ 1.61	0.56%	$ 62,449.41	$ 1.61	0.57%	$ -
127	2.5.1.0	Roofing Systems	2.090	Rf 1.1	$ 286,349.19	$ 5.96	3.51%	$ 231,646.39	$ 5.96	3.54%	$ -
154	2.6.3.0	Floor Systems	3.800	Flr 3	$ 438,154.00	$ 9.12	5.37%	$ 354,451.13	$ 9.12	5.41%	$ -
172	2.7.2.0	Ceiling Systems	3.163	Clng 2	$ 384,586.03	$ 10.47	4.71%	$ 406,709.91	$ 10.47	4.75%	$ -
185	2.8.4.0	Modular Onsite Connections	4.167	M Cn 2.3	$ 128,733.23	$ 3.58	1.58%	$ 139,223.27	$ 3.58	1.59%	$ -
204		Plumbing Systems									
205	3.1.5.0	Plumbing Fixtures	3.850	Plmbng Fix 5	$ 57,299.61	$ 1.81	0.70%	$ 70,215.77	$ 1.81	0.71%	$ -
222	.2.8.0	Plumbing Distribution	4.250	Plmbng Dis 8	$ 646,610.06	$ 13.46	7.93%	$ 523,084.78	$ 13.46	7.99%	$ -
230		HVAC Systems									
231	4.1.2.0	Heating and Cooling System	3.700	HVAC Sys 1.2	$ 129,516.05	$ 4.44	1.59%	$ 172,417.73	$ 4.44	1.60%	$ -
236	4.2.3.0	Ducting	4.250	HVAC Dct 3	$ 139,063.58	$ 4.72	1.70%	$ 183,494.22	$ 4.72	1.72%	$ -
243	4.3.2.0	Fire Protection Systems	4.158	HVAC FPS 2	$ 60,680.63	$ 1.37	0.74%	$ 53,035.77	$ 1.37	0.75%	$ -
247		Electrical Work									
248	5.1.3.0	Electrical Service/Distribution	4.500	Elec Srvc 3	$ 218,320.59	$ 4.55	2.68%	$ 176,613.66	$ 4.55	2.70%	$ -
254	5.2.3.0	Lighting and Branch Wiring	4.750	Elec Wrng 3	$ 319,443.75	$ 8.04	3.92%	$ 312,534.59	$ 8.04	3.95%	$ -
263	5.3.3.0	Other Electrical Systems	3.500	Elec Othr 3	$ 76,236.20	$ 2.18	0.93%	$ 84,750.01	$ 2.18	0.94%	$ -
274		Finishes									
275	6.1.4.0	Exterior Finishes	4.250	Ex Fnsh 3.1	$ 213,907.03	$ 6.64	2.62%	$ 258,045.78	$ 6.64	2.64%	$ -
293	6.2.1.0	Wall Finishes	3.675	W Fnsh 1.1	$ 284,519.41	$ 9.38	3.49%	$ 364,299.91	$ 9.38	3.52%	$ -
297	6.3.8.0	Floor Finishes	3.917	Flr Fnsh 8	$ 123,849.00	$ 3.52	1.52%	$ 136,581.39	$ 3.52	1.53%	$ -
298	6.4.2.0	Ceiling Finishes	2.850	Clng Fnsh 2	$ 121,514.94	$ 3.03	1.49%	$ 117,555.96	$ 3.03	1.50%	$ -
302	6.5.6.0	MilWork	3.725	Mlwrk 6	$ 295,771.81	$ 9.01	3.63%	$ 350,196.94	$ 9.01	3.65%	$ -
322	6.6.5.0	Cabinets & Countertops	4.625	Cbnt 5	$ 729,694.75	$ 15.19	8.94%	$ 590,297.38	$ 15.19	9.02%	$ -
332	6.7.1.0	Furniture & Appliances	3.000	Furniture & Appliances	$ -	$ -	0.00%	$ -	$ -	0.00%	$ -
334											
335		**Total**	**96.736**	-------------	**$ 8,158,751.00**	**$ 210.00**	**100.00%**	**$ 8,093,743.50**	**$ 208.33**	**100.00%**	**$ 1.67**

Figure 4-11 TCMd estimate and specification list



Actual Cost	$ 164.78	Calculated	$ 173.47
Actual Ranking	74.75	Delta (Est-Act)	$ 8.69
		Accuracy %	94.99%

Figure 4-12: Ranking value sensitivity analysis

The optimization modelling of value ranking TCMd is constrained by the set of discrete values of SASs, as illustrated in Appendix F. Running the optimization model on the same intervals generates a detailed comparison between the deterministic and stochastic approaches, as illustrated in Figure 4-13 and Table 4-6.

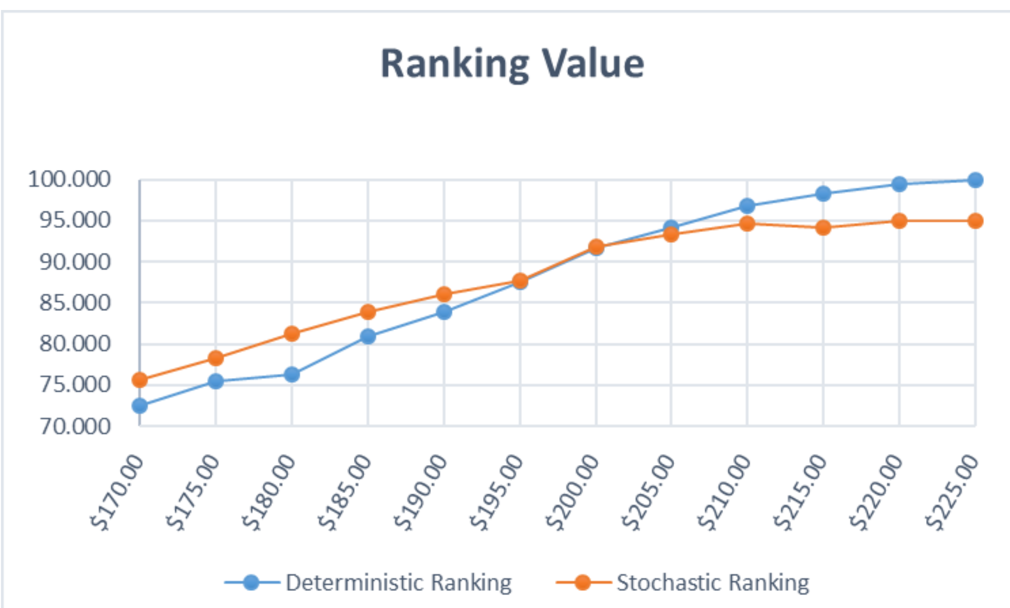


Figure 4-13: Value ranking comparison results

Table 4-6: Project cost and ranking value comparison results

ID	Target Cost	Deterministic Ranking	Stochastic Ranking	Deterministic Estimate	Stochastic Estimate
1	$170.00	72.552	75.568	$169.90	$169.83
2	$175.00	75.519	78.215	$174.99	$174.98
3	$180.00	76.377	81.273	$179.95	$179.84
4	$185.00	80.986	83.839	$184.93	$184.82
5	$190.00	83.878	86.106	$189.93	$188.67
6	$195.00	87.570	87.756	$194.81	$194.71
7	$200.00	91.695	91.829	$199.94	$199.59
8	$205.00	94.211	93.284	$204.80	$204.81
9	$210.00	96.736	94.614	$208.33	$206.67
10	$215.00	98.261	94.100	$214.54	$211.79
11	$220.00	99.386	94.917	$219.79	$215.39
12	$225.00	99.945	94.917	$222.39	$215.39

TCMd rule-based analysis (RBA) represents a deterministic methodology that explores the whole pool of alternatives according to a predefined set of rules and a SAS user-defined priority list. TCMd simulated annealing (SA) optimization signifies a stochastic searching method that follows a randomized heuristic algorithm in seeking an optimal solution. The comparison results between RBA and SA show that a randomized heuristic algorithm yields higher ranking values than the deterministic algorithm when the target value is closer to the lower boundary min.Est. The logical explanation of this observation is that the priority list that controls RBA prevents the algorithm from achieving a higher ranking value for the overall project at the expense of maximizing the ranking value for SAS with higher priority indices. On the contrary, for larger target cost values, RBA yields a higher overall project ranking than does SA, which can be explained as the result of having sufficient cost to improve the value ranking of all SASs with all their priority indices, while the random nature of SA reaches a near-optimal solution and not the global optimum solution. Increasing the number of iterations should eventually drive the SA algorithm to reach the optimal global solution.

4.2.2. Energy-Based TCMd

The application of energy-based TCMd in the case study is based on the results of energy functions as illustrated in Appendix E, along with the available distinct SAS alternative values as listed in Appendix F. Having run the case study on RBA and SA tools, utilizing a target value (TC$ = \$225/ft^2), the optimal solutions for both methods are listed in Table 4-7.

Table 4-7: RBA and SA TCMd optimal solutions

Energy-Based TCMd	EUI	Ranking	Residual	Distance
RBA	1.33874774	99.87793732	2.876899958	7.593631744
SA	1.398890853	94.31700134	6.750013828	17.55350876

It is clear that the deterministic method yields the global optimal solution due to the extensive search of all available energy models under a predetermined set of rules. Figure 4-14 displays the Euclidean distance (the multi-objective function measurement variable) for the 288 possible energy models. Observation of the RBA results identifies no particular trend, suggesting the need for either an extensive search method, similar to RBA, or a randomized optimization technique that explores the available solutions seeking to optimize the outcome.

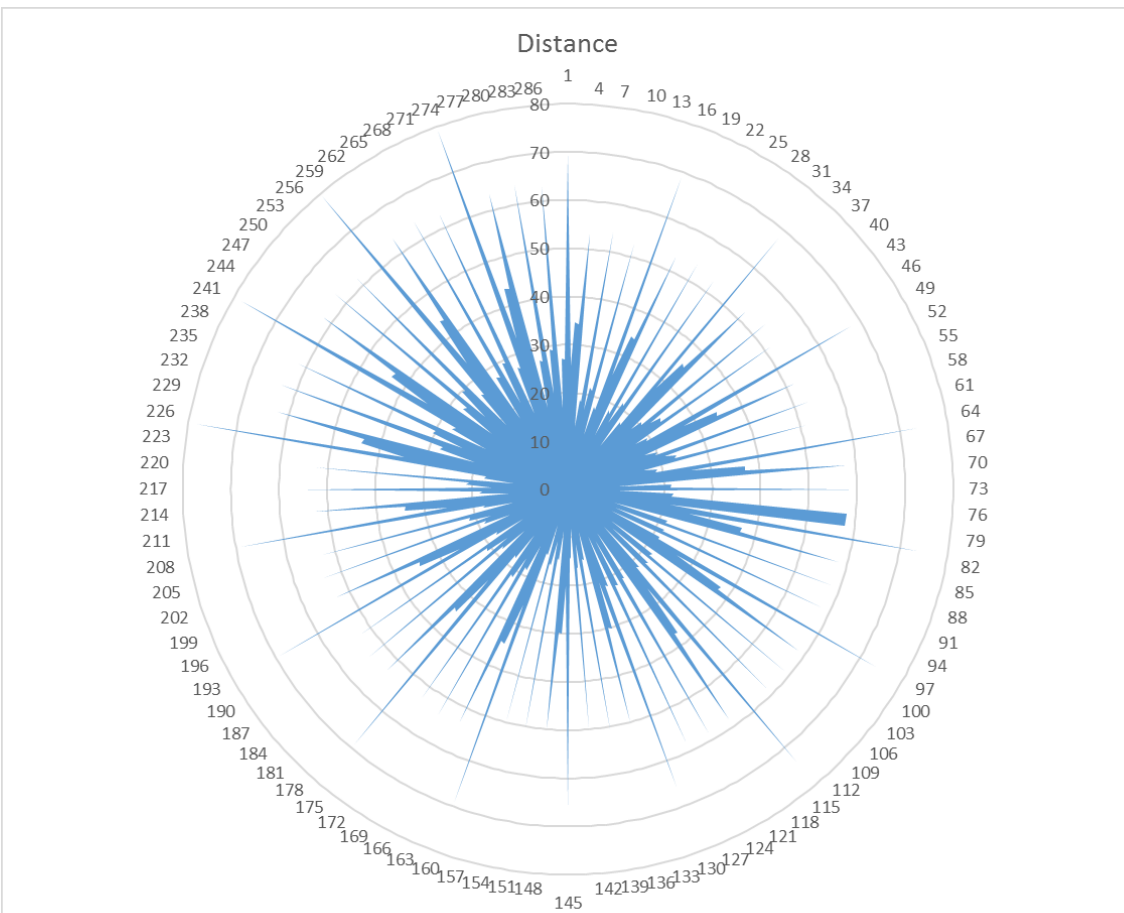


Figure 4-14: RBA Euclidean distances

SA optimization seeks an optimal solution through stochastic and probabilistic local search. Figure 4-15 provides a snapshot of the search algorithm, which shows the method followed by the algorithm to escape local optimal. This method is carried out by accepting a less optimum solution, "hill-climbing", in order to reach the global optimum solution.

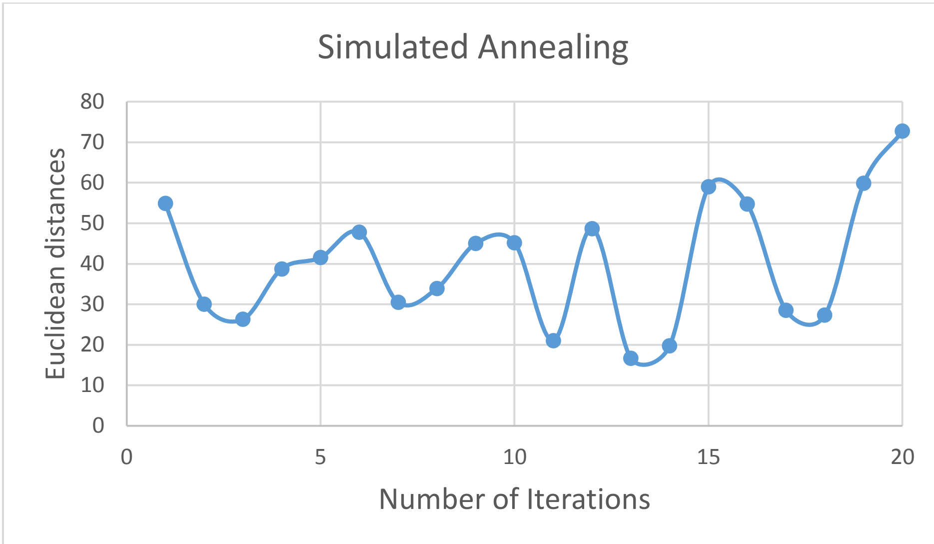


Figure 4-15: Simulated annealing search process

While SA fails to reach the global optimal solution, as displayed by the RBA, the generated solution is considered acceptable due to the small delta between the two methods. Table 4-8 compares the SASs selected by both methods. A SAS-pair comparison shows that 16 of the 26 SASs have an exact match, and the remaining 10 SASs are close to optimality. In can be expected that increasing the number of iterations in SA would ultimately allow the algorithm to reach the global optimal solution.

Table 4-8: RBA and SA TCMd comparison results

ID	Project Systems	RBA		SA	
1.0.	**Site work**				
1.1.	General Conditions	GC 3	4.192	GC 3	4.192
1.2.	Site	SW 3	4.625	SW 3	4.625
1.3.	Foundations	Fnd 6	4.175	Fnd 6	4.175
2.0.	**Building Structure**				
2.1.	Exterior Walls	Ex W 1.2	3.381	Ex W 1.2	3.381
2.2.	Interior Walls	In W 1.4	2.793	In W 1.4	2.793
2.3.	Windows	W 2.3	4.450	W 2.3	4.45
2.4.	Doors	Dr 2	4.110	Dr 9	3.74

2.5.	Roofing Systems	Rf 1.1	2.090	Rf 1.2	1.99
2.6.	Floor Systems	Flr 3	3.800	Flr 3	3.8
2.7.	Ceiling Systems	Clng 2	3.163	Clng 2	3.163
2.8.	Modular Onsite Connections	M Cn 2.3	4.167	M Cn 2.3	4.167
3.0.	**Plumbing Systems**				
3.1.	Plumbing Fixtures	Plmbng Fix 5	3.850	Plmbng Fix 5	3.85
3.2.	Plumbing Distribution	Plmbng Dis 8	4.250	Plmbng Dis 3	4.125
4.0.	HVAC Systems				
4.1.	Heating and Cooling System	HVAC Sys 2.3	3.633	HVAC Sys 1.1	3.45
4.2.	Ducting	HVAC Dct 3	4.250	HVAC Dct 2	3.6
4.3.	Fire Protection Systems	HVAC FPS 2	4.158	HVAC FPS 2	4.158
5.0.	**Electrical Work**				
5.1.	Electrical Service/Distribution	Elec Srvc 3	4.500	Elec Srvc 3	4.5
5.2.	Lighting and Branch Wiring	Elec Wrng 3	4.750	Elec Wrng 4	4.5
5.3.	Other Electrical Systems	Elec Othr 3	3.500	Elec Othr 3	3.5
6.0.	**Finishes**				
6.1.	Exterior Finishes	Ex Fnsh 3.1	4.250	Ex Fnsh 3.1	4.25
6.2.	Wall Finishes	W Fnsh 1.1	3.675	W Fnsh 2.1	3.3
6.3.	Floor Finishes	Flr Fnsh 8	3.917	Flr Fnsh 7	3.633
6.4.	Ceiling Finishes	Clng Fnsh 2	2.850	Clng Fnsh 3	2.6
6.5.	MilWork	Mlwrk 6	3.725	Mlwrk 4	3.15
6.6.	Cabinets & Countertops	Cbnt 5	4.625	Cbnt 2	2.225
6.7.	Furniture & Appliances	Furniture & Appliances	3.000	Furn 1	3

Chapter 5: Conclusion

5.1. General Conclusions

Insufficient design details, increasing client expectations, and competitive market conditions are challenges that decision makers face during the early design stages of a project. The cost effectiveness and overall performance of construction projects are negatively affected by these challenges. To solve these construction challenges, target costing (TC) technique provides the ideal framework to guide the distribution of project cost among the multidisciplinary systems (architectural, structural, mechanical and electrical) in order to improve the design effectiveness under a target cost. However, the current applications of TC depend heavily on the intuition and expertise of decision makers. They follow a heuristic improvement process that lacks a structured system to efficiently guide the distribution of project costs among the project's various assembly and sub-assembly systems. Understanding the relationships among the various components of construction projects is essential for the development of a well-structured TC framework that transforms the construction project from a single entity with complex interactions into smaller manageable sub-systems with distinct input parameters and measurable output metrics. Improved design and modelling practices, simplified estimating process, and enhanced energy analysis are the direct results of the efficient implementation of TC in the construction industry.

The data collected from the pool of available projects assists in the establishment of construction alternative systems with distinct sets of design inputs and measurable cost and performance outputs, which in turn promotes the standardization and automation of the design-estimate process. Standardization of the characteristics of project sub-systems establishes the key factors necessary for the proper implementation of TC during the early design stages by supporting the following four tasks: (1) selecting a compatible alternative group of sub-systems from a pool of available projects, (2) evaluating the overall project value based on the quality of the individual sub-systems, (3) generating detailed estimates based on distinct design input data, and (4) exploring all possible configurations among the sub-systems in order to assess the outcomes in term of the project's overall energy efficiency.

The proposed target cost modelling (TCMd) process introduces opportunities to improve the project value and overall energy efficiency. TCMd provides a full estimate with a detailed specification list and an annual energy use intensity index (EUI) according to a target cost, project design, and client requirements. Enhancements in the energy consumption and project quality are expected as a result of the application of the developed TCMd tools. Moreover, the automation of the design-estimate process provides advantages in term of reducing tedious manual activities, eliminating assumptions and human error, and facilitating the implementation of scope changes.

5.2. Research Contributions

- The development of a three-level hierarchically structured dataset for offsite construction projects: assembly systems, sub-assembly systems (SASs), and construction components. Assembly systems represent the organizational level, which is utilized to define the overall project cost and performance; SAS is the main analysis level that governs the analysis of alternative values; and construction component is the basic level of TCMd. The developed offsite construction dataset results in a pool of SAS alternatives, which provides opportunities for understanding offsite construction project breakdown structure, exploring the available project configurations, and analyzing the interaction among current systems. Furthermore, the dynamic data collection platforms act as a dynamic repository for updating and storing offsite construction project data.
- The introduction of the construction factors (CnFs) concept allows for the standardization of design criteria into measurable sets of parameters that govern project compatibility analysis and value studies. The compatibility matrix is a rule-based expert system that systematically analyzes the relationships among SAS alternatives in order to constrain the selection of SAS alternatives according to specific design criteria and to eliminate the need for the traditional subjective evaluation process. Project ranking value is a quality measurement of the project value based on the ranking value of the selected SAS alternatives that reflects the performance of SAS based on distinct performance metrics.
- The introduction of the costing factors (CFs) concept establishes the link between the offsite project design process and target costing analysis. CFs are influential factors that translate the design criteria into measurable cost-oriented factors that allow for the standardization of SAS alternative value analysis by providing quantifiable representation of the project design, which in turn promotes the utilization of mathematical tools such as regression analysis to develop costing equations that automatically calculated the cost of each available SAS alternative according to distinct design inputs. The costing equations achieve a balance between the traditional (floor-area-based) conceptual inaccurate estimate

and fully detailed (material-takeoff-based) time-consuming one by establishing an estimation method with an average accuracy level of 86.53%, which is considered acceptable for the early design stages.

- The developed methodology uses rule-based analysis (RBA) for the purpose of automatically selecting the SAS alternatives that yield the highest ranking values for the overall project. RBA is a set of priority-driven rules that mimic human intelligence in order to extract the necessary expert knowledge to distribute project cost over the appropriate SASs. The developed RBA is heavily dependent on the priority value assigned to each sub-assembly in accordance with a user-defined priority list The development of RBA within the Excel Macro environment enables the automation of the target costing process and eliminates time-consuming costing tasks. The purpose of the developed computer tool, value ranking TCMd, is to automatically generate a project estimate along with a detailed list of project specifications.
- The introduction of energy factors and energy mathematical models promotes the exploration of all possible configurations of energy models according to a specific project design. Through the utilization of mathematical tools, such as artificial neural network (ANN), the developed energy equations automatically generate a list of all possible simulated results of the energy consumption of a project.
- The development of a rule-based analysis (RBA) for the purpose of selecting the alternatives that yield the highest overall project ranking value, the highest energy efficiency, and lowest residual value between the project estimate and the target cost. The energy-based TCMd is developed under the Excel Macro environment, and can automatically generate the optimum solution along with a detailed list of specifications.
- The evaluation between the supervised priority-driven RBA, and unsupervised stochastic optimization algorithms, such as simulated annealing, for both the value-ranking TCMd, and energy-based TCMd.
- The developed TCMd tools have been tested using the case study (48-suite residential multi-family offsite construction project, located in Edmonton, Alberta, Canada).

5.3. Research Limitations

- This research focuses on the application of target costing (TC) technique in offsite construction projects based on the collected pool of available projects grouped under four representative project types: residential single-family, residential multi-family, hotel, and workforce camp. The sub-assembly system (SAS) alternatives used to generate the construction, costing, and energy factors encompass the majority of offsite construction projects; nevertheless, an unaccounted alternative system could exist, which entails updating the developed dataset using the interactive data collection platforms, upgrading the introduced factors, and the corresponding costing and energy equations.
- The development of ranking values of the SAS alternatives has been performed during a series of focus group meetings with a group of industry experts for the purpose of evaluating the key performance metrics for each individual SAS; however, the values assigned are subjective and may vary based on the experience level of the focus group.
- The accuracy of the developed costing equation is dependent on the number of available offsite construction projects; although the 25-project dataset has resulted in an acceptable accuracy level for the costing equations, obtaining more data can further improve those equations.
- The energy equations have been developed through the utilization of energy simulation tools. The simulated energy outputs are acceptable for the purpose of evaluating the project's overall energy performance in accordance with the available alternative energy models; nevertheless, actual energy data would have returned a more accurate result.

5.4. Recommendations for Future Research

This research is the first step in a broader initiative towards the development of a comprehensive decision support system (DSS) that encompasses the various aspects and stages of offsite construction. Improvements to the current target cost modelling (TCMd) system can be achieved by considering the following steps:

1- To expand the developed dataset by continually collecting and updating the SAS alternative systems, along with the established factors and equations.

2- To further study the relationship among SAS alternatives to enrich the compatibility matrix by including factors related to onsite/offsite safety factors in the compatibility studies.

3- To further analyze the available SAS alternatives in order to reduce the impact of the associated subjectivity on the respective ranking values.
4- To include productivity analysis studies that cover the offsite manufacturing and onsite assembly stages for the purpose of generating a skill-based target schedule, which meets strict timelines and enhances the project overall production rate.
5- To incorporate risk analysis aspects into the overall project performance metrics during the process of analyzing SAS alternatives.
6- To perform time-cost trade off through the collaboration between skill-based target scheduling and target cost modelling in order to achieve a desired balance between the two targets.
7- To update the energy dataset through the utilization of actual energy data collected from a number of sample projects.
8- To include environmental-based target cost modelling aspects that focus on the greenhouse gas emissions and carbon footprint throughout the lifecycle of the project and sub-systems.

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Appendix A: First Iteration SAS Costing Equations

ID	Costing Equation
01-01	$\mathrm{GC_i} = \beta_0 + \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Lot_{Size} + \beta_{i6} \times Ft_{Print}$
01-02	$\mathrm{St_i} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Ft_{Print}$
01-03	$Fnd_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot_{Perimeter} + \beta_{i6} \times Ft_{Print}$
02-01	$ExW_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times ExW_{length} + \beta_{i6} \times ExW_{Area}$
02-02	$InW_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times InW_{length} + \beta_{i6} \times InW_{Area}$
02-03	$Wnd_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.Glazing_{Area} + \beta_{i6} \times SGlazing_{Area} + \beta_{i7} \times NGlazing_{Area} + \beta_{i8} \times EGlazing_{Area} + \beta_{i9} \times WGlazing_{Area} + \beta_{i10} \times Glazing_{Type} + \beta_{i11} \times Wnd_{Framing}$
02-04	$Dr_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.ExDr + \beta_{i6} \times S.ExDr + \beta_{i7} \times N.ExDr + \beta_{i8} \times E.ExDr + \beta_{i9} \times W.ExDr + \beta_{i10} \times Dr_{Count} + \beta_{i11} \times Dr_{Material}$
02-05	$Rf_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Rf_{Perimeter} + \beta_{i6} \times Rf_{Area} + \beta_{i7} \times Rf_{Type} + \beta_{i8} \times Rf_{Slope}$
02-06	$Flr_{\mathrm{i}} = \beta_{i0} + \beta_1 \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Mods + \beta_{i6} \times Avg.Mod_{Perimeter} + \beta_{i7} \times Avg.Mod_{Area}$
02-07	$Clng_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Mods + \beta_{i6} \times Avg.Mod_{Perimeter} + \beta_{i7} \times Avg.Mod_{Area}$
02-08	$Mod.Cn_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Mods + \beta_{i6} \times Avg.Mod_{Perimeter} + \beta_{i7} \times Avg.Mod_{Area}$

03-01	$Plm.Fix_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.ktchn + \beta_{i6} \times No.Bth + \beta_{i7} \times No.Snk + \beta_{i8} \times No.Tubs + \beta_{i9} \times No.WC + \beta_{i10} \times No.DW + \beta_{i11} \times No.Wtr_{Heater} + \beta_{i12} \times No.Hose_{Bib}$
03-02	$Plm.Dis_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Fxtr + \beta_{i6} \times No.Flr + \beta_{i7} \times Flr_{Height} + \beta_{i8} \times No.Suites + \beta_{i9} \times No.Mods$
04-01	$HVAC_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.Bldng_{Size} + \beta_{i6} \times Crdr_{Area} + \beta_{i7} \times Cmn_{Area} + \beta_{i8} \times Avg.Rm_{Size}$
04-02	$Dct_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.ktchn + \beta_{i6} \times No.WC + \beta_{i7} \times No.DW + \beta_{i8} \times No.Flr + \beta_{i9} \times Flr_{Height} + \beta_{i10} \times No.Mods + \beta_{i11} \times No.Suties + \beta_{i12} \times No.Hose_{Bib}$
04-03	$FRS_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.Ft_{print} + \beta_{i6} \times No.Flr$
05-01	$Elec.Dis_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Suites + \beta_{i6} \times Avg.Suite_{Size} + \beta_{i7} \times Tot.Elec_{Fixtures}$
05-02	$Elec.Wrng_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Suites + \beta_{i6} \times Avg.Suite_{Size} + \beta_{i7} \times Tot.Elec_{Fixtures} + \beta_{i8} \times No.Rcptcl + \beta_{i9} \times No.WC + \beta_{i10} \times No.Swtch + \beta_{i11} \times No.lt_{Fixtures} + \beta_{i12} \times No.Thrmst + \beta_{i13} \times No.PTAC$
05-03	$Elec.Othr_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Suites$
06-01	$Ex.Fnsh_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Flr_{Height} + \beta_{i6} \times No.Flr + \beta_{i7} \times No.Mods + \beta_{i8} \times No.Wnd + \beta_{i9} \times Avg.Wnd_{Perimeter} + \beta_{i10} \times Flr_{Perimeter}$
06-02	$W.Fnsh_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.W_{Length(Suite)} + \beta_{i6} \times Tot.W_{Length(Kitchen/Wc)} + \beta_{i7} \times ExW_{Area} + +\beta_{i8} \times InW_{Area}$

06-03	$Flr.Fnsh_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.Flr_{Area(Suite)} + \beta_{i6} \times Tot.Flr_{Area(Kitchen/WC)}$
06-04	$Clng.Fnsh_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.Flr_{Area(Suite)} + \beta_{i6} \times Tot.Flr_{Area(Kitchen/WC)}$
06-05	$Mlwrk_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times Tot.W_{Length(Suite)} + \beta_{i6} \times Tot.W_{Length(Kitchen/Wc)} + \beta_{i7} \times No.Wnd + \beta_{i8} \times No.WC + \beta_{i9} \times Avg.Wnd_{Perimeter} + \beta_{i10} \times Dr_{Count}$
06-06	$Cbnt_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times Flr_{Area} + \beta_{i5} \times No.Suites + \beta_{i6} \times No.Kitchens + \beta_{i7} \times No.WC$
06-07	$Frn_{\mathrm{i}} = \beta_{i0} + \beta_{i1} \times R + \beta_{i2} \times Yr + \beta_{i3} \times Dur + \beta_{i4} \times No.Suites$

Appendix B: Costing Equations Validation Results

ID	SAS	AIP (%)	AVP (%)	RMSE	MAE	fi
01-01	**General Conditions**	15.14	84.86	3.110726293	2.86	258.85
01-02	**Site**	14.49	85.51	2.057569829	1.80	357.36
01-03	**Foundation Systems**	12.10	87.90	1.656950135	1.47	405.28
02-01	**Exterior Wall Systems**	18.58	81.42	3.526940334	2.90	256.43
02-02	**Interior Wall Systems**	8.07	91.93	1.27151654	1.19	457.41
02-03	**Windows**	14.15	85.85	0.648456884	0.59	629.09
02-04	**Doors**	21.80	78.20	0.286254713	0.23	811.75
02-05	**Roofing Systems**	9.61	90.39	0.524630189	0.51	661.26
02-06	**Floor Systems**	13.08	86.92	1.3690886	1.22	449.55
02-07	**Ceiling Systems**	9.57	90.43	1.107796786	0.76	568.38
02-08	**Modular Onsite Connections**	6.84	93.16	0.231166672	0.19	843.31
03-01	**Plumbing Fixtures**	14.27	85.73	0.260954721	0.22	821.41
03-02	**Plumbing Distribution**	9.08	90.92	0.839141557	0.75	571.19
04-01	**Heating and Cooling System**	7.29	92.71	0.573958958	0.36	736.21
04-02	**Ducting**	27.66	72.34	1.147037834	0.85	539.57
04-03	**Fire Protection Systems**	7.79	92.21	0.141865575	0.11	903.54
05-01	**Electrical Service/Distribution**	18.23	81.77	0.803570422	0.74	575.85
05-02	**Lighting and Branch Wiring**	13.62	86.38	1.134334271	0.98	505.82
05-03	**Other Electrical Systems**	13.16	86.84	0.312140274	0.26	795.66
06-01	**Exterior Finishes**	5.27	94.73	0.25637834	0.23	809.77
06-02	**Wall Finishes**	22.26	77.74	1.70760692	1.68	373.28
06-03	**Floor Finishes**	9.63	90.37	0.437567452	0.32	756.19
06-04	**Ceiling Finishes**	16.92	83.08	0.458421282	0.43	699.33
06-05	**Millwork**	8.32	91.68	0.839554651	0.68	594.12
06-06	**Cabinets & Countertops**	20.02	79.98	3.871186188	2.59	278.24

Appendix C: Green Building Studio Report

Energy Analysis Report

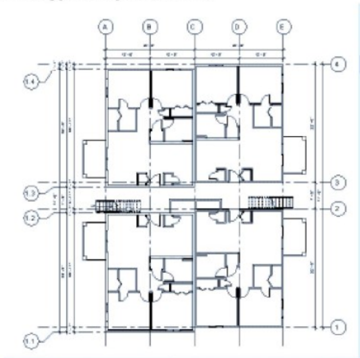
AUTODESK.

2016-03-14- 1- Residential - Apartment

Apartment Analysis

Analyzed at 2016-03-15 9:08:08 AM

Energy Analysis Result



Building Performance Factors

Location:	Edmonton, AB
Weather Station:	15992
Outdoor Temperature:	Max: 87°F/Min: -35°F
Floor Area:	6,889 sf
Exterior Wall Area:	5,406 sf
Average Lighting Power:	0.73 W / ft²
People:	57 people
Exterior Window Ratio:	0.08
Electrical Cost:	$0.10 / kWh
Fuel Cost:	$0.69 / Therm

Energy Use Intensity

Electricity EUI:	10 kWh / sf / yr
Fuel EUI:	141 kBtu / sf / yr
Total EUI:	175 kBtu / sf / yr

Life Cycle Energy Use/Cost

Life Cycle Electricity Use:	1,693,654 kWh
Life Cycle Fuel Use:	235,909 Therms
Life Cycle Energy Cost:	$151,640

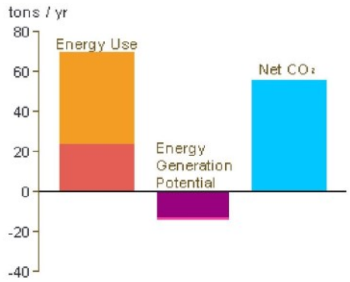
*30-year life and 6.1% discount rate for costs

Renewable Energy Potential

Roof Mounted PV System (Low efficiency):	10,205 kWh / yr
Roof Mounted PV System (Medium efficiency):	20,410 kWh / yr
Roof Mounted PV System (High efficiency):	30,614 kWh / yr
Single 15' Wind Turbine Potential:	1,951 kWh / yr

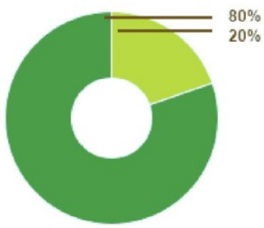
*PV efficiencies are assumed to be 5%, 10% and 15% for low, medium and high efficiency systems

Annual Carbon Emissions



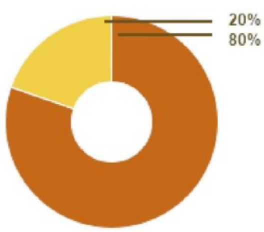
	(tons / yr)
Electricity Consumption	23
Fuel Consumption	45
Roof PV Potential (High Efficiency)	-12
Single 15' Wind Turbine Potential	0
Net CO_2	56

Annual Energy Use/Cost



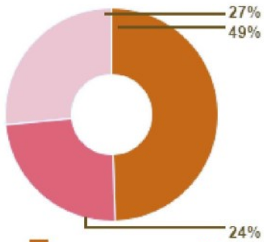
Electricity	20%	$5,741	56,455	kWh
Fuel	80%	$5,392	7,863	Therms
		$11,134		

Energy Use: Fuel



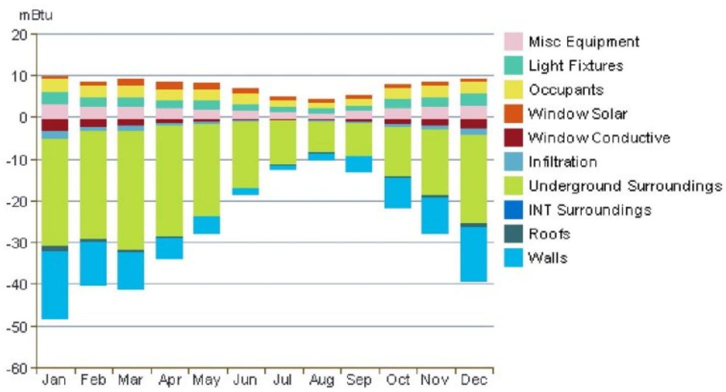
			(Therms)
HVAC	80%	$4,328	6,312
Domestic Hot Water	20%	$1,063	1,551
		$5,391	7,863

Energy Use: Electricity

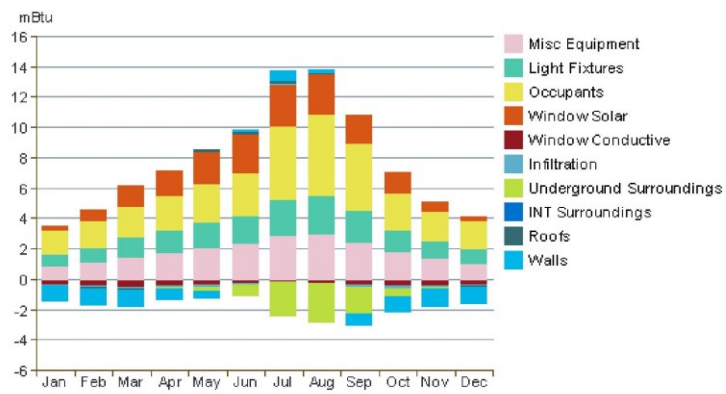


			(kWh)
HVAC	49%	$2,841	27,937
Lighting	24%	$1,375	13,529
Misc Equipment	27%	$1,524	14,988
		$5,740	56,454

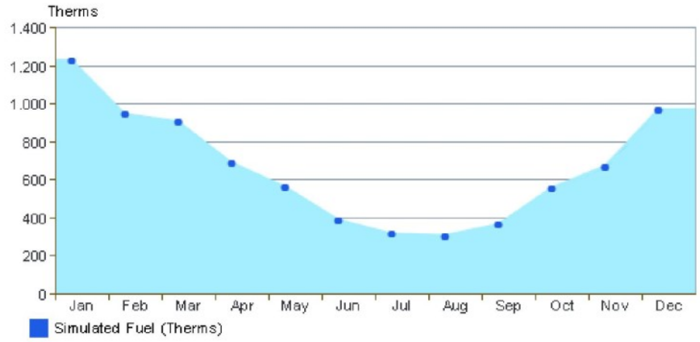
Monthly Heating Load



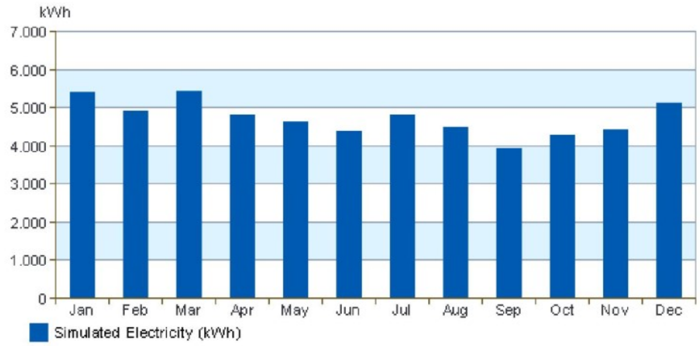
Monthly Cooling Load



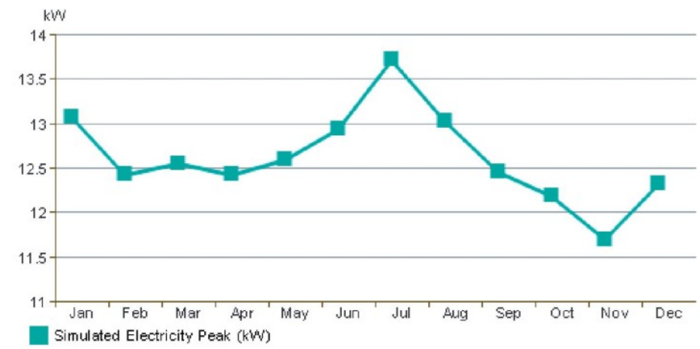
Monthly Fuel Consumption



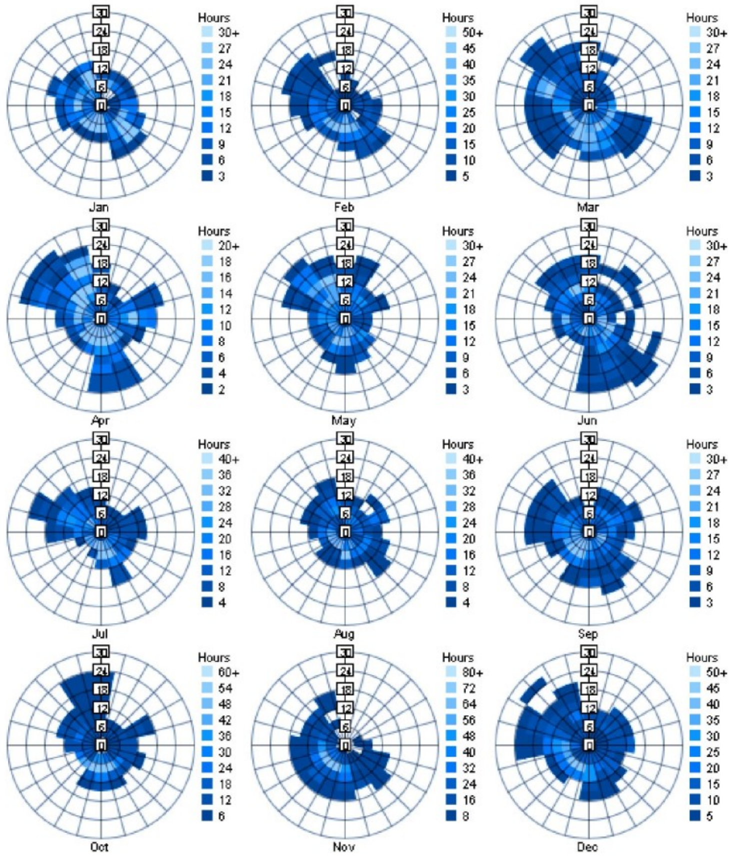
Monthly Electricity Consumption



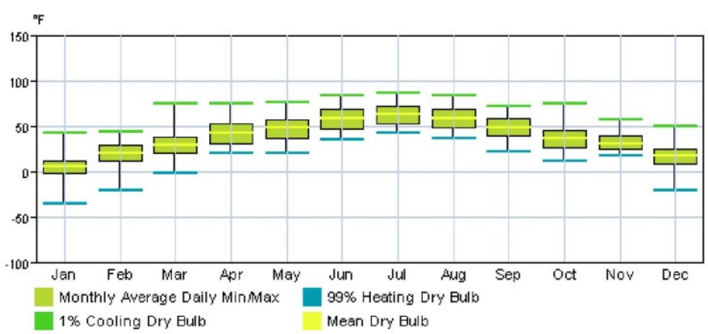
Monthly Peak Demand



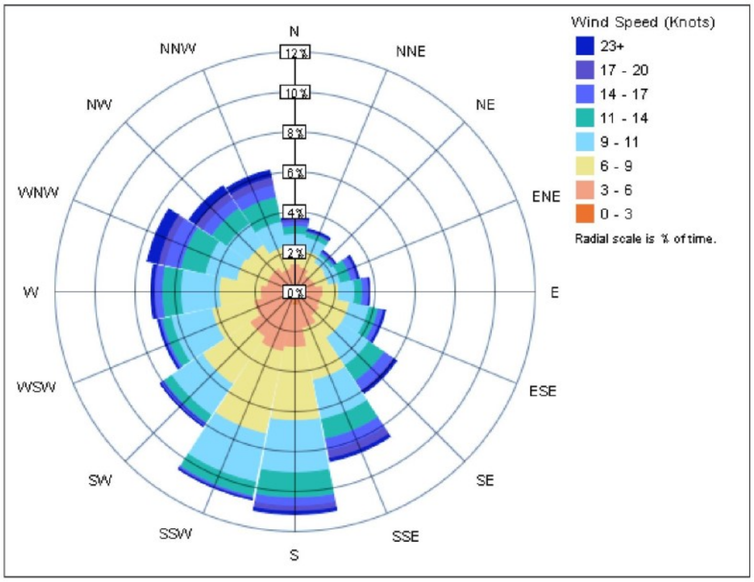
Annual Wind Rose (Speed Distribution)



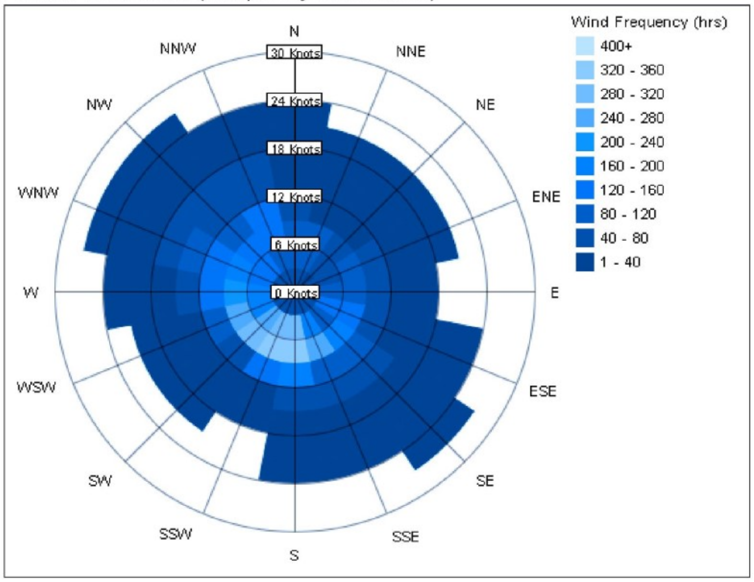
Monthly Design Data



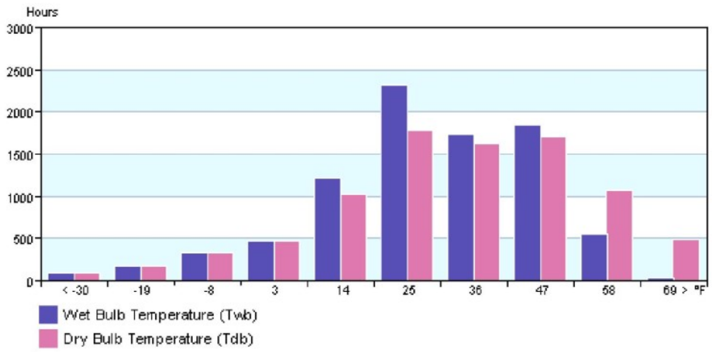
Annual Temperature Bins



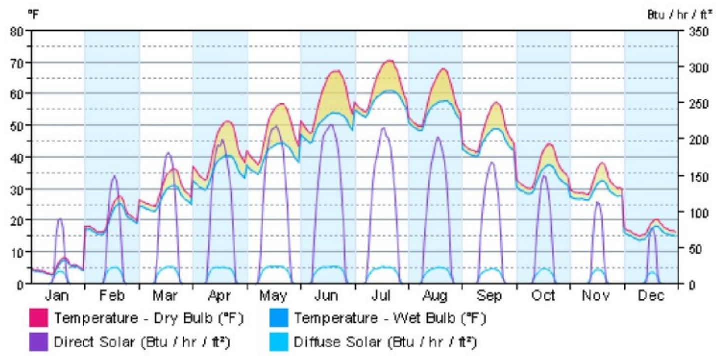
Annual Wind Rose (Frequency Distribution)



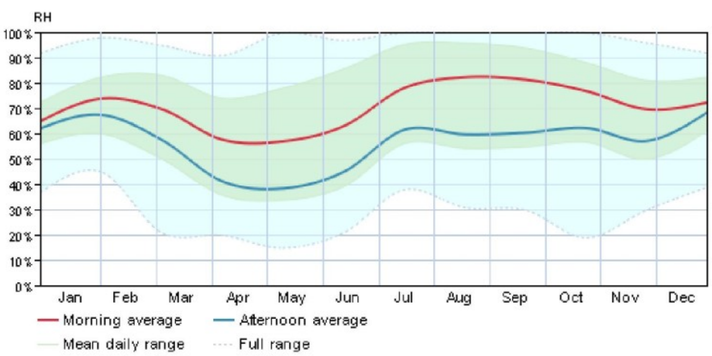
Monthly Wind Roses



Diurnal Weather Averages



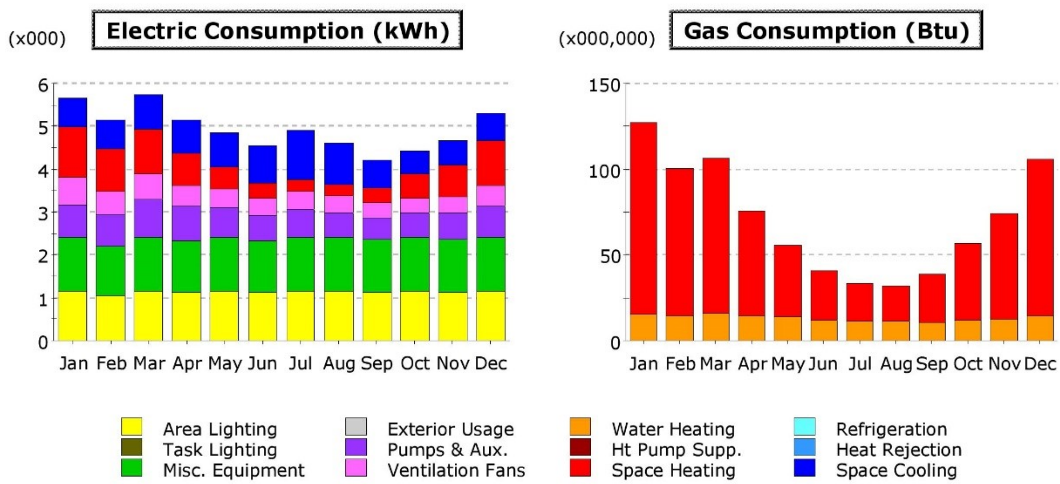
Humidity



Energy Analysis Data

Appendix D: eQUEST Energy Report

Project/Run: Appendix C - Apartment - Baseline Design   Run Date/Time: 03/15/16 @ 10:46



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.65	0.67	0.80	0.79	0.81	0.88	1.15	0.97	0.64	0.55	0.58	0.62	9.12
Heat Reject.	-	-	-	-	0.00	0.00	0.00	0.01	0.00	-	-	-	0.01
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	1.19	0.98	1.05	0.74	0.51	0.35	0.26	0.25	0.34	0.55	0.75	1.06	8.03
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	0.62	0.53	0.57	0.48	0.43	0.40	0.42	0.41	0.36	0.35	0.36	0.49	5.40
Pumps & Aux.	0.75	0.77	0.88	0.80	0.69	0.59	0.63	0.56	0.53	0.55	0.64	0.71	8.09
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.27	1.15	1.27	1.23	1.27	1.23	1.27	1.27	1.23	1.27	1.23	1.27	14.99
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	1.15	1.04	1.15	1.11	1.15	1.11	1.15	1.15	1.11	1.15	1.11	1.15	13.53
Total	5.64	5.14	5.72	5.15	4.86	4.56	4.90	4.62	4.20	4.42	4.67	5.29	59.17

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	111.51	85.95	90.15	60.91	41.79	28.41	21.69	20.79	27.81	44.74	61.51	91.50	686.75
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	15.73	14.51	16.05	14.87	13.99	12.31	11.70	11.13	10.93	12.02	12.76	14.54	160.54
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	127.24	100.45	106.21	75.78	55.78	40.72	33.39	31.92	38.74	56.76	74.26	106.05	847.29

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Appendix E: Multi-Objective Optimization Energy Functions

ID	EUI	Ex_W	W	Dr	Rf	HVAC
1	1.52	0.061	0.348	0.348	0.024	0.190
2	1.50	0.054	0.348	0.348	0.024	0.190
3	1.49	0.049	0.348	0.348	0.024	0.190
4	1.49	0.047	0.348	0.348	0.024	0.190
5	1.44	0.061	0.270	0.348	0.024	0.190
6	1.42	0.054	0.270	0.348	0.024	0.190
7	1.40	0.049	0.270	0.348	0.024	0.190
8	1.40	0.047	0.270	0.348	0.024	0.190
9	1.50	0.061	0.348	0.270	0.024	0.190
10	1.48	0.054	0.348	0.270	0.024	0.190
11	1.47	0.049	0.348	0.270	0.024	0.190
12	1.46	0.047	0.348	0.270	0.024	0.190
13	1.42	0.061	0.270	0.270	0.024	0.190
14	1.40	0.054	0.270	0.270	0.024	0.190
15	1.38	0.049	0.270	0.270	0.024	0.190
16	1.37	0.047	0.270	0.270	0.024	0.190
17	1.51	0.061	0.348	0.348	0.020	0.190
18	1.50	0.054	0.348	0.348	0.020	0.190
19	1.48	0.049	0.348	0.348	0.020	0.190
20	1.48	0.047	0.348	0.348	0.020	0.190
21	1.43	0.061	0.270	0.348	0.020	0.190
22	1.41	0.054	0.270	0.348	0.020	0.190
23	1.40	0.049	0.270	0.348	0.020	0.190
24	1.39	0.047	0.270	0.348	0.020	0.190
25	1.49	0.061	0.348	0.270	0.020	0.190
26	1.47	0.054	0.348	0.270	0.020	0.190
27	1.46	0.049	0.348	0.270	0.020	0.190
28	1.45	0.047	0.348	0.270	0.020	0.190
29	1.41	0.061	0.270	0.270	0.020	0.190
30	1.39	0.054	0.270	0.270	0.020	0.190
31	1.37	0.049	0.270	0.270	0.020	0.190
32	1.36	0.047	0.270	0.270	0.020	0.190

33	1.61	0.061	0.348	0.348	0.024	0.197
34	1.59	0.054	0.348	0.348	0.024	0.197
35	1.58	0.049	0.348	0.348	0.024	0.197
36	1.58	0.047	0.348	0.348	0.024	0.197
37	1.53	0.061	0.270	0.348	0.024	0.197
38	1.51	0.054	0.270	0.348	0.024	0.197
39	1.49	0.049	0.270	0.348	0.024	0.197
40	1.48	0.047	0.270	0.348	0.024	0.197
41	1.59	0.061	0.348	0.270	0.024	0.197
42	1.57	0.054	0.348	0.270	0.024	0.197
43	1.56	0.049	0.348	0.270	0.024	0.197
44	1.55	0.047	0.348	0.270	0.024	0.197
45	1.51	0.061	0.270	0.270	0.024	0.197
46	1.49	0.054	0.270	0.270	0.024	0.197
47	1.47	0.049	0.270	0.270	0.024	0.197
48	1.46	0.047	0.270	0.270	0.024	0.197
49	1.60	0.061	0.348	0.348	0.020	0.197
50	1.58	0.054	0.348	0.348	0.020	0.197
51	1.57	0.049	0.348	0.348	0.020	0.197
52	1.56	0.047	0.348	0.348	0.020	0.197
53	1.52	0.061	0.270	0.348	0.020	0.197
54	1.50	0.054	0.270	0.348	0.020	0.197
55	1.48	0.049	0.270	0.348	0.020	0.197
56	1.47	0.047	0.270	0.348	0.020	0.197
57	1.57	0.061	0.348	0.270	0.020	0.197
58	1.56	0.054	0.348	0.270	0.020	0.197
59	1.55	0.049	0.348	0.270	0.020	0.197
60	1.54	0.047	0.348	0.270	0.020	0.197
61	1.50	0.061	0.270	0.270	0.020	0.197
62	1.48	0.054	0.270	0.270	0.020	0.197
63	1.46	0.049	0.270	0.270	0.020	0.197
64	1.45	0.047	0.270	0.270	0.020	0.197
65	1.32	0.061	0.348	0.348	0.024	0.174
66	1.31	0.054	0.348	0.348	0.024	0.174
67	1.30	0.049	0.348	0.348	0.024	0.174
68	1.29	0.047	0.348	0.348	0.024	0.174
69	1.28	0.061	0.270	0.348	0.024	0.174

70	1.26	0.054	0.270	0.348	0.024	0.174
71	1.25	0.049	0.270	0.348	0.024	0.174
72	1.24	0.047	0.270	0.348	0.024	0.174
73	1.30	0.061	0.348	0.270	0.024	0.174
74	1.29	0.054	0.348	0.270	0.024	0.174
75	1.28	0.049	0.348	0.270	0.024	0.174
76	1.28	0.047	0.348	0.270	0.024	0.174
77	1.26	0.061	0.270	0.270	0.024	0.174
78	1.24	0.061	0.270	0.270	0.024	0.174
79	1.23	0.061	0.270	0.270	0.024	0.174
80	1.23	0.047	0.270	0.270	0.024	0.174
81	1.31	0.061	0.348	0.348	0.020	0.174
82	1.30	0.054	0.348	0.348	0.020	0.174
83	1.29	0.049	0.348	0.348	0.020	0.174
84	1.28	0.047	0.348	0.348	0.020	0.174
85	1.27	0.061	0.270	0.348	0.020	0.174
86	1.25	0.054	0.270	0.348	0.020	0.174
87	1.24	0.049	0.270	0.348	0.020	0.174
88	1.23	0.047	0.270	0.348	0.020	0.174
89	1.29	0.061	0.348	0.270	0.020	0.174
90	1.28	0.054	0.348	0.270	0.020	0.174
91	1.27	0.049	0.348	0.270	0.020	0.174
92	1.27	0.047	0.348	0.270	0.020	0.174
93	1.25	0.061	0.270	0.270	0.020	0.174
94	1.24	0.054	0.270	0.270	0.020	0.174
95	1.22	0.049	0.270	0.270	0.020	0.174
96	1.22	0.047	0.270	0.270	0.020	0.174
97	1.36	0.061	0.348	0.348	0.024	0.178
98	1.35	0.054	0.348	0.348	0.024	0.178
99	1.34	0.049	0.348	0.348	0.024	0.178
100	1.34	0.047	0.348	0.348	0.024	0.178
101	1.32	0.061	0.270	0.348	0.024	0.178
102	1.30	0.054	0.270	0.348	0.024	0.178
103	1.29	0.049	0.270	0.348	0.024	0.178
104	1.28	0.047	0.270	0.348	0.024	0.178
105	1.35	0.061	0.348	0.270	0.024	0.178
106	1.33	0.054	0.348	0.270	0.024	0.178

107	1.33	0.049	0.348	0.270	0.024	0.178
108	1.32	0.047	0.348	0.270	0.024	0.178
109	1.30	0.061	0.270	0.270	0.024	0.178
110	1.29	0.054	0.270	0.270	0.024	0.178
111	1.27	0.049	0.270	0.270	0.024	0.178
112	1.27	0.047	0.270	0.270	0.024	0.178
113	1.35	0.061	0.348	0.348	0.020	0.178
114	1.34	0.054	0.348	0.348	0.020	0.178
115	1.33	0.049	0.348	0.348	0.020	0.178
116	1.33	0.047	0.348	0.348	0.020	0.178
117	1.31	0.061	0.270	0.348	0.020	0.178
118	1.29	0.054	0.270	0.348	0.020	0.178
119	1.28	0.049	0.270	0.348	0.020	0.178
120	1.28	0.047	0.270	0.348	0.020	0.178
121	1.34	0.061	0.348	0.270	0.020	0.178
122	1.32	0.054	0.348	0.270	0.020	0.178
123	1.32	0.049	0.348	0.270	0.020	0.178
124	1.31	0.047	0.348	0.270	0.020	0.178
125	1.29	0.061	0.270	0.270	0.020	0.178
126	1.28	0.054	0.270	0.270	0.020	0.178
127	1.27	0.049	0.270	0.270	0.020	0.178
128	1.26	0.047	0.270	0.270	0.020	0.178
129	1.43	0.061	0.348	0.348	0.024	0.183
130	1.42	0.054	0.348	0.348	0.024	0.183
131	1.41	0.049	0.348	0.348	0.024	0.183
132	1.40	0.047	0.348	0.348	0.024	0.183
133	1.38	0.061	0.270	0.348	0.024	0.183
134	1.36	0.054	0.270	0.348	0.024	0.183
135	1.35	0.049	0.270	0.348	0.024	0.183
136	1.35	0.047	0.270	0.348	0.024	0.183
137	1.41	0.061	0.348	0.270	0.024	0.183
138	1.40	0.054	0.348	0.270	0.024	0.183
139	1.39	0.049	0.348	0.270	0.024	0.183
140	1.39	0.047	0.348	0.270	0.024	0.183
141	1.36	0.061	0.270	0.270	0.024	0.183
142	1.35	0.054	0.270	0.270	0.024	0.183
143	1.34	0.049	0.270	0.270	0.024	0.183

144	1.33	0.047	0.270	0.270	0.024	0.183
145	1.42	0.061	0.348	0.348	0.020	0.183
146	1.41	0.054	0.348	0.348	0.020	0.183
147	1.40	0.049	0.348	0.348	0.020	0.183
148	1.39	0.047	0.348	0.348	0.020	0.183
149	1.37	0.061	0.270	0.348	0.020	0.183
150	1.36	0.054	0.270	0.348	0.020	0.183
151	1.34	0.049	0.270	0.348	0.020	0.183
152	1.34	0.047	0.270	0.348	0.020	0.183
153	1.40	0.061	0.348	0.270	0.020	0.183
154	1.39	0.054	0.348	0.270	0.020	0.183
155	1.38	0.049	0.348	0.270	0.020	0.183
156	1.38	0.047	0.348	0.270	0.020	0.183
157	1.35	0.061	0.270	0.270	0.020	0.183
158	1.34	0.054	0.270	0.270	0.020	0.183
159	1.33	0.049	0.270	0.270	0.020	0.183
160	1.32	0.047	0.270	0.270	0.020	0.183
161	1.52	0.061	0.348	0.348	0.024	0.190
162	1.51	0.054	0.348	0.348	0.024	0.190
163	1.49	0.049	0.348	0.348	0.024	0.190
164	1.49	0.047	0.348	0.348	0.024	0.190
165	1.44	0.061	0.270	0.348	0.024	0.190
166	1.42	0.054	0.270	0.348	0.024	0.190
167	1.41	0.049	0.270	0.348	0.024	0.190
168	1.40	0.047	0.270	0.348	0.024	0.190
169	1.50	0.061	0.348	0.270	0.024	0.190
170	1.48	0.054	0.348	0.270	0.024	0.190
171	1.47	0.049	0.348	0.270	0.024	0.190
172	1.46	0.047	0.348	0.270	0.024	0.190
173	1.42	0.061	0.270	0.270	0.024	0.190
174	1.40	0.054	0.270	0.270	0.024	0.190
175	1.38	0.049	0.270	0.270	0.024	0.190
176	1.37	0.047	0.270	0.270	0.024	0.190
177	1.51	0.061	0.348	0.348	0.020	0.190
178	1.49	0.054	0.348	0.348	0.020	0.190
179	1.48	0.049	0.348	0.348	0.020	0.190
180	1.48	0.047	0.348	0.348	0.020	0.190

181	1.43	0.061	0.270	0.348	0.020	0.190
182	1.41	0.054	0.270	0.348	0.020	0.190
183	1.39	0.049	0.270	0.348	0.020	0.190
184	1.38	0.047	0.270	0.348	0.020	0.190
185	1.49	0.061	0.348	0.270	0.020	0.190
186	1.47	0.054	0.348	0.270	0.020	0.190
187	1.46	0.049	0.348	0.270	0.020	0.190
188	1.45	0.047	0.348	0.270	0.020	0.190
189	1.41	0.061	0.270	0.270	0.020	0.190
190	1.39	0.054	0.270	0.270	0.020	0.190
191	1.37	0.049	0.270	0.270	0.020	0.190
192	1.36	0.047	0.270	0.270	0.020	0.190
193	1.52	0.061	0.348	0.348	0.024	0.190
194	1.50	0.054	0.348	0.348	0.024	0.190
195	1.49	0.049	0.348	0.348	0.024	0.190
196	1.49	0.047	0.348	0.348	0.024	0.190
197	1.44	0.061	0.270	0.348	0.024	0.190
198	1.42	0.054	0.270	0.348	0.024	0.190
199	1.40	0.049	0.270	0.348	0.024	0.190
200	1.40	0.047	0.270	0.348	0.024	0.190
201	1.50	0.061	0.348	0.270	0.024	0.190
202	1.48	0.054	0.348	0.270	0.024	0.190
203	1.47	0.049	0.348	0.270	0.024	0.190
204	1.46	0.047	0.348	0.270	0.024	0.190
205	1.42	0.061	0.270	0.270	0.024	0.190
206	1.40	0.054	0.270	0.270	0.024	0.190
207	1.38	0.049	0.270	0.270	0.024	0.190
208	1.37	0.047	0.270	0.270	0.024	0.190
209	1.51	0.061	0.348	0.348	0.020	0.190
210	1.49	0.054	0.348	0.348	0.020	0.190
211	1.48	0.049	0.348	0.348	0.020	0.190
212	1.48	0.047	0.348	0.348	0.020	0.190
213	1.43	0.061	0.270	0.348	0.020	0.190
214	1.41	0.054	0.270	0.348	0.020	0.190
215	1.39	0.049	0.270	0.348	0.020	0.190
216	1.38	0.047	0.270	0.348	0.020	0.190
217	1.49	0.061	0.348	0.270	0.020	0.190

218	1.47	0.054	0.348	0.270	0.020	0.190
219	1.46	0.049	0.348	0.270	0.020	0.190
220	1.45	0.047	0.348	0.270	0.020	0.190
221	1.41	0.061	0.270	0.270	0.020	0.190
222	1.39	0.054	0.270	0.270	0.020	0.190
223	1.37	0.049	0.270	0.270	0.020	0.190
224	1.36	0.047	0.270	0.270	0.020	0.190
225	1.59	0.061	0.348	0.348	0.024	0.194
226	1.57	0.054	0.348	0.348	0.024	0.194
227	1.56	0.049	0.348	0.348	0.024	0.194
228	1.55	0.047	0.348	0.348	0.024	0.194
229	1.51	0.061	0.270	0.348	0.024	0.194
230	1.48	0.054	0.270	0.348	0.024	0.194
231	1.47	0.049	0.270	0.348	0.024	0.194
232	1.46	0.047	0.270	0.348	0.024	0.194
233	1.56	0.061	0.348	0.270	0.024	0.194
234	1.55	0.054	0.348	0.270	0.024	0.194
235	1.53	0.049	0.348	0.270	0.024	0.194
236	1.53	0.047	0.348	0.270	0.024	0.194
237	1.48	0.061	0.270	0.270	0.024	0.194
238	1.46	0.054	0.270	0.270	0.024	0.194
239	1.44	0.049	0.270	0.270	0.024	0.194
240	1.43	0.047	0.270	0.270	0.024	0.194
241	1.57	0.061	0.348	0.348	0.020	0.194
242	1.56	0.054	0.348	0.348	0.020	0.194
243	1.55	0.049	0.348	0.348	0.020	0.194
244	1.54	0.047	0.348	0.348	0.020	0.194
245	1.49	0.061	0.270	0.348	0.020	0.194
246	1.47	0.054	0.270	0.348	0.020	0.194
247	1.45	0.049	0.270	0.348	0.020	0.194
248	1.44	0.047	0.270	0.348	0.020	0.194
249	1.55	0.061	0.348	0.270	0.020	0.194
250	1.53	0.054	0.348	0.270	0.020	0.194
251	1.52	0.049	0.348	0.270	0.020	0.194
252	1.51	0.047	0.348	0.270	0.020	0.194
253	1.47	0.061	0.270	0.270	0.020	0.194
254	1.45	0.054	0.270	0.270	0.020	0.194

255	1.43	0.049	0.270	0.270	0.020	0.194
256	1.42	0.047	0.270	0.270	0.020	0.194
257	1.48	0.061	0.348	0.348	0.024	0.214
258	1.47	0.054	0.348	0.348	0.024	0.214
259	1.46	0.049	0.348	0.348	0.024	0.214
260	1.46	0.047	0.348	0.348	0.024	0.214
261	1.41	0.061	0.270	0.348	0.024	0.214
262	1.39	0.054	0.270	0.348	0.024	0.214
263	1.37	0.049	0.270	0.348	0.024	0.214
264	1.37	0.047	0.270	0.348	0.024	0.214
265	1.47	0.061	0.348	0.270	0.024	0.214
266	1.45	0.054	0.348	0.270	0.024	0.214
267	1.45	0.049	0.348	0.270	0.024	0.214
268	1.44	0.047	0.348	0.270	0.024	0.214
269	1.39	0.061	0.270	0.270	0.024	0.214
270	1.37	0.054	0.270	0.270	0.024	0.214
271	1.36	0.049	0.270	0.270	0.024	0.214
272	1.35	0.047	0.270	0.270	0.024	0.214
273	1.47	0.061	0.348	0.348	0.020	0.214
274	1.46	0.054	0.348	0.348	0.020	0.214
275	1.45	0.049	0.348	0.348	0.020	0.214
276	1.45	0.047	0.348	0.348	0.020	0.214
277	1.40	0.061	0.270	0.348	0.020	0.214
278	1.38	0.054	0.270	0.348	0.020	0.214
279	1.36	0.049	0.270	0.348	0.020	0.214
280	1.36	0.047	0.270	0.348	0.020	0.214
281	1.46	0.061	0.348	0.270	0.020	0.214
282	1.44	0.054	0.348	0.270	0.020	0.214
283	1.44	0.049	0.348	0.270	0.020	0.214
284	1.44	0.047	0.348	0.270	0.020	0.214
285	1.38	0.061	0.270	0.270	0.020	0.214
286	1.36	0.054	0.270	0.270	0.020	0.214
287	1.35	0.049	0.270	0.270	0.020	0.214
288	1.35	0.047	0.270	0.270	0.020	0.214

Appendix F: Multi-Objective Optimization Constraints

Model Constraints:

Sub-Assembly Systems

$$\{GC\} = \bigcup_{i=1}^{n_1=8} GC_i(Rn_i, Cst_i, Eng_i) \quad (1)$$

General Conditions	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
GC 1	3.633	$21.75	N/A
GC 2	3.717	$22.14	N/A
GC 3	4.192	$24.35	N/A
GC 4	2.508	$16.51	N/A
GC 5	3.475	$21.01	N/A
GC 6	1.967	$13.99	N/A
GC 7	2.325	$15.66	N/A
GC 8	2.292	$15.50	N/A

$$\{SW\} = \bigcup_{i=1}^{n_2=5} SW_i(Rn_i, Cst_i, Eng_i) \quad (2)$$

Site	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
SW 1	3.125	$12.87	N/A
SW 2	3.250	$13.04	N/A
SW 3	4.625	$14.96	N/A
SW 4	2.100	$11.44	N/A
SW 5	1.075	$10.01	N/A

$$\{Fnd\} = \bigcup_{i=1}^{n_3=7} Fnd_i(Rn_i, Cst_i, Eng_i) \quad (3)$$

Foundations	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Fnd 1	2.550	$10.40	N/A
Fnd 2	3.300	$13.46	N/A
Fnd 3	3.500	$14.27	N/A
Fnd 4	2.650	$10.81	N/A
Fnd 5	3.525	$14.37	N/A
Fnd 6	4.175	$17.02	N/A
Fnd 7	3.825	$15.60	N/A

$$\{ExW\} = \bigcup_{i=1}^{n_4=10} ExW_i(Rn_i, Cst_i, Eng_i) \quad (4)$$

Exterior Walls	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Ex W 1.1	3.213	$18.27	0.0540
Ex W 1.2	3.381	$19.42	0.0540
Ex W 1.3	2.856	$15.84	0.0540
Ex W 1.4	3.238	$18.44	0.0540
Ex W 1.5	3.169	$17.97	0.0491
Ex W 1.6	3.688	∞	0.0540
Ex W 1.7	2.694	$14.73	0.0540
Ex W 1.8	2.813	$15.54	0.0491
Ex W 1.9	3.173	$18.00	0.0468
Ex W 1.10	2.506	$13.45	0.0613

$$\{InW\} = \bigcup_{i=1}^{n_5=7} InW_i(Rn_i, Cst_i, Eng_i) \quad (5)$$

Interior Walls	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
In W 1.1	1.481	$15.95	N/A
In W 1.2	2.479	$15.95	N/A
In W 1.3	2.171	$15.95	N/A
In W 1.4	2.793	$15.95	N/A
In W 1.5	2.929	∞	N/A
In W 1.6	1.343	$15.95	N/A
In W 1.7	1.629	$15.95	N/A

$$\{W\} = \bigcup_{i=1}^{n_6=12} W_i(Rn_i, Cst_i, Eng_i) \quad (6)$$

Windows	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
W 1.1	2.000	$8.21	0.3482
W 1.2	2.225	$8.62	0.3482
W 1.3	2.288	$8.73	0.3482
W 1.4	2.513	$9.13	0.3482
W 1.5	2.325	$8.80	0.3482
W 1.6	3.250	$10.45	0.2700
W 2.1	2.725	$9.51	0.3482
W 2.2	2.850	$9.73	0.3482
W 2.3	4.450	$12.59	0.2700

W 2.4	3.925	$11.65	0.2700
W 2.5	3.088	$10.16	0.3482
W 2.6	3.413	$10.74	0.3482

$$\{Dr\} = \bigcup_{i=1}^{n_7=10} Dr_i(Rn_i, Cst_i, Eng_i) \tag{7}$$

Doors	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Dr 1	2.860	$1.12	0.3482
Dr 2	4.110	$1.61	0.2700
Dr 3	2.440	$0.95	0.3482
Dr 4	2.990	$1.17	0.3482
Dr 5	3.820	$1.49	0.3482
Dr 6	2.490	$0.97	0.3482
Dr 7	2.750	$1.08	0.2700
Dr 8	3.410	$1.33	0.2700
Dr 9	3.740	$1.46	0.2700
Dr 10	4.020	$1.57	0.3482

$$\{Rf\} = \bigcup_{i=1}^{n_8=7} Rf_i(Rn_i, Cst_i, Eng_i) \tag{8}$$

Roofing Systems	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Rf 1.1	2.090	$5.80	0.0200
Rf 1.2	1.990	$5.80	0.0235
Rf 1.3	1.760	$5.80	0.0235
Rf 2.1	2.220	∞	0.0235
Rf 2.2	2.110	∞	0.0235
Rf 2.3	2.440	∞	0.0200
Rf 2.4	2.880	∞	0.0200

$$\{Flr\} = \bigcup_{i=1}^{n_9=7} Flr_i(Rn_i, Cst_i, Eng_i) \tag{9}$$

Floor Systems	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Flr 1	3.388	$9.12	N/A
Flr 2	3.488	$9.12	N/A
Flr 3	3.800	$9.12	N/A
Flr 4	3.613	$9.12	N/A
Flr 5	2.825	$9.12	N/A

Flr 6	4.013	∞	N/A
Flr 7	3.593	$9.12	N/A

$$\{Clng\} = \bigcup_{i=1}^{n_{10}=6} Clng_i(Rn_i, Cst_i, Eng_i) \tag{10}$$

Ceiling Systems	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Clng 1	2.588	$8.01	N/A
Clng 2	3.163	$10.47	N/A
Clng 3	2.775	$8.81	N/A
Clng 4	2.663	$8.33	N/A
Clng 5	3.438	∞	N/A
Clng 6	3.063	$10.04	N/A

$$\{Mod\_Cn\} = \bigcup_{i=1}^{n_{11}=7} Mod\_Cn_i(Rn_i, Cst_i, Eng_i) \tag{11}$$

Ceiling Systems	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
M Cn 1.1	3.483	$3.00	N/A
M Cn 2.1	3.717	$3.20	N/A
M Cn 2.2	4.000	$3.44	N/A
M Cn 2.3	4.167	$3.58	N/A
M Cn 2.4	3.533	$3.04	N/A
M Cn 3.1	3.867	∞	N/A
M Cn 4.1	3.117	$2.68	N/A

$$\{P\_Fx\} = \bigcup_{i=1}^{n_{12}=9} P\_Fx_i(Rn_i, Cst_i, Eng_i) \tag{12}$$

Plumbing Fixtures	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Plmbng Fix 1	2.850	$1.47	N/A
Plmbng Fix 2	2.050	$1.19	N/A
Plmbng Fix 3	3.025	$1.53	N/A
Plmbng Fix 4	3.350	$1.64	N/A
Plmbng Fix 5	3.850	$1.81	N/A
Plmbng Fix 6	3.150	$1.57	N/A
Plmbng Fix 7	3.750	$1.77	N/A
Plmbng Fix 8	3.300	$1.62	N/A
Plmbng Fix 9	2.550	$1.36	N/A

$$\{P\_Ds\} = \bigcup_{i=1}^{n_{13}=8} P\_Ds_i(Rn_i, Cst_i, Eng_i) \quad (13)$$

Plumbing Distribution	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Plmbng Dis 1	2.300	$13.46	N/A
Plmbng Dis 2	3.950	$13.46	N/A
Plmbng Dis 3	4.125	$13.46	N/A
Plmbng Dis 4	2.475	$13.46	N/A
Plmbng Dis 5	3.025	$13.46	N/A
Plmbng Dis 6	2.360	$13.46	N/A
Plmbng Dis 7	3.200	$13.46	N/A
Plmbng Dis 8	4.250	$13.46	N/A

$$\{HVAC\} = \bigcup_{i=1}^{n_{14}=9} HVAC_i(Rn_i, Cst_i, Eng_i) \quad (14)$$

Heating and Cooling System	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
HVAC Sys 1.1	3.450	$4.06	0.1896
HVAC Sys 1.2	3.700	$4.44	0.1966
HVAC Sys 2.1	2.900	$3.23	0.1738
HVAC Sys 2.2	3.167	$3.63	0.1175
HVAC Sys 2.3	3.633	$4.34	0.1830
HVAC Sys 3.1	3.017	$3.40	0.1904
HVAC Sys 3.2	2.683	$2.90	0.1896
HVAC Sys 4.1	2.767	$3.02	0.1941
HVAC Sys 5.1	2.550	$2.70	0.2138

$$\{Dct\} = \bigcup_{i=1}^{n_{15}=6} Dct_i(Rn_i, Cst_i, Eng_i) \quad (15)$$

Ducting	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
HVAC Dct 1	2.550	$2.90	N/A
HVAC Dct 2	3.600	$4.02	N/A
HVAC Dct 3	4.250	$4.72	N/A
HVAC Dct 4	3.750	$4.19	N/A
HVAC Dct 5	3.200	$3.59	N/A
HVAC Dct 6	3.400	$3.81	N/A

$$\{FPS\} = \bigcup_{i=1}^{n_{16}=2} FPS_i(Rn_i, Cst_i, Eng_i) \quad (16)$$

Ducting	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
HVAC FPS 1	3.852	$1.26	N/A
HVAC FPS 2	4.158	$1.37	N/A

$$\{E\_Srvc\} = \bigcup_{i=1}^{n_{17}=4} E\_Srvc_i(Rn_i, Cst_i, Eng_i) \quad (17)$$

Electrical Service/Distribution	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Elec Srvc 1	2.850	$4.55	N/A
Elec Srvc 2	4.250	$4.55	N/A
Elec Srvc 3	4.500	$4.55	N/A
Elec Srvc 4	3.400	$4.55	N/A

$$\{E\_Wrng\} = \bigcup_{i=1}^{n_{18}=6} E\_Wrng_i(Rn_i, Cst_i, Eng_i) \quad (18)$$

Lighting and Branch Wiring	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Elec Wrng 1	3.400	$7.05	N/A
Elec Wrng 2	2.850	$6.65	N/A
Elec Wrng 3	4.750	$8.04	N/A
Elec Wrng 4	4.500	$7.86	N/A
Elec Wrng 5	3.200	$6.91	N/A
Elec Wrng 6	3.600	$7.20	N/A

$$\{E\_Oth\} = \bigcup_{i=1}^{n_{19}=4} E\_Oth_i(Rn_i, Cst_i, Eng_i) \quad (19)$$

Other Electrical Systems	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Elec Othr 1	3.200	$1.96	N/A
Elec Othr 2	3.400	$2.11	N/A
Elec Othr 3	3.500	$2.18	N/A
Elec Othr 4	2.700	$1.59	N/A

$$\{Ex\_Fnsh\} = \bigcup_{i=1}^{n_{20}=4} Ex\_Fnsh_i(Rn_i, Cst_i, Eng_i) \quad (20)$$

Exterior Finishes	**Ranking (Rn)**	**Unit Cost (Cst)**	**Energy Factors (Eng)**
Ex Fnsh 1.1	3.200	$5.00	N/A
Ex Fnsh 1.2	2.850	$4.45	N/A
Ex Fnsh 2.1	3.600	$5.63	N/A
Ex Fnsh 3.1	4.250	$6.64	N/A

$$\{W\_Fnsh\} = \bigcup_{i=1}^{n_{21}=4} W\_Fnsh_i(Rn_i, Cst_i, Eng_i) \quad (21)$$

Wall Finishes	**Ranking (Rn)**	**Unit Cost (Cst)**	**Energy Factors (Eng)**
W Fnsh 1.1	3.675	$9.38	N/A
W Fnsh 1.2	2.325	$5.92	N/A
W Fnsh 2.1	3.300	$8.42	N/A
W Fnsh 3.1	3.500	$8.93	N/A

$$\{Flr\_Fnsh\} = \bigcup_{i=1}^{n_{22}=8} Flr\_Fnsh_i(Rn_i, Cst_i, Eng_i) \quad (22)$$

Floor Finishes	**Ranking (Rn)**	**Unit Cost (Cst)**	**Energy Factors (Eng)**
Flr Fnsh 1	3.083	$2.66	N/A
Flr Fnsh 2	3.333	$2.92	N/A
Flr Fnsh 3	3.133	$2.72	N/A
Flr Fnsh 4	3.567	$3.16	N/A
Flr Fnsh 5	3.000	$2.58	N/A
Flr Fnsh 6	3.717	$3.31	N/A
Flr Fnsh 7	3.633	$3.23	N/A
Flr Fnsh 8	3.917	$3.52	N/A

$$\{Clng\_Fnsh\} = \bigcup_{i=1}^{n_{23}=3} Clng\_Fnsh_i(Rn_i, Cst_i, Eng_i) \quad (23)$$

Ceiling Finishes	**Ranking (Rn)**	**Unit Cost (Cst)**	**Energy Factors (Eng)**
Clng Fnsh 1	2.400	$2.53	N/A
Clng Fnsh 2	2.850	$3.03	N/A
Clng Fnsh 3	2.600	$2.75	N/A

$$\{Mlwrk\} = \bigcup_{i=1}^{n_{24}=6} Mlwrk_i(Rn_i, Cst_i, Eng_i) \quad (24)$$

MilWork	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Mlwrk 1	2.350	$6.56	N/A
Mlwrk 2	3.325	$8.30	N/A
Mlwrk 3	2.975	$7.68	N/A
Mlwrk 4	3.150	$7.99	N/A
Mlwrk 5	2.125	$6.16	N/A
Mlwrk 6	3.725	$9.01	N/A

$$\{Cbnt\} = \bigcup_{i=1}^{n_{25}=9} Cbnt_i(Rn_i, Cst_i, Eng_i) \quad (25)$$

Cabinets & Countertops	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Cbnt 1	2.175	$15.19	N/A
Cbnt 2	2.225	$15.19	N/A
Cbnt 3	2.050	$15.19	N/A
Cbnt 4	2.775	$15.19	N/A
Cbnt 5	4.625	$15.19	N/A
Cbnt 6	1.750	$15.19	N/A
Cbnt 7	1.550	$15.19	N/A
Cbnt 8	2.125	$15.19	N/A
Cbnt 9	3.350	$15.19	N/A

$$\{Furn\} = \bigcup_{i=1}^{n_{26}=1} Furn_i(Rn_i, Cst_i, Eng_i) \quad (26)$$

Furniture & Appliances	Ranking (Rn)	Unit Cost (Cst)	Energy Factors (Eng)
Furn 1	3	0	N/A