A Cost-estimating Building Information Modeling Tool Developed on Sketchup Platform for Single-Family Residential Design

Qisheng Wen

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science in Construction Management

University of Washington

2022

Committee:

Bill Bender, Chair

Ken-Yu Lin

Lingzi Wu

Program Authorized to Offer Degree:

Construction Management

University of Washington

Abstract

A Cost-estimating Building Information Modeling Tool Developed on Sketchup Platform for Single-Family Residential Design

Qisheng Wen

Chair of the Supervisory Committee:

Professor Bill Bender

Construction Management

Building Information Modeling (BIM) has become a popular tool in design and construction. Despite its wide applications, the cost-estimating function of BIM is not robust enough, especially for projects in the schematic design stage. One hurdle for BIM-based estimating is that the architects' 3D models lack cost information. Architects typically do not have the necessary information of cost until the late design stage, when estimates are provided by contractors.

To overcome that hurdle, this research invents a new estimating tool on the platform of Sketchup. This tool integrates the contractor's cost-estimate database with architects' knowledge base. It leverages BIM technology to provide simple and reliable cost estimates for single-family housing projects. With this tool, architects can easily estimate construction cost from their schematic Sketchup models.

Contents

List of Figures

Acknowledgments

In the first place, I want to thank Professor Bender, whose estimate class initially inspired my research. Along the 2 years, Professor Bender encouraged my work and gave me endless inspirations and support. My accomplishments cannot be achieved without Professor Bender's generous help.

I want to thank Professor Ken-Yu Lin and Dr. Zhenyu Zhang. They gave me many opportunities. Also I am grateful for receiving the *John E. Schaufelberger Endowed Fellowship*. I would like to thank the support from Professor John Schaufelberger. And I would like to thank Professor Lingzi Wu who helped me overcome research difficulties.

At last, I also want to mention the love and support from my family. They are my parents Zhenli and Liangde, as well as my wife Siyao.

Chapter 1 Introduction

1.1 Cost uncertainty of single-family projects in design stage

In the building industry, specialization speeds up projects, but it also brings fragmentation and communication challenges. Over the past 100 years of industrialization, the old profession of "master builder" has evolved into 3 separate professions as architects, engineers and contractors. An owner or developer first contracts architects and engineers to create design and then finds a contractor for the construction. This separation between the design and the construction brings many problems. The architect may ignore constructability or cost, the contractors might misinterpret the design and owners may not grasp cost consideration until late in the design stage.

The Spearin Doctrine holds the owners responsible for the design in the construction phase. Irresponsible architects can take advantage of contractual barriers to protect their ignorance with regards to cost. Since the architects' responsibility is limited to produce design, rather than the final fulfillment of project costs. The success of a building project involves a joint effort of many professions, however, the fragmentation of professions allows an architect to focus solely on selling the design, while leaving constructability and cost issues unchecked.

Image selling is a way for an architect to underserve or do a disservice to clients. The fragmented industry encourages architects to sell unrealistic costly designs. Because a building project requires significant amount of investment, architects tend to use appealing design and under-estimated cost to win further commission from owners. Therefore, architects tend to "dream big" and make unrealistic schematic designs with imaginary graphics to cater the owner's ambition. But because of the ignorance of constructability and cost, the owner will eventually be hit with budget over-run and extra expenses in design rework. An under-estimated budget helps the architect to win in a project but it also put the owner at risk for cost escalation during construction.

1.2 Industry fragmentation crippled architects' ability in cost estimating

In traditional Design-Bid-Build (DBB) contracts, the contractor is the responsible party for construction cost. The contractor manages the budget and expenses of the project, while the architect is excluded from the construction spending. Due to this industry fragmentation, architects are not well informed about construction cost. Early design estimates can be deceiving or over-optimistic. To make up for architect's shortcoming in estimating, owners may bring contractors into design through special contracts, such as preconstruction services, General Contractor Construction Manager (GCCM) or Integrated Project Delivery (IPD).

General Contractor Construction Manager (GCCM) lets the owner hire a construction manager to supervise the design process. Via the early involvement of a construction professional, the owner obtains a reliable cost evaluation of design.

The Design Build (DB) delivery method is another collaborative Project Delivery Method (PDM). It resonates the job commissioning of traditional master builders in 19th century before the industrialization times, when the client only commits the builder to take care of all services including design engineering and construction. Using DB, the owner commits a joint party of architect, engineer and contractor via a single contract for a comprehensive project delivery.

Researchers[1] have found by improving collaboration of design and construction, the alternative PDM of CMGC or DB can make a difference in project cost success. The improvements brought by alternative PDM implicitly proves the fragmentation issue in traditional DBB. By promoting collaboration, those PDMs are able to reduce change orders, claims, delay or cost overruns that occur in traditional DBB.

1.3 BIM technology and its shortcomings in cost estimating

Besides collaborative delivery methods, BIM technology is also a tool to promote collaboration in a way that it helps to visualize projects in 3D. BIM makes communication easier among all project stakeholders. According to the 2014 BIM report from the construction company Mortenson, the most beneficial BIM applications include: 3D coordination, construction system design, Design Review and Digital Fabrication.

Other than the technology advancements in the preceding applications, Cost Estimate (CE) is under-developed in BIM applications. Although there are many BIM tools with estimating functions, those tools are less popular compared to other BIM applications. The difficulty in using BIM estimating is that it requires detailed 3D models, which is too time-consuming for the estimators to build a viable BIM model. Also, as quantity

[1] Kulkarni, Aditi, Zofia K. Rybkowski, and James Smith. "Cost comparison of collaborative and IPD-like project delivery methods versus competitive non-collaborative project delivery methods." PhD diss., Texas A & M University, 2012.

Konchar, Mark, and Victor Sanvido. "Comparison of US project delivery systems." Journal of construction engineering and management 124, no. 6 (1998): 435-444.

Rojas, Eddy M., and Ian Kell. "Comparative analysis of project delivery systems cost performance in Pacific Northwest public schools." Journal of Construction Engineering and Management 134, no. 6 (2008): 387-397.

calculations pertain to standard cost items, and the variability of projects it is difficult to use BIM models acquired from other project parties.

For example, to get the rebar quantity of a concrete footing, it is difficult to have a computer recognize which dimension should be used to calculate the quantity. Among the 4 dimensions associate with the 3D BIM model, the computer needs to specifically choose the *spacing* parameter and divide the *length* and *width* parameter to get the rebar quantity in x and y axis. However, smart BIM automation is not yet widely available. Cost estimation still relies on a manual process. Especially in early design stages when the architects do not have detailed BIM models for CE, but have to make rough schematic estimates.

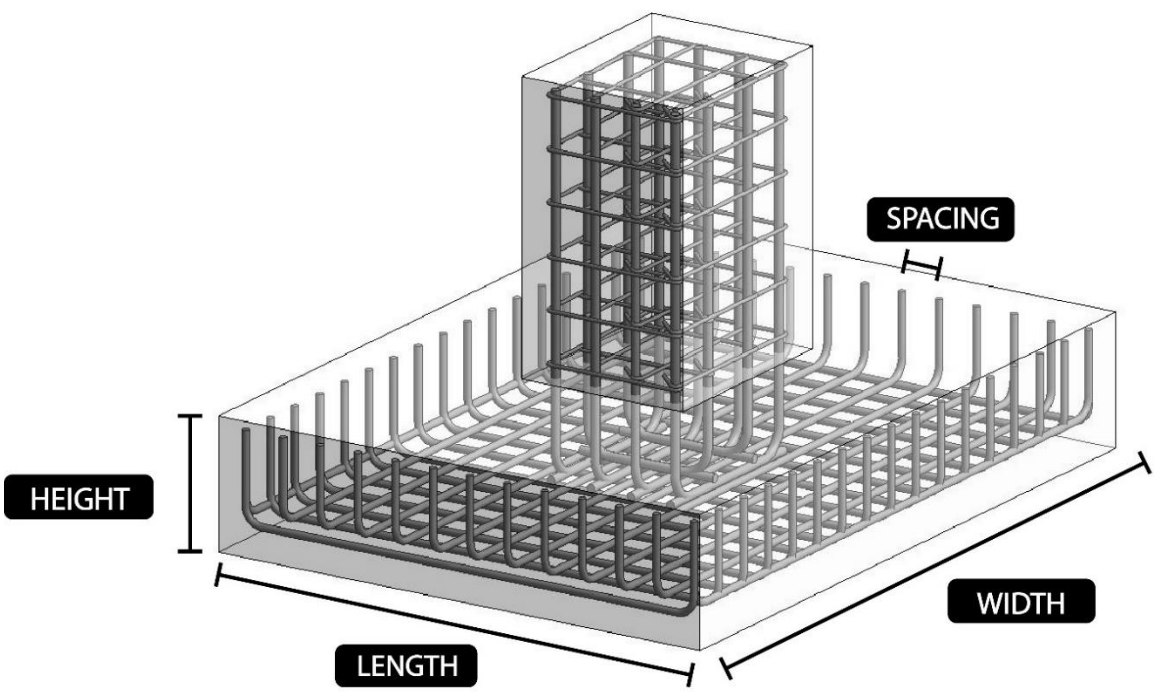

Figure 1.1. Traditional BIM model for CE use

(Image Credit: Karl Tanner[2])

[2] Karl Tanner, "Creating a Rebar Schedule in Revit – with Images!", RevitIQ, April 23 2018, URL: https://revitiq.com/rebar-schedule-revit/

1.4 Architect's risky estimate

Hiring professional contractors is expensive. Typically the architect would only consult contractors in pre-construction services which is scheduled after the design is fully developed. In most cases, cost experts are not available for architects to examine the cost impact of each design decision.

BIM technology has not yet brought up smart solutions for cost estimating in early design stage. Existing estimate functions rely on well-defined BIM models, which are not available in early design stage.

To get more reliable and prompt cost information, architects usually make ad-hoc estimates and these may be wildly inaccurate. In this sense, the knowledge and skills to make reliable estimates are needed in the early design stages.

1.5 Develop a Sketchup extension for Cost Estimating

Sketchup is a modeling tool. Many architects use it to create 3D models in early design stage. As a highly efficient modeling tool, Sketchup is widely used in the architectural industry. Its handy modeling technology of "Push/Pull" was patented in 2003.

On top of the powerful modeling function, Sketchup supports users to further develop the software via Sketchup extensions. There is an online community (Sketchup Extension Warehouse) for users to share and trade user-made Sketchup extensions. Those extensions were all created from an Application Program Interface (API[3])

[3] API is a technical term in software engineering for "Application Programming Interface". It allows users to program the software.

development tool provided by Sketchup. Through the API, users can access the programs that Sketchup is built upon and extends functionality of Sketchup.

The efficiency in handling 3D geometry makes Sketchup a good platform to host an estimating tool. API provides ways to develop Sketchup functions beyond form iteration. With API, user can extract geometry data from Sketchup models and conduct cost analysis. In this case, the author programs API to create the Sketchup Estimating functionality, mining cost data from Sketchup models.

1.6 Research scope

This research scope is limited to small scale residential wood construction in the Pacific Northwest (PNW) region, because in PNW, the Single-Family Residence (SFR) follows the same building convention and shares common construction methods and resources. The scope reduces variance across building projects, leading to a manageable task of constructing a knowledge base that is universally applicable. Also this research focuses on structures and building envelopes. It does not include interior finish, mechanical equipment, electrical devices and plumbing, because those features are typically omitted in building's schematic design.

SFR is a common development type. Within the Seattle-Bellevue-Everett (SBE) metropolitan area, there were 5,275 active SFR projects in 2019, with sizes varying from 700 sf to 5,000 sf. The most common type is a spec home, which is a type of SFR that builds as inexpensively and fast as possible. The timeline of new spec home project is as follows:

1. Feasibility study, program planning - 1 week;
2. Acquisition - 1 week.
3. **schematic design - 1 month**
   - Floor Plan – 2 weeks
   - Massing design – 1 week
   - Elevation – 1 week
4. Documentation - 1 month
5. Permitting - 8 months
6. Construction - 12 months
7. Selling - 3 months

Figure 1.2. Typical schedule of a spec home project

To develop SFR projects, developers obtain construction loans to finance their projects. With an active loan and growing interest, the developer is poised to hasten the design. For schematic design, there is only a tight time window. The schematic design for most spec homes takes less than 1 month. Within that time span, a majority of design work is completed. Floor plans and 3D modeling are developed in the design, but the building assembly details and specifications are yet to be determined.

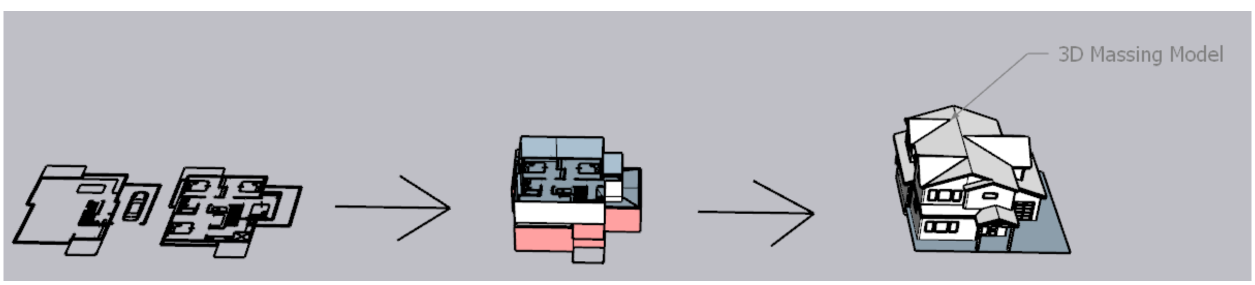

Figure 1.3. Modeling process from floor plan to a generic 3D model

For the SFR project, schematic design yields parametric models which are generic. Their purpose is to visualize massing ideas and to explore elevation features. Because of the lack of details, architects do not have the tools to analyze the cost data from that generic model.

1.7 Research question

Traditionally, BIM-based cost estimate requires detailed model. But in early schematic design stage, the architects produce only generic massing models which only have envelope geometries and lack cost data. Existing BIM-based estimating tools cannot process the generic schematic models. This paper proposes the research question of: Is there a way to improve existing cost estimating with BIM and promote cost considerations of Single-Family Residential design in the early schematic stage?

1.8 Research goals and objectives

1.8.1 Take advantage of BIM to automate QTO and cost calculation for generic digital models

Although BIM has been a popular tool in the building industry, the existing BIM collaborations are limited to model sharing between project parties. BIM applications make it easy to "pass on" deliverables. Regarding the limitations of existing BIM tools, the author seeks a new way of collaboration - that is to empower designers with a simplistic cost estimating tool. The author seeks a new BIM tool to advise architects with contractors' knowledge and automatically evaluates cost impact of design decisions in schematic design. This tool promotes cost considerations of the design and encourages the architect to think like contractors thus integrating the fragmented professions.

1.8.2 Promote cost considerations in early design stage

As early designs are generic and crude, the tool will be generic enough to allow flexibility, but also be definitive enough to ensure accuracy. While it is a paradox to be both schematic and well-defined, the cost tool aims to satisfy both of these two demands. More specifically, this new tool will store definitive cost data for typical construction details. With this pre-build knowledge framework plus a convenient user interface, it smartly applies the cost items to 3D design models, automatically detailing the schematic model after consulting the user's assumptions. The pre-build knowledge framework and user interface are keys to the tool's ability of automation in design development. With this feature, this tool will provide a quick assessment of Level-3 estimate (detail level classification[4] by The American Society of Professional Estimators), while traditionally it is only possible for Level-2 estimate in the schematic design.

1.8.3 Make cost estimate simple and viable

Due to the fast pace in SFR design, the new BIM-estimating tool should emphasize simplicity and convenience. It needs to produce results quickly and effortlessly, so that architects can get prompt cost-feedback for their design charrette.

Considering architects may have limited experience with QTO and estimate, the tool should also provide necessary instructions to guide non-professional user when they dive into realm of construction costs.

[4] Standard Estimating Practice Sixth Edition, American Society of Professional Estimators, Bni Publications, Inc, 2004, ISBN 1557014817

Chapter 2 Literature review

2.1 Construction Cost Estimate (CE)

Project Management Institute (PMI2019) defines CE as a continuing process. It is dynamic and change-driven. PMI puts CE into 2 stages: the initial CE and the change-control CE. The initial estimate is for purpose of a feasibility study. Its goal is to set a baseline for project programming, scale, and required resources. As the project moves on, specified design information becomes available. The estimator can make accurate calculations from the design specifications. When the project moves into construction, the estimator uses change-control CE to caliper initial results and deal with uncertainties during construction.

Echoing the 2 stages, Niazi et al. (2006) categorize methods of CE into 2 types: Qualitative methods for early design stage and Quantitative methods for final phases of design. In the early schematic stage when the design has limited information, estimators resort to similar projects or profession judgement to make assumptions. According to Niazi, qualitative methods consists of 2 major branches: intuitive methods and analogical methods.

Intuitive methods use the estimator's input to overcome unspecified design. Aram et al points out that intuitive methods rely on an estimate framework, which automatically completes missing design elements. Such framework includes prescriptive cost rules. Staub et al take the intuitive methods into practice and create a practical estimate framework, by which professional estimator can reuse cost data and customize assumptions.

Analogical methods of CE are approaches that extract data from similar completed cases. Researchers focus on how to link history cases with a current project. Poli et al promoted Regression Analysis (RA) to refine cost data from similar projects. With the advancement of computer science, Neural Network (NN) is also a common tool in discovering the cost relations between cases. (Wang et al)

Consensus: All the existing early-stage CE methods require the expertise of a professional estimator. If architects are to make the early stage estimates, they need two aspects of knowledge: first is the cost data from similar projects, second is cost rules including Quantity Take Off (QTO) rules, adjustment parameters (such as coefficients resulted from RA or NN) and other factors that may affect estimate.

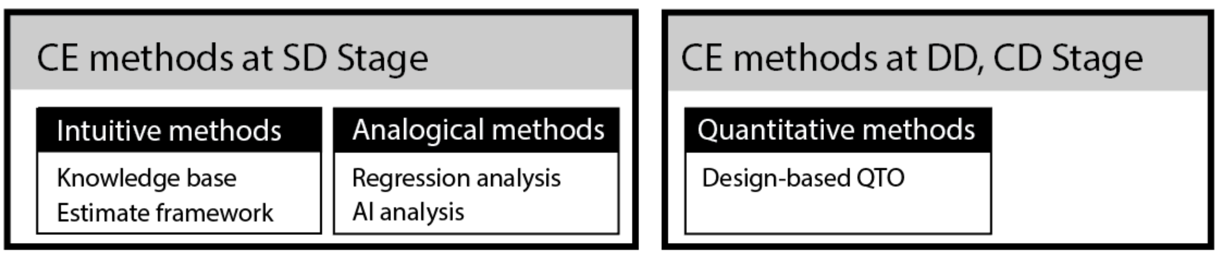

Figure 2.1. Existing CE methods

2.2 Existing BIM based Cost Estimate

There are many existing BIM tools developed to conduct cost estimation. Monteiro et al discussed current practices of BIM-based automatic QTO. Monteiro points out the weakness of BIM-based CE: First, the extracted data from BIM is specific and formatted, which is hard for further process. Second the BIM model for QTO purpose needs to be explicit, thus burdened with overwhelming details. Third there are not any BIM functions to transform QTO to cost data.

In conclusion, existing BIM-based CE tools can only provide limited automation. It requires professional estimators to operate. Several existing BIM-based CE tools are studied as follows.

Revit

Revit is a popular BIM platform. To implement the cost estimate function, programmers of Autodesk Revit set a cost parameter for all 3D model elements. With the schedule function, Revit can create a quantity list of cost items for building models. Then the quantity list can be developed into a cost sheet in other tools such as excel.

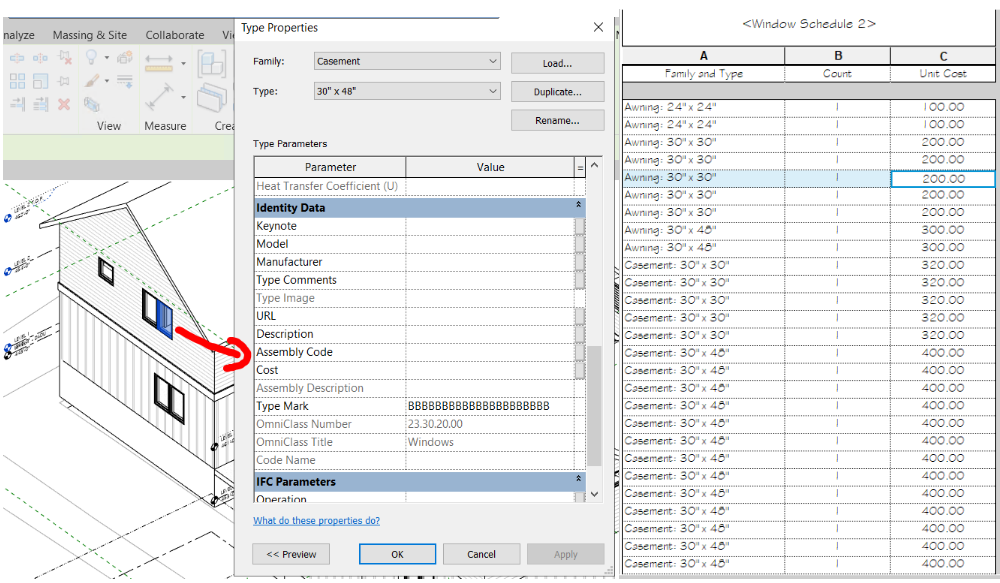

Figure 2.2. Revit creates quantity list from prebuilt cost parameter

The problem of utilizing Revit for cost estimating is the cost data must be held by a defined object. This takes a huge effort to populate every cost item into their correspondent 3D element. Also in schematic design, 3D models are always too simple to hold detailed cost data.

Navisworks

Navisworks is commonly used by designers and general contractors. Navisworks can also extract cost information from 3D models and generate a cost summary. This tool exams 3D model attributes and generates QTO based on a calculation formula.

The shortcomings of Navisworks is different from those in Revit. It does not need detailed geometry to host the cost data and it can read the geometry and allow users to define the quality formula thus bridging the 3D Model data with cost data.

However, Navisworks accepts a narrow range of model types. There are few model types other than Revit models that can be fed into Navisworks for cost analysis. Therefore, for schematic models, Navisworks are not able to recognize anything except Revit.

Also Navisworks does not have modeling function to tweak designs. It means any design change has to be sent back to Revit for modeling and then imported back to Navisworks. This redundant cross-platform transmission is time-consuming.

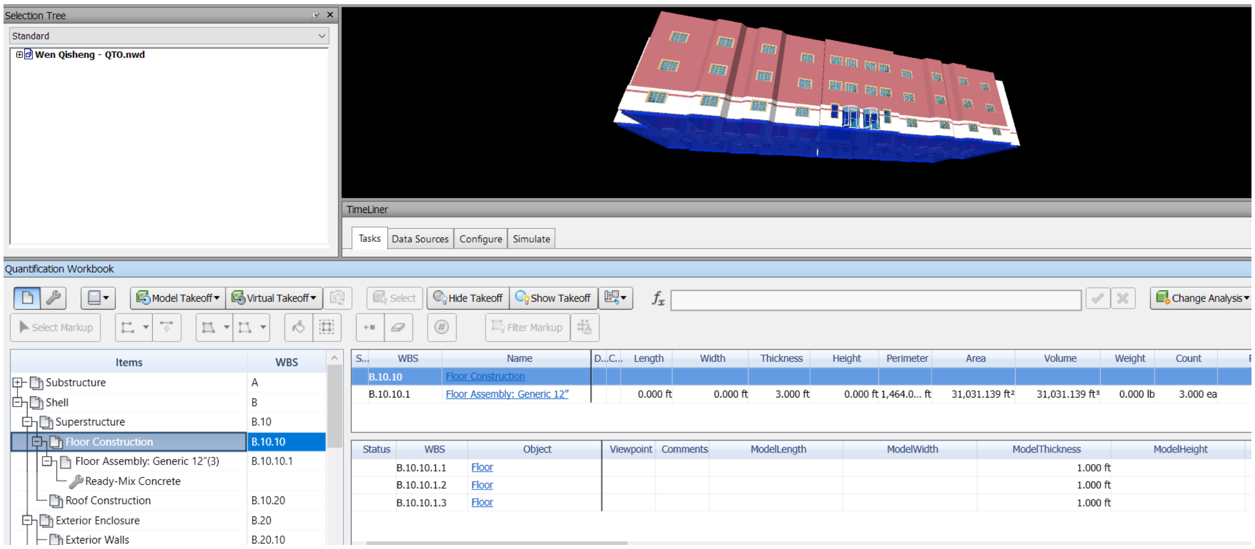

Figure 2.3. Prebuilt quantification workbook in Navisworks

Sketchup Quantifier

Sketchup is a popular tool for architects to build architectural models. While most architects know Sketchup well, they have little knowledge of estimating construction cost with Sketchup. There is not an inherent Sketchup function that is deliberately designed for QTO or estimating. Some 3rd party extensions on Sketchup Extension warehouse can advise architects on project cost.

Quantifier Pro is one of a few existing Sketchup estimating tools published on Sketchup Extension Warehouse. Quantifier Pro can calculate quantities and produce cost reports from Sketchup models. Its function and interface is similar to Navisworks. However it does not provide a pre-built cost database. For every model, the user needs to set up their own cost database and such data are not transmissible among models.

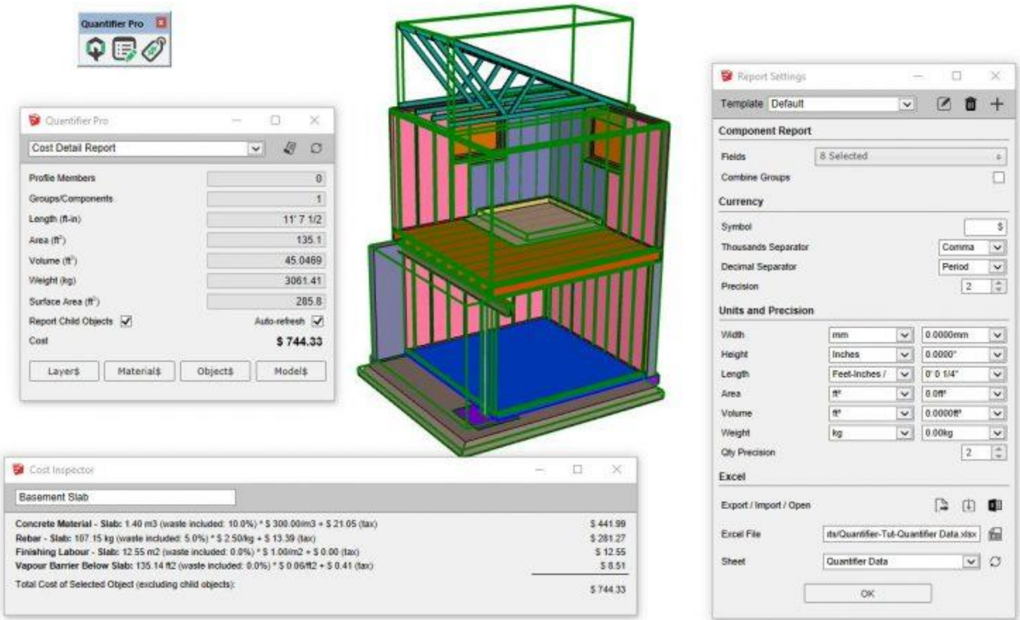

Figure 2.4. Sketchup cost estimate app.

2.3 Literature consensus

There are a plethora of CE methods in early design stages, but many existing BIM tools in the market only adopt the CE methods that are for late-stage fully-developed designs. The existing cost estimation tools are not suitable for early design CE functions. Learning from existing literature on early stage CE, to perform this task, a tool should have two essential components: 1. prescriptive knowledge and cost data base; 2. friendly interface which accepts the user's input as experiential data. Currently most CE tools do not support a pre-built cost database due to unpredictable costs in projects and many existing CE tools have an intricate framework which is confusing to use.

The author aims to find improvements in these two core components. The ultimate goal is to develop a new CE tool, which has informative cost data and also intuitive interface. Via this tool, the author provides early-stage cost facilitation for architects. Further, this cost tool helps to bridge design to construction.

Chapter 3 Methodology

The author creates a Sketchup based CE tool with an intuitive CE function that extends the capability of current BIM CE tools used in schematic design. The author provides case studies to demonstrate the detailed functionality of the CE tool.

3.1 Introduction

The author observed SFR projects in Seattle area and collected empirical knowledge to develop a knowledge framework.

Based on the literature study, a successful CE tool requires two key elements: effective knowledge framework and customization from users. From more than 50 SFR projects in Seattle area, the author summarizes design conventions used in the projects and turns them into universal cost rules. Based on these rules, assumptions are made, schematic design are specified, and QTO formulas are deducted. In this way, the CE tool automatically calculates quantities and generates an estimate.

To get cost data, the CE tool references other databases of construction cost. The unit cost data from RS Means[5] and The Guide[6] are programmed into the tool's database.

To communicate with the user, the author built the User Interface (UI) with webpage technology. The webpage technology creates interactive dialogues to communicate with users, guiding users through various estimation steps. Additionally, this UI is designed to provide an easy customization on prescribed data. Learning from the failure cases in

---

[5] Gordian. "RSMeans Residential Cost Data, 2017." (2017).
[6] 2021 The Guide© Building Construction Material Prices, https://www.rsmeans.com/products/books/2022-cost-data-books

existing CE tools, pre-build functions and databases cannot handle every design case. Therefore it is essential that this tool allows users to adjust the formula.

Additionally, this tool leverages the advantages of web technology. It fetches up-to-date square-foot cost data from pre-build database in the Cloud. From the web-hosted database, the tool sends the up-to-date cost data to end users. The cost database is periodically is updated by referencing updates from cost researchers. In this way, the tool liberates the architects from looking up cost references, enabling them to conveniently acquire the cost information of their project.

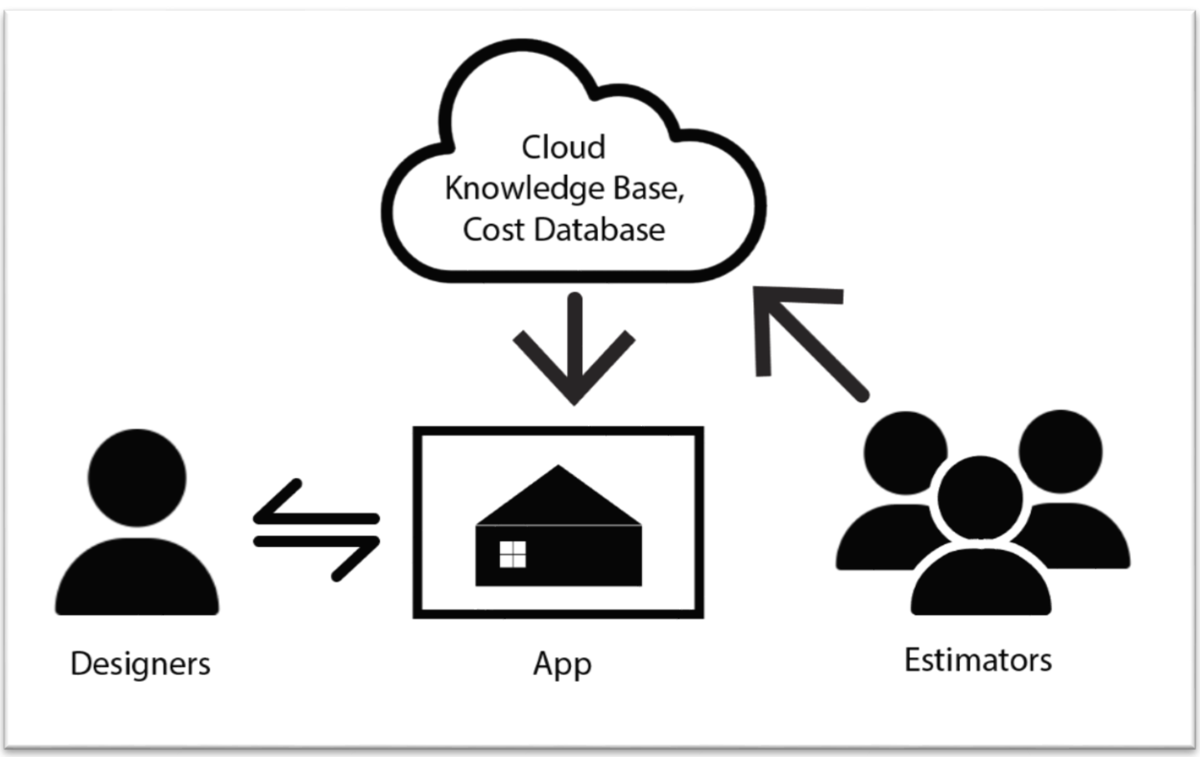

Figure 3.1. Function model of the App

3.2 Case study

The author demonstrates the CE tool in three application cases. Design scenarios are presented to prove the tool's three practical usages, which are:

1. Rough square foot estimating;
2. Detailed assembly estimate;
3. Cost evaluation for design alternatives;

Chapter 4 Developing the CE tool

Most schematic design models in Sketchup are built with generic single-sided 2D faces. Assemblies and details are not included in the schematic models. Though the generic model lacks details, some key cost quantities can still be extracted from the model geometry. These quantities include building footprint size, structure height and exterior walls.

The tool imitates an estimator's rationale in evaluating project cost from square-foot data. Cost experts' knowledge of experiential square-foot cost is prescriptively written into the tool's program. Combining this knowledge base with the machine-recognizing ability, the CE tool can automatically take quantities from the architect's model and calculate cost estimate through the square-foot cost estimate method.

4.1 Automatic geometry recognition in Sketchup

Sketchup does not provide square-foot QTO functions but the digital model has basic geometry data such as location, 3D coordinates, length and area. The author designed algorithm of Sketchup API to look up this geometry data.

In order to find cost from generic Sketchup models, the tool needs to recognize the model geometries as not only dots, lines or faces but in a tectonic meaning as building components. Only in this way, it can then apply proper QTO formulas to the quantity data extracted from the geometry.

Automatically recognize building footprint

The author built a scanner program to let Sketchup automatically recognize building footprints. A building footprint is an area bounded by exterior walls. In the first step, the algorithm detects face geometries which represent walls. This is accomplished by examining the normal (vector perpendicular to the face) of every face geometry. If a face has a z-axis of a value of 0, the face is selected. As building walls are typically over 1 sf, smaller faces under 1 sf are ruled out. In the second step, the program figures out building boundaries from location data of the collected walls. It reads corner points from the wall faces, then comprehensively decides the extent of a building's footprint from the farthest and nearest points. Finally, after establishing the boundary data, the program examines all horizontal faces whose normal is parallel to the z-axis. Those within the building boundary are collected as footprint faces. (With help from another algorithm which filters out overlapped floors)

To allow users to check on the result, the program paints the recognized footprint face in a red color. A check function is created to illustrate the selected footprint faces.

```
def self.wall? face
  normal = plane_normal(face.plane)
  if normal[2] == 0
    max_height = height(face.edges)
    if max_height > 30 && max_height < 40*12
      return true
    end
  end
  return false
end
```

Figure 4.1. Algorithm to detect building boundary

```
scopes_itt.each{|scope|
  # puts scope.non_overlaping?(scope1).to_s
  if !(scope.non_overlaping?(scope1))
    overlaped = true
    overlap_cnd << scope
    # puts "overlapping"
    scopes.delete(scope)
  end
}
if !overlaped
  sel_faces << sel_scopes[scope1]
```

Figure 4.2. Algorithm to rule out overlapped geometry

Manually designate other building components

Another way to add tectonic definition to 3D model is by taking user's input. The author created a paint tool which lets the user choose from a palette of material resembling building components. The user can apply the material to the model faces, then the tool can read those faces as building components based on their material.

```
def self.roofing_inject(entity)
  mat = entity.material
  if !mat.nil?
    puts entity.material.name
    if mat.name == 'Roof'
      puts "got one"
      @roofing_area += entity.area/144
    end
  end
end
```

Figure 4.3. Algorithm to read user-designated roof geometry of material called "Roof"

4.2 Square-foot CE Knowledge base

At the schematic design stage, architects use a rough budget estimate to align the design and the budget. Because of the uncertainty in design at this early stage, the common method used for rough-level-of-magnitude estimate is square-foot estimating method. Estimators get square-foot cost from completed projects that are of similar size and scale.

To develop the new estimate tool, square-foot cost data from past SFR projects are referenced. Aside from the baseline data, square-foot cost data may vary from locations, building category, project scale and cost experts often make comprehensive considerations over these key cost factors. To imitate this rationale, the function is designed to take multiple factors into account as well. More specifically, it is equipped with an interface that collects necessary project information from the user. When user activates the square-foot-cost function, the tool prompts the user with a small questionnaire to inquire about the details. After the user answered several questions, the tool applies pre-built weights to evaluate the factors and adjust the square-foot cost.

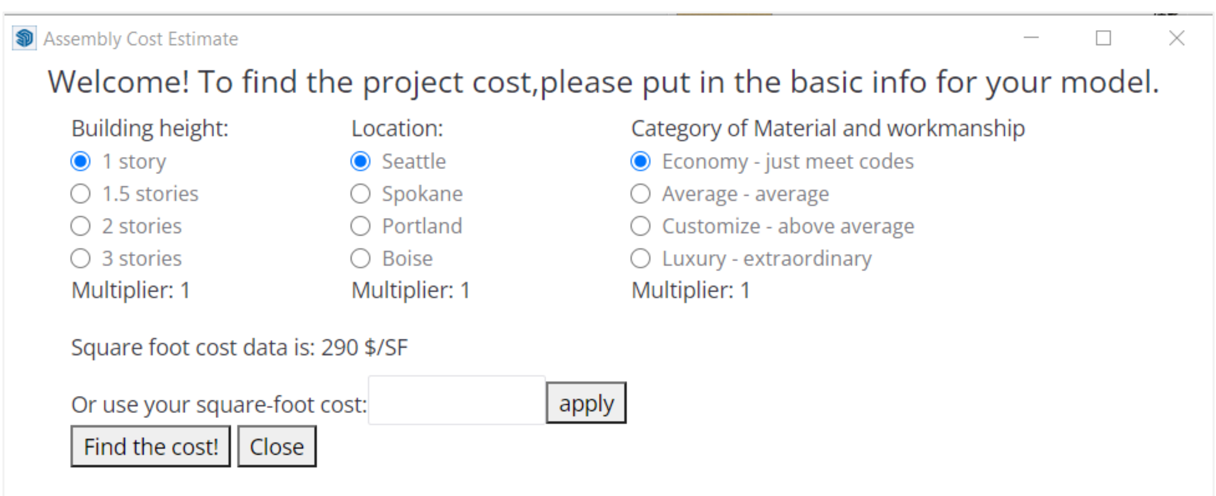

Figure 4.4. UI of square-foot cost function

The first step is to input the cost factors and decide a proper square-foot cost. As shown in the image above, three cost factors are presented as choices to the user. By choosing the applicable option, the user adds weights for each option in project types, scale and location. The weights of each choice is referenced from RS Means. The RS Means provides coefficients for those factors as follows:

Scale Factor

Level	1 Level	1.5 Level	2 Level	3 Level
Factor	1	0.99	0.97	0.95

Location Factor

Location	Seattle	Spokane	Portland	Boise
Factor	1	0.93	0.95	0.87

Upgrade Factor

Category	economy	average	customize	luxury
Factor	1	1.15	1.36	1.67

Figure 4.5. Main factors for user to choose

With the user's input, the tool then provided the gross square footage of the project. The convenient Sketch-up 3D interface allows users to designate the building footprint. Then the tool can extract the area data from the selected model geometry. Multiplying it with the building stories and square-foot cost data, a final square cost estimate is produced.

In the final step, if the user deems the estimate details are not accurate, the interface has an input function which takes the user's customized number. After calipering the quantity and cost data, the user obtains a refined estimate.

4.3 Assembly CE Knowledge base

Assemblies cost estimate is an estimate method used in later stage of design. This estimate method develops cost data from quantities specified by design. Assemblies cost estimate is more detailed than square-foot cost method. But assemblies estimate relies on the specifications of a developed design. It is only used at late design stages such as design development or construction documentation.

In the PNW (Pacific North West), SFR is mostly V-B type (wood frame) construction. The SFR buildings use typical assemblies of a wood structure. By limiting the subject scope to PNW, it is possible to construct a knowledge framework and QTO formulas for the assemblies. This pre-build design knowledge enables the Sketchup Estimating tool to make assumptions and overcome the missing details in design.

The author has interned for two years at an architectural company in Seattle and completed construction documentation for more than 50 SFRs in the PNW region. Through this internship experience, the author found the following common building conventions of PNW SFR:

01 Foundation:

There are 2 types of concrete foundations used through all SFR projects. One is 8"x16" Wall Stem Footing (WSF). This type of footing is typically set along the perimeter of the SFR. Another less common WSF is Shear Wall Stem Footing (SWSF). Comparing to WSF, SWSF has a bigger profile of 10“x30".

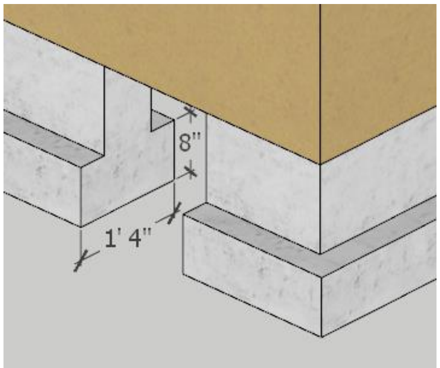

Figure 4.6. WSF

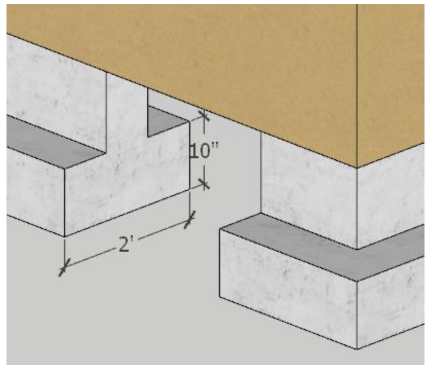

Figure 4.7. SWSF

For spread footings there are 2 common types. One is 24"x24" concrete spread footing (24 FTG), which is typically for porch column support. The other type is 36" x 36" spread footing (36 FTG) which supports main building structure.

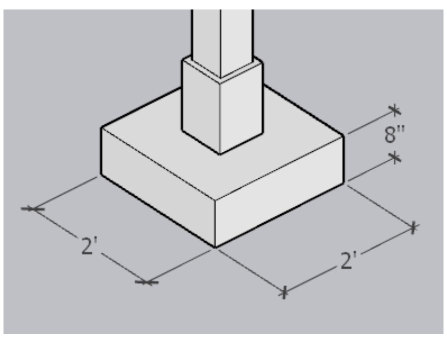

Figure 4.8. - 24 FTG

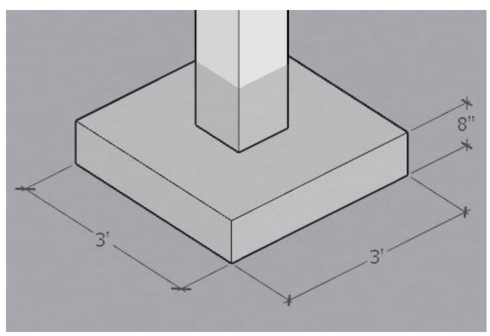

Figure 4.9. - 36 FTG

To calculate the quantity for stem walls, the tool assumes all wall-stem foundations are along the perimeter, which is a typical structural design. By scanning the Sketchup Model. The Sketchup Estimating tool can get the perimeter of designated footprint.

When estimating QTO for shear walls and spread footings, the tool uses empirical data to predict spread footing quantity.

Foundation Assembly Type	QTO Parameters to acquire from model
Typical Wall Stem Footing 8"x16"	Footprint Perimeter
Shear Wall Stem Footing 10"x30"	Shear Wall Length
Column Spread Footing 24"x24"	Number of Footings
Column Spread Footing 36"x36"	Number of Footings

Figure 4.10. QTO parameters for 4 common foundation types

To caliper the results and to find the proper foundation type, a dialog is prompted for user's specification on quantities and footing types. A complete interface of the Sketchup Estimating tool is designed as in the picture below:

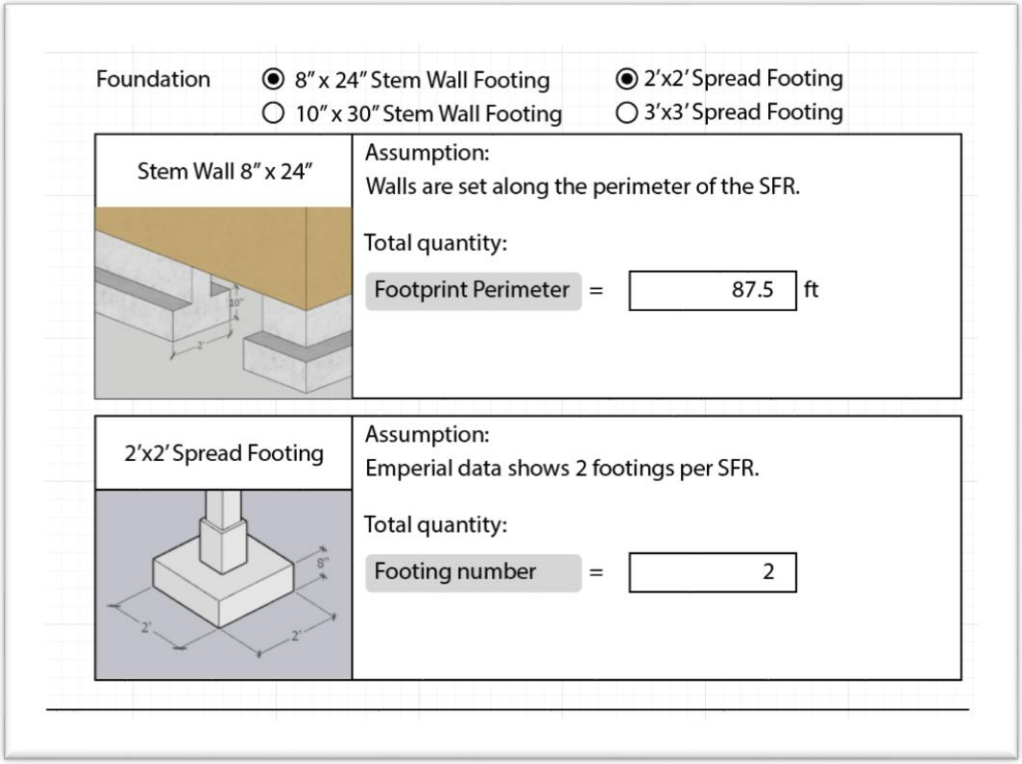

Figure 4.11. UI of foundation QTO

02 Substructure:

In the PNW, some substructures are wood frames built upon concrete foundation and crawl space under the 1st floor.

For the other houses, the substructures are typically use 1 type of Slab-On-Grade (SOG) substructure – 8" concrete foundation walls with 4" concrete slab. 4” slab is the most common type of SOG for SFR projects. The Sketchup Estimating Tool default to this type unless user otherwise picked a crawl space system as substructure.

The quantity of SOG assemblies can be read from the Sketchup Model. The Sketchup Estimating tool needs to read the area of the building footprint. The area data is automatically collected from the user-designated footprint geometry.

For the below-grade concrete walls, the Sketchup Estimating tool needs to read the footprint perimeter and the height of the walls.

Substructure Assembly Type	QTO Parameters to acquire from model
Typical 4" Slab-on-grade	Footprint Area
Typical 8" Concrete Wall	Footprint Perimeter x Height

Figure 4.12. QTO parameters for 2 common sub structure types

The Sketchup Estimating tool provides input windows for the user to customize the quantity data. Also the UI shows the user its QTO logic and assumptions from pre-built design rules. If users are unsatisfied with the assumptions, they can input their own number. The UI interface for the sub structure is shown below：

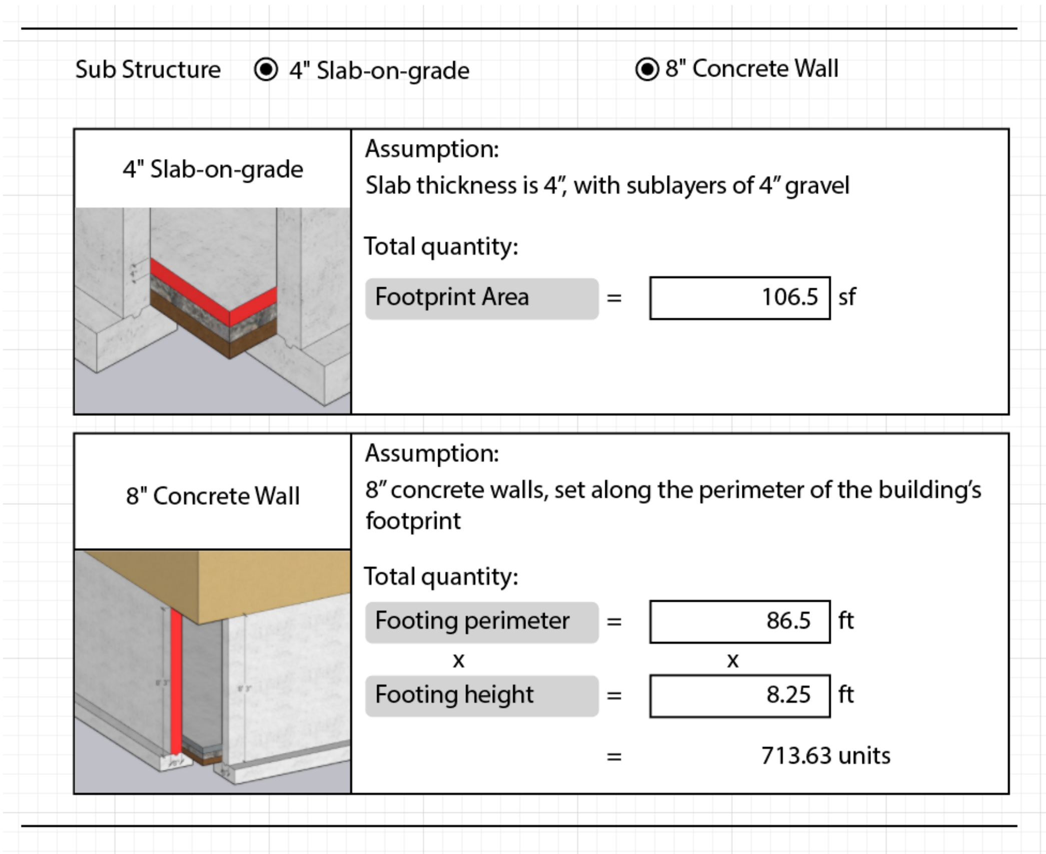

Figure 4.13. UI of substructure QTO

03 Super Structure:

03A Floor

For floor spans that are less than 15', typical floor assembly is 11-1/2" composite wood joist (commonly 12" TJI). The spacing for composite wood joist are typically 16".

Less commonly for larger spans which are over 15', 2"x12" (16" O.C.) lumber framing may be chosen. And engineers may specify engineered wood lumber for large spans or loads. One common type is Laminated Strand Lumber (LSL).

The quantity of floor members is calculated in the following steps: 1. acquire the area of the building footprint (s); 2 acquire building levels (n) from user input; 3 calculate total quantity with the formula: s * n.

Floor Assembly Type	QTO Parameters to acquire from model
Floor by 2" x12" lumber	floor area
Floor by 11.75" TJI	floor area

Figure 4.14. QTO parameters for 2 common floor types

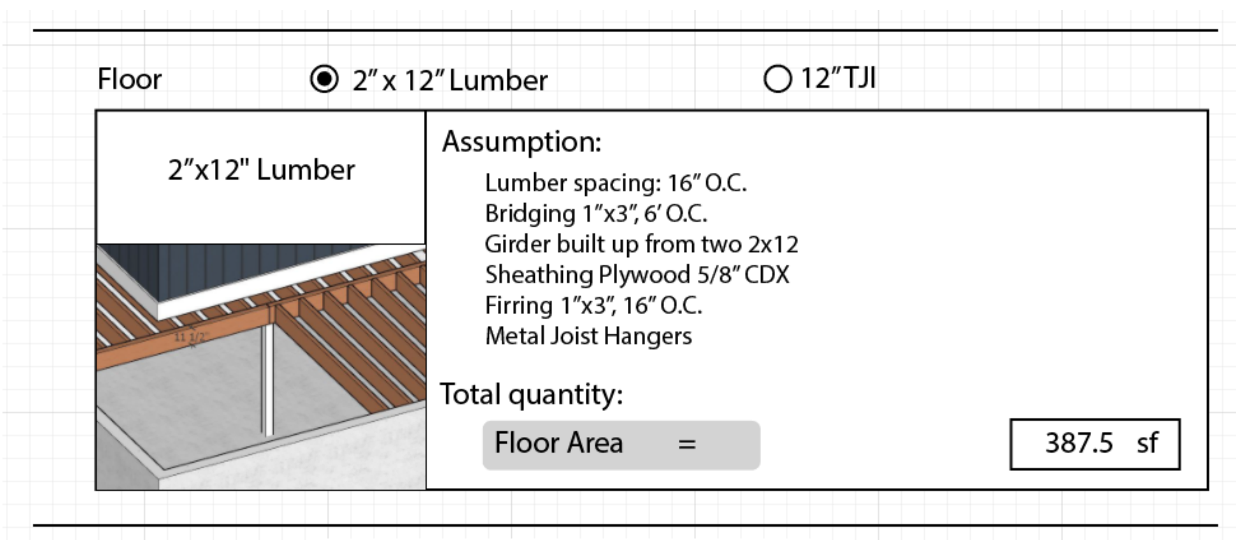

Figure 4.15. UI of floor QTO

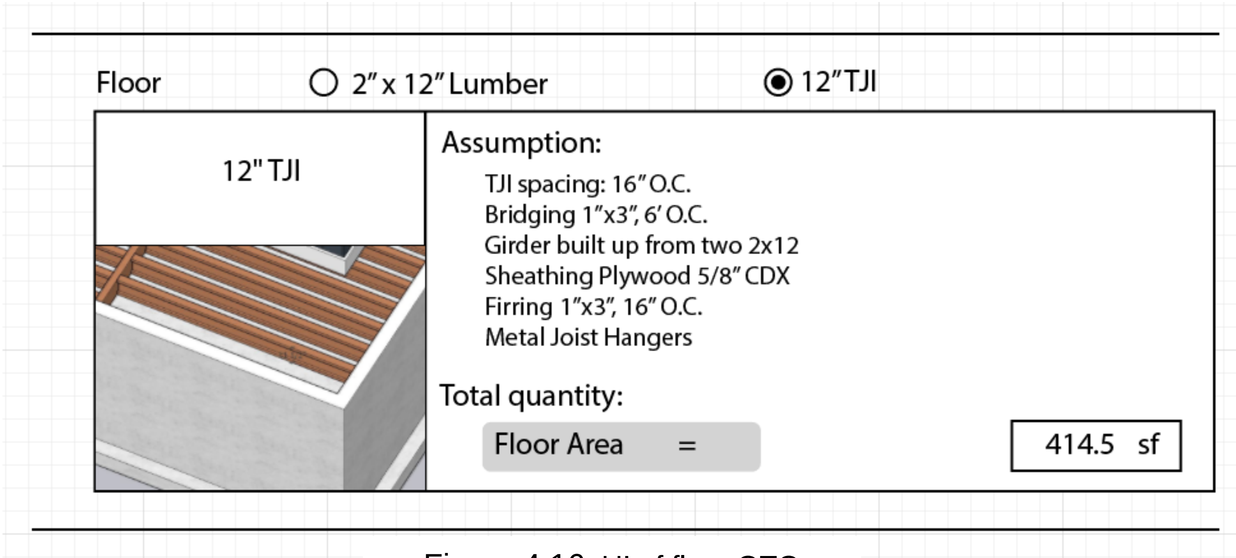

Figure 4.16. UI of floor QTO

03B Roof

Most SFR projects use prefabricated wood trusses for the roof structure. Less commonly, rafter framing (typically 2x12) is also used. The unit price of roof systems are based on the area of the roof footprint.

The quantity of roof structure is calculated from roof ridge lines in Sketchup model. The Sketchup Estimating tool reads the building footprint as the roof area.

Roof Assembly Type	QTO Parameters to acquire from model
Roof by 2" x12" lumber	building footprint area
Roof by MGF	building footprint area

Figure 4.17. QTO parameters for roof types

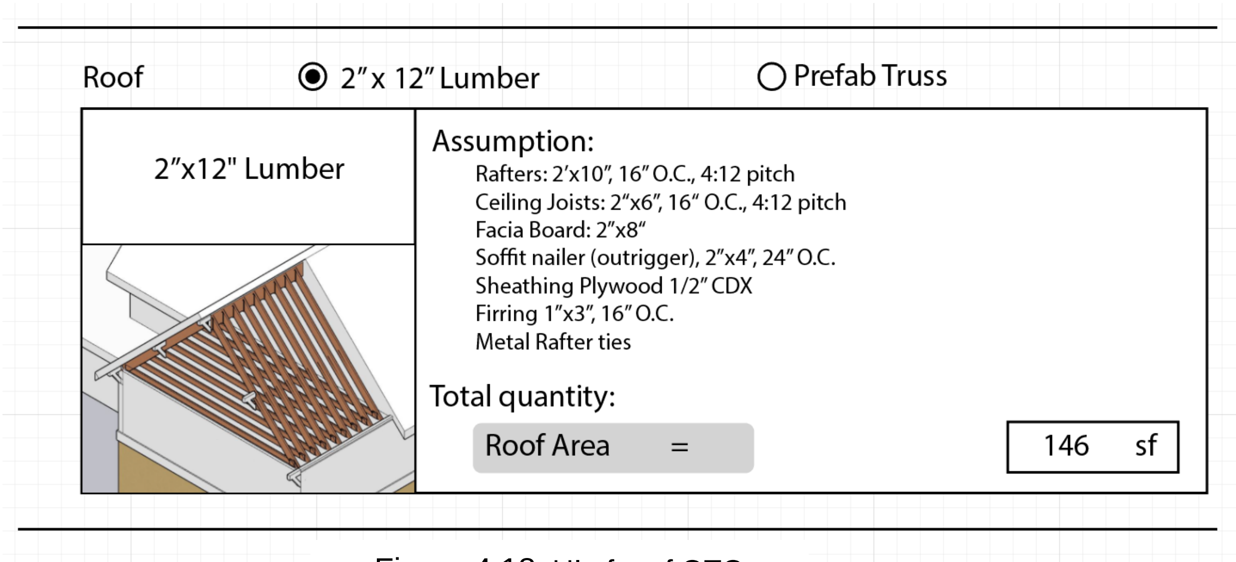

Figure 4.18. UI of roof QTO

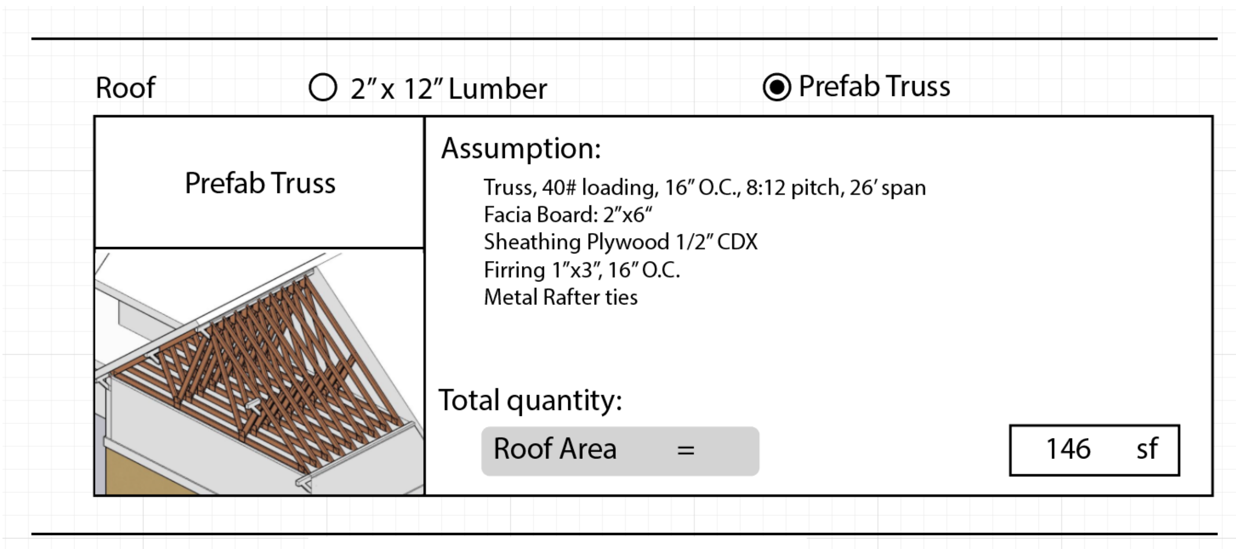

Figure 4.19. UI of roof QTO

04 Shell - Exterior Closure:

04A Exterior walls

Most SFRs are built using wood as the structure. As SFRs typically have no more than three levels, 2x6 wood stud walls are most common. When fire rating is required, 1 extra layer of Type X gypsum board is added. Another type of common residential exterior is garage walls, which also adopts the 2x6 wood structure but does not have insulation.

However, the cost of exterior walls varies because of the finish material. Siding materials like ship-lap wood planks and Hardy board & batten are a lot cheaper than brick veneer or metal siding.

The quantity of exterior wall depends on the perimeter (p) of building footprint and ceiling height at each level (n). For living room levels, the typical height is 9', others are typically 8'. So the total exterior wall area (s) can be calculated from s = p * 9' + p * (n – 1) * 8'.

Wall Assembly Type	QTO Parameters to acquire from model
2x6 wood 16" O.C.	s = p * 9' + p * (n – 1) * 8'

Figure 4.20. QTO parameters for wall types

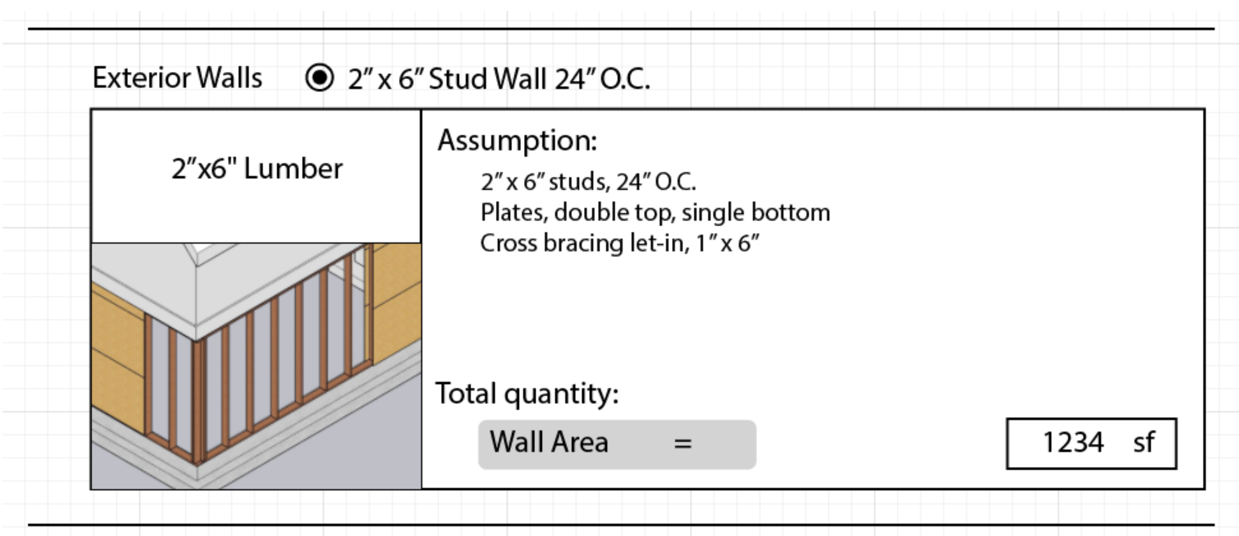

Figure 4.21. UI of wall QTO

05 Roof finish

There are 2 types of roof commonly used across all SFRs. They are asphalt shingle roof and metal (aluminum clipboard) roof.

The QTO of roof finish is based on roof areas, which can be directly read from Sketchup model.

Standing seam metal roof

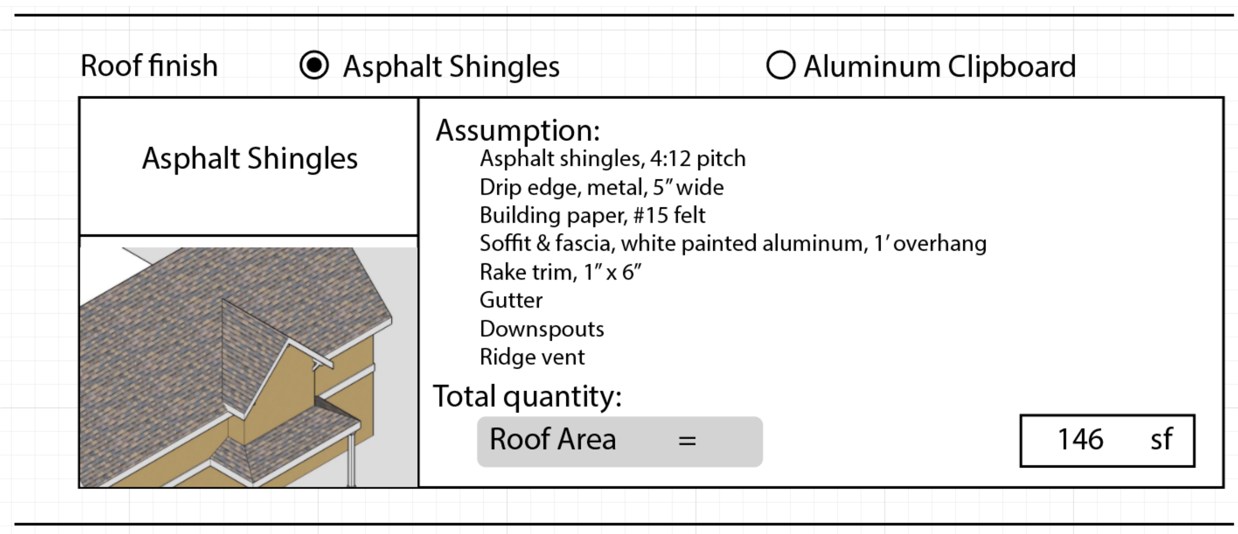

Figure 4.22. UI of roof finish QTO

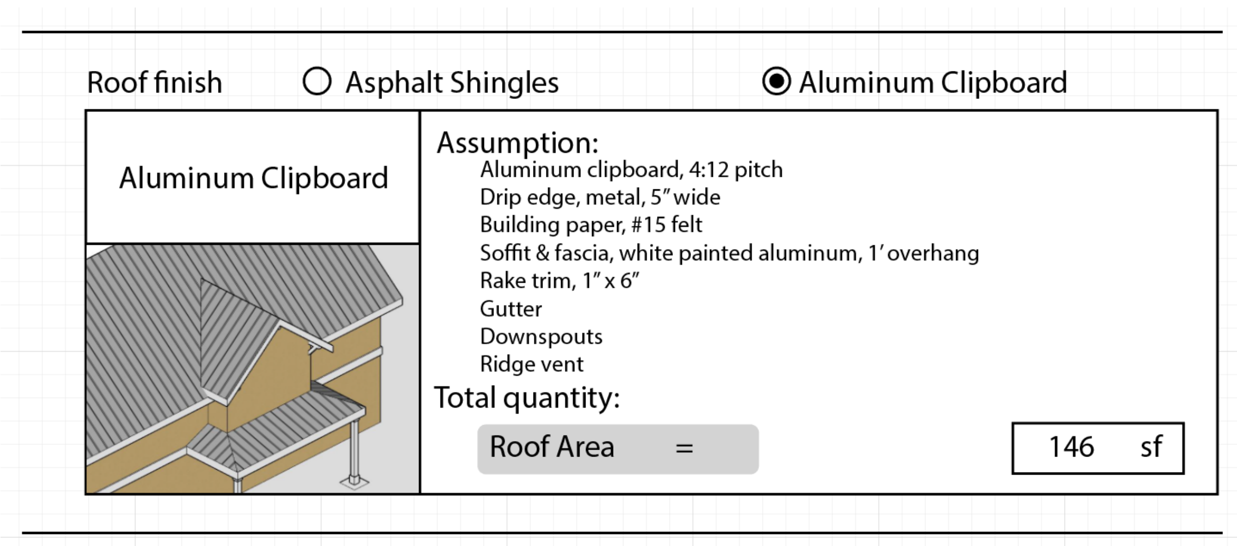

Figure 4.23. UI of roof finish QTO

06 Interior

06A partition walls

Typical SFR interior partition walls use 2x4-stud framing.

For SFR projects, interior walls can be absent in digital models. As interior walls have limited types, they can be efficiently represented in just plan drawings. 3D models are mostly used for envelope design, thus missing the digital geometry for interior walls.

To overcome this problem in QTO analysis, the tool's knowledge base makes assumptions from empirical data from previous designs. Data from past projects are referenced to draw a relationship between partition wall and total project square footage. For every square foot of living area, there are about 0.81 SF interior walls.

Name	Image	Number of Bedrooms	Number of Bathrooms	Number of Stories	Living Area / SF	Interior Wall Area / SF
4143		2	2.5	2	1133	866
4147		3	2.5	3	1422	1236
7343 A		4	3.5	2	2556	2423
7343 B		3	2.5	2	1324	864

Figure 4.24. Empirical data to generate the 0.81 ratio of wall area / footprint area

4.4 Assembly CE Cost database

The Sketchup Estimating tool has prescribed cost data and formulas for the following assemblies.

01 Foundation

Most typical foundation structure is Stem Wall Foundation (SWF). Other foundation types such as spread footing, corner footing, and shear wall foundation are much less common than the typical stem wall foundation. The cost data for each of the foundation types are listed as in the chart below.

Foundation	Cost (Material and Labor)
Typical Wall Stem Footing 8"x16"	31.62$/LF
Shear Wall Stem Footing 10"x30"	41.82$/LF
Column Spread Footing 24"x24"	47.53$/EA
Column Spread Footing 36"x36"	106.94$/EA

Figure 4.25. Unit price of foundations

02 Substructure - Slab on grade

The square footage cost data is referenced from RS Means. User can also override the square foot cost data from knowledge base. And user can input a new unit price through an tool interface.

Substructure	Cost (Material and Labor)
Typical 4" Slab On Grade	3.98$/SF
Typical 8" Concrete Wall	22.59$/FT

Figure 4.26. Unit price of substructure

03 Superstructure

03A Floor Construction

Floor	Cost (Material and Labor)
11.5" Composite Wood Joist, 16" spacing	7.21$/SF
2"x12" stick framing, 16" spacing	9.22 $/SF
11.75" TJI	10.02 $/SF

Figure 4.27. Unit price of superstructure

03B Roof Construction

Roof	Cost (Material and Labor)
Prefab Truss 16" O.C., 8:12 pitch	9.37 $/SF
MFG 24" O.C., 8:12 pitch	6.6 $/SF
2x8 Rafter, 8:12 pitch	8.46 $/SF

Figure 4.28. Unit price of roof

04 Shell - Exterior Closure

Exterior Wall	Cost (Material and Labor)
2x6 wood 16" O.C.	5.15 $/SF

Figure 4.29. Unit price of exterior walls

Exterior Wall (2x6 wood 16" O.C.)	Cost (Material and Labor)
6" Shiplap Walls	8.22 $/SF
Board & Batten Walls	8.24 $/SF
Grey Face Brick Walls	16.94 $/SF
White Cedar Shingle Walls	5.85 $/SF

Figure 4.30. Unit price of exterior wall finish

05 Shell - Roofing

Roof	Cost (Material and Labor)
Asphalt Shingles	8 $/SF
Aluminum Clapboard	49 $/SF

Figure 4.31. Unit price of roof finish

06 Interiors - Interior Construction

Interior Wall	Cost (Material and Labor)
2x4 16" O.C.	2.1SF

Figure 4.32. Unit price of interior finish

Chapter 5 Applications

This chapter shows the applications of this Sketchup CE tool. A variety of architectural design work can benefit from the tool. Through three application scenarios, the author demonstrates the functionality of the two core functions - the Square-foot Estimating function and Assembly-based Estimating function.

5.1 Application Scenario 1: Square-foot cost estimate case

An architect designed a 3,000-sf SFR. A Sketchup model is built to explore design of building appearance and elevation features. The model is generic. It is built with essential massing features. The architect designed all the exterior walls and roofs, but not all windows or doors. None of the upper floors and interior walls are designed.

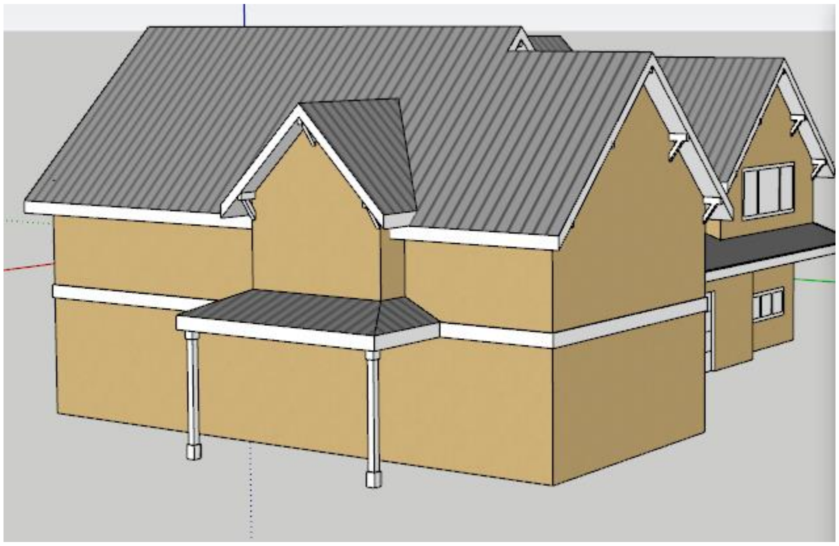

Figure 5.1. The massing model from the architect

With existing CE tools on the market, the architect cannot use the design model for cost analysis purposes because the model is too generic. Neither explicit quantity data is present in the digital model geometry objects, nor the computer perceives and distinguishes the geometries as building components. This is the situation where the Sketchup tool, referred to as Cost Guru, supports cost estimating.

After installation of the Sketchup extension, *Cost Guru*, a tool panel will show up in Sketchup. As in the image below, the first icon on the left is for the square-foot estimate function. The icon is designed with the appearance of a box with a red button. This design implies the function behind this icon - that is to get the footprint area information of a building model.

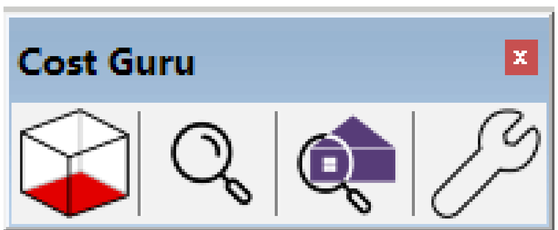

Figure 5.2. The tool panel of Cost Guru

After clicking the box icon, the user will be prompted with a form as shown in the Figure below. It presents the user with a few cost-related premises that Cost Guru needs the user to check when making a square-foot cost analysis. Cost Guru has default values for these premises. Users can input the unique information of their own projects.

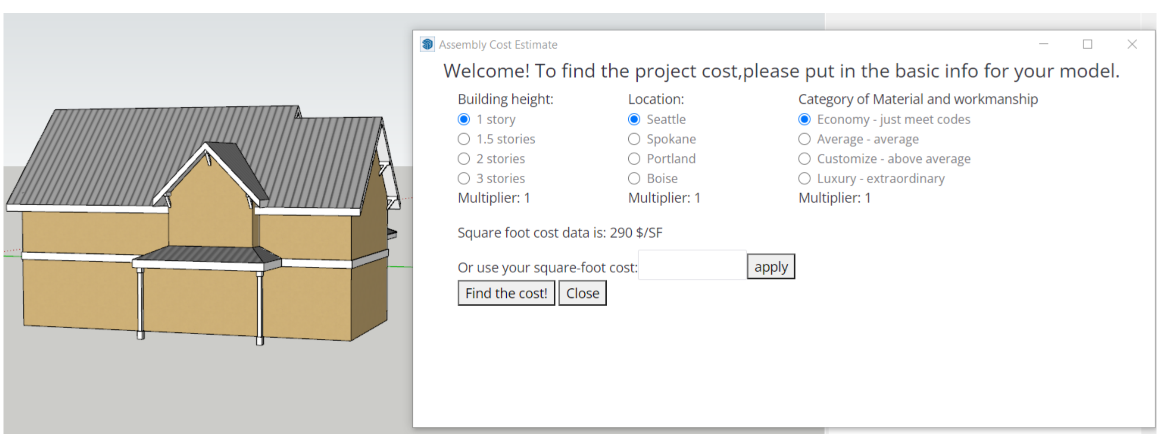

Figure 5.3. Initial form to collect user input

The form is interactive. When the user chooses a different premise, the correspondent multiplier as well as square-foot cost are updated based on that choice.

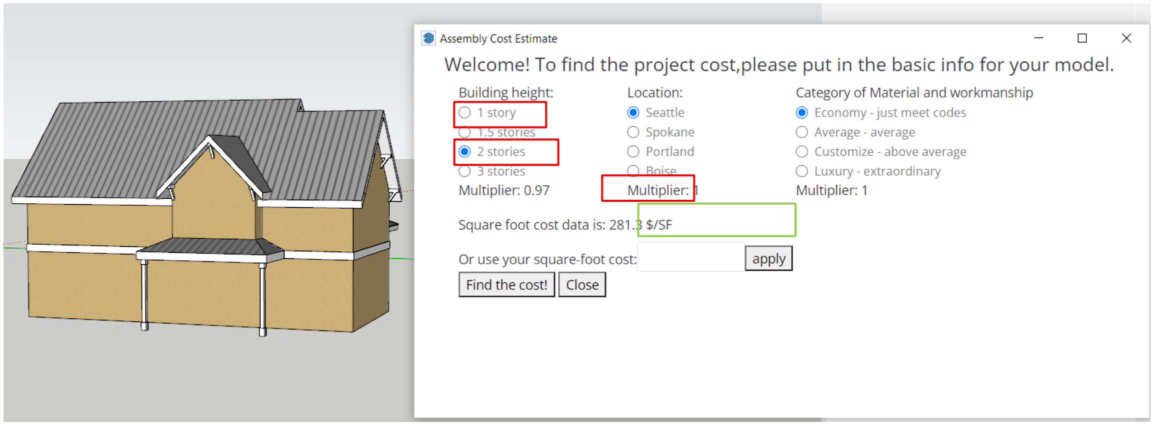

Figure 5.4. Interactive form

After the user has checked all three multiplier factors, if they disagree with the tool's adjusted spare-foot cost, they can override that data by putting down their own number in the box shown in above figure.

When all the above configuration is complete, the user gets the right square-foot cost. Now if the user hits the "Find the cost!" button, the tool scans through the Sketchup model, reads the model's footprint and generates a total square-foot area as the result of its QTO. Finally a total project cost is also calculated as shown in the figure below.

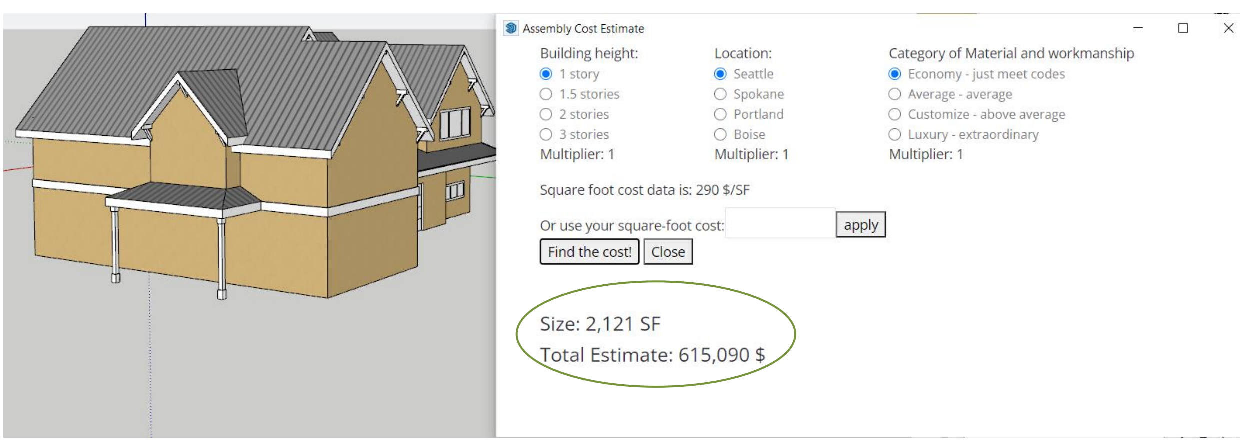

Figure 5.5. UI of rough-level-of-magnitude Estimate

Although Cost Guru performs the footprint QTO automatically, it also provides a check function to let the user to examine the QTO. By clicking the icon with magnifier in the tool panel, the user will see the red building footprint the tool used for QTO calculation.

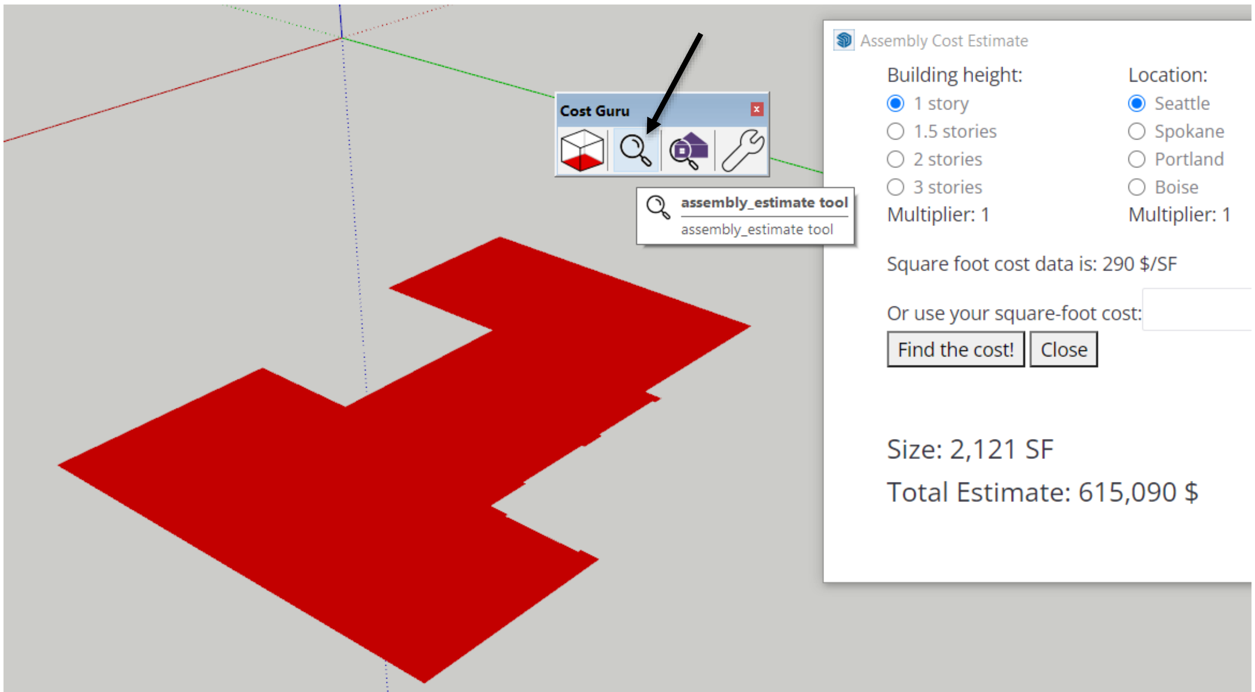

Figure 5.6. Function for checking automatic QTO

The tool's Square-foot Estimate (SE) function can provide quick estimate based on geometry of Sketchup models. After acquiring user's input via the interface, it generates a total project cost based on a model's footprint. In this way, it promptly provides cost feedback to the architect.

5.2 Application Scenario 2: Assembly Estimate

Cost Guru can also provide in-depth cost estimates via assembly estimate method. While square-foot cost estimate has limitations in evaluating design details, assembly estimate method is a more detailed cost analysis based on specific building components. To fulfill this functionality, Cost Guru is equipped with pre-built knowledge base and cost database, which provides specifications to design, promoting accuracy of estimating analysis.

Cost Guru starts the assembly cost estimate when users click on the third icon from the left in the tool panel. The icon is a magnifier examining the window, which implies the function focuses on detailed analysis based on building components.

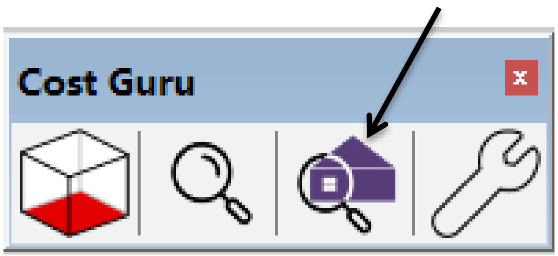

Figure 5.7. The button to start assembly estimate

When the function starts, it first prompts the user with a questionnaire of building systems. According to rules of ASTM uni-format, building components can be categorized into a few systems. Given the scope of the tool, 7 systems are taken into the tool's analysis scope. They are 1 Foundation, 2 Substructure, 3 Floor, 4 Exterior Wall, 5 Roof, 6 Roof Finish and 7 Windows doors and interior walls. The user should selects the applicable systems in their project. This process specifies the design details for the generic design.

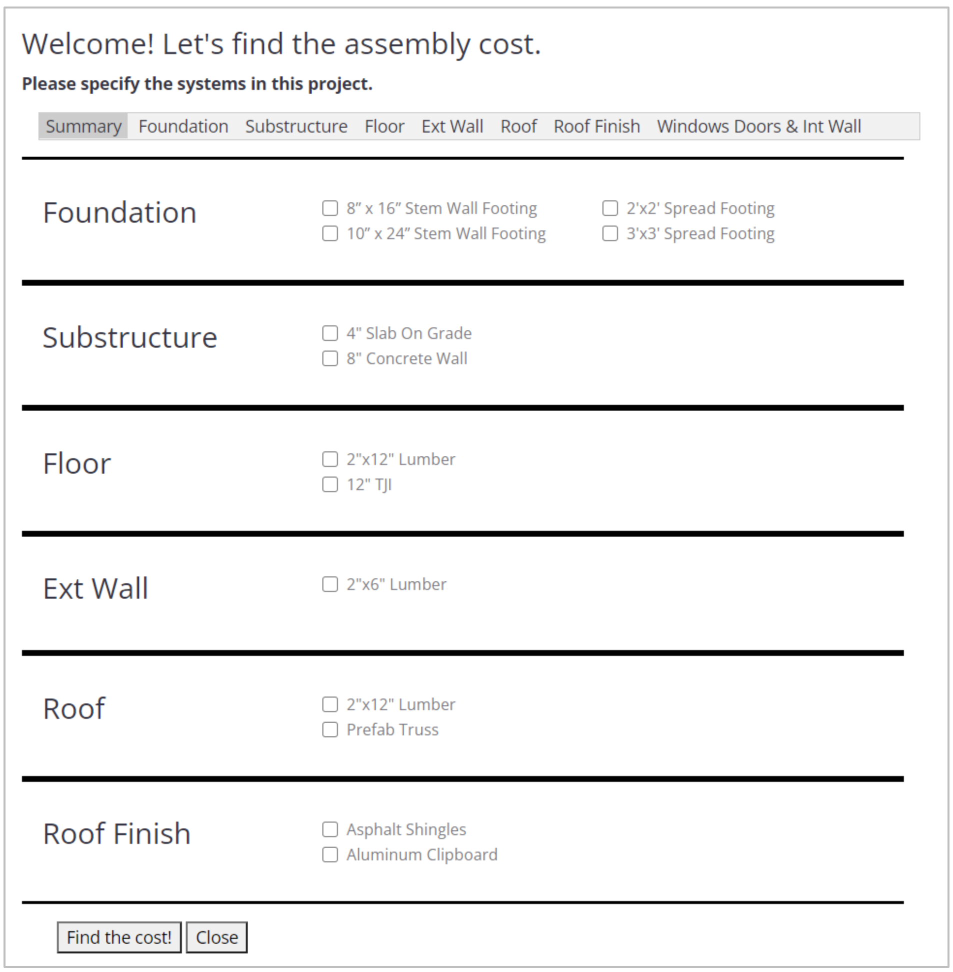

Figure 5.8. User Questionnaire

After configuring all the assembly systems, the user clicks "Find the cost!", then the tool does what it is good at – automatic QTO. In a few mini-seconds, the analysis result is displayed under each building system. A total project cost is displayed on top of the list.

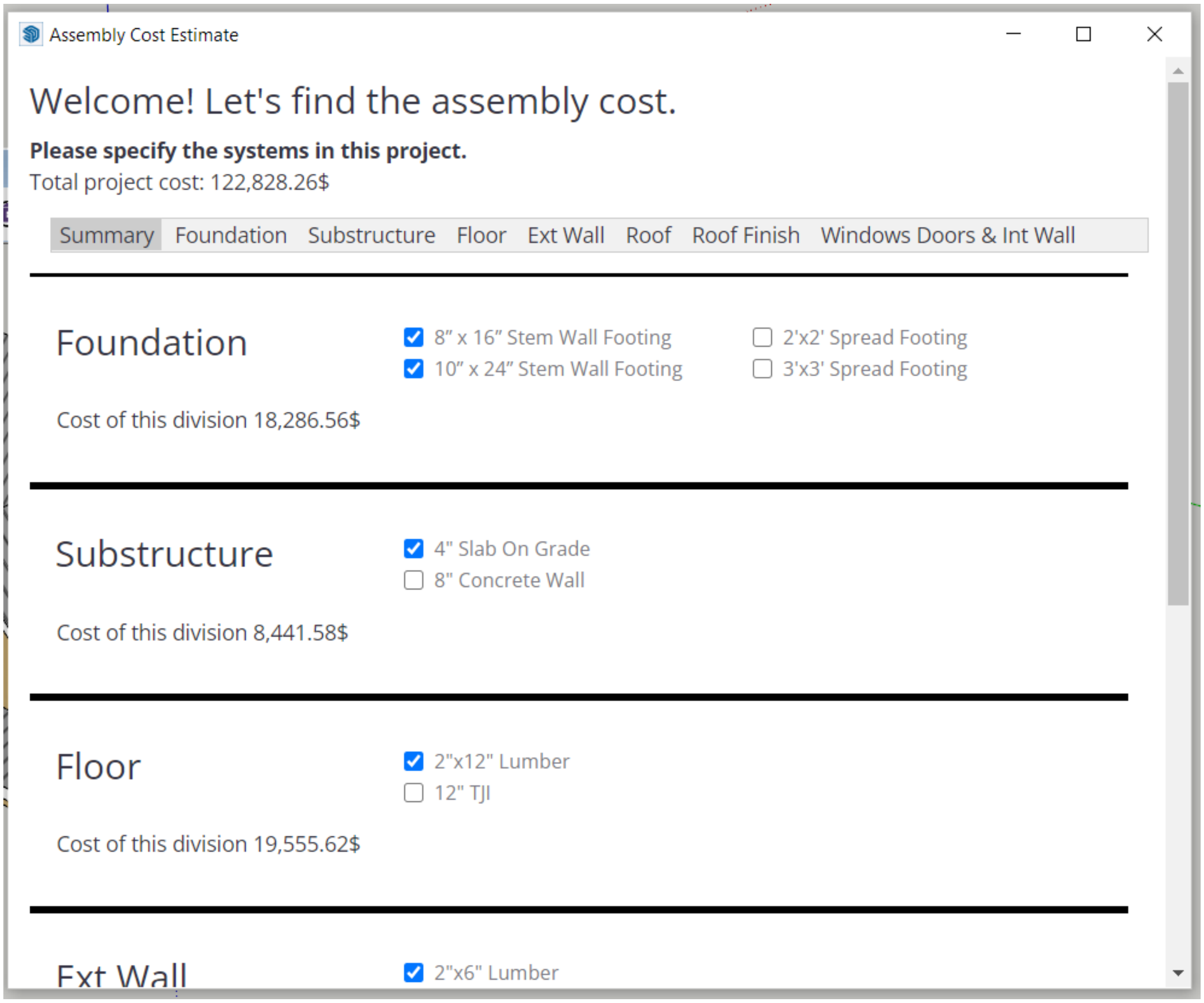

Figure 5.9. Assembly cost analysis result

Also detailed quantity information with illustrations of their corresponding systems are displayed. Because assembly cost data is detailed and lengthy, the results are categorized and tucked into page tabs. By clicking into each tab in the header, the user can check the computer's QTO results. Also the calculation formula and the unit cost data are presented to the user. Input boxes are provided for the user to input their own QTO, formula and unit cost, therefore they can override the tool's calculation and manually refine the cost analysis. If any overriding action is taken, the tool will withdraw its previous results, and wait until the user click "Find the cost!" button again. Then the total cost and costs for each assembly system are recalculated and the new result is once again presented to the user.

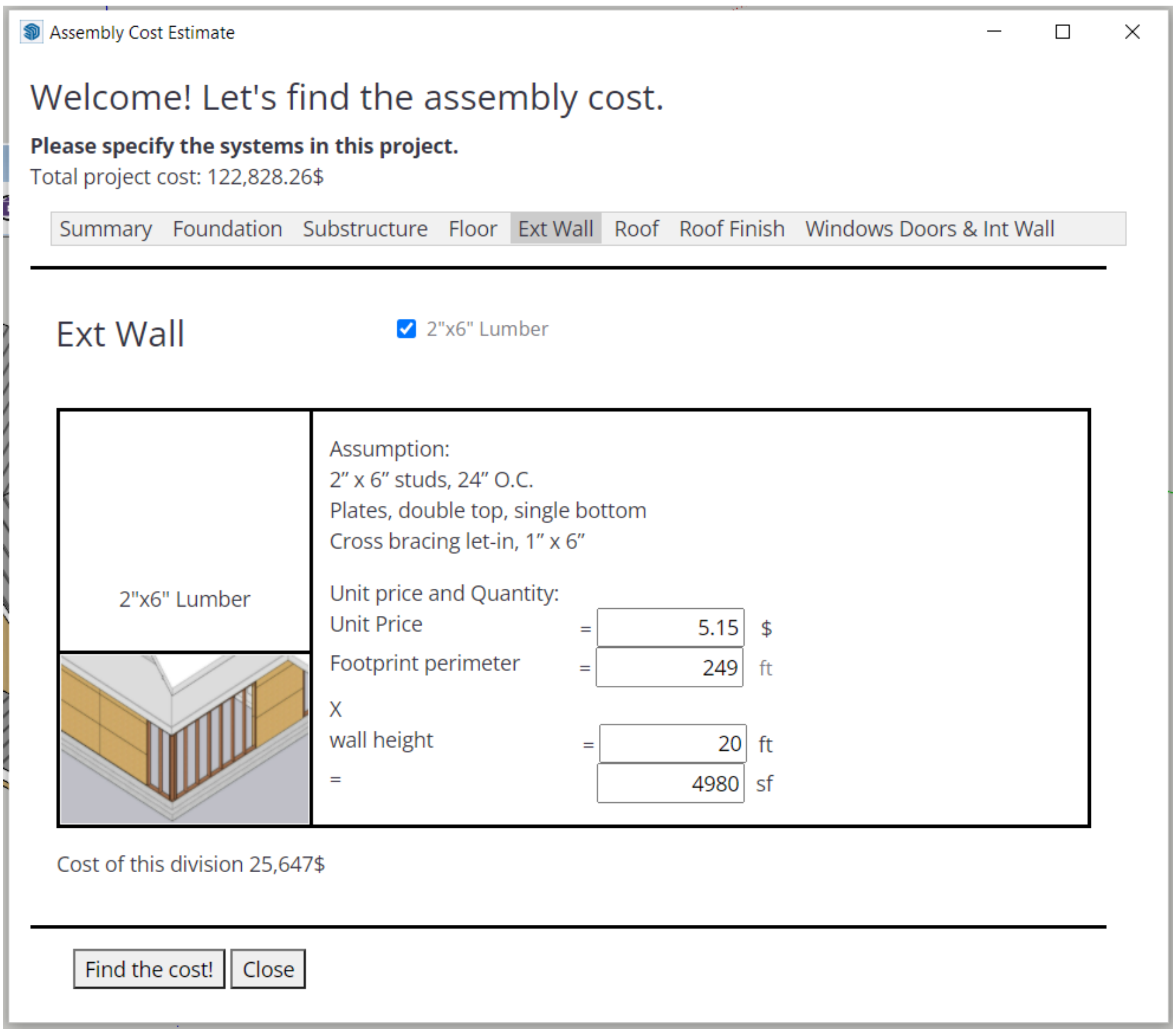

Figure 5.10. Tool's rationale in automatic CE is presented to user for user's overriding

5.3 Application Scenario 3: Evaluate design alternatives

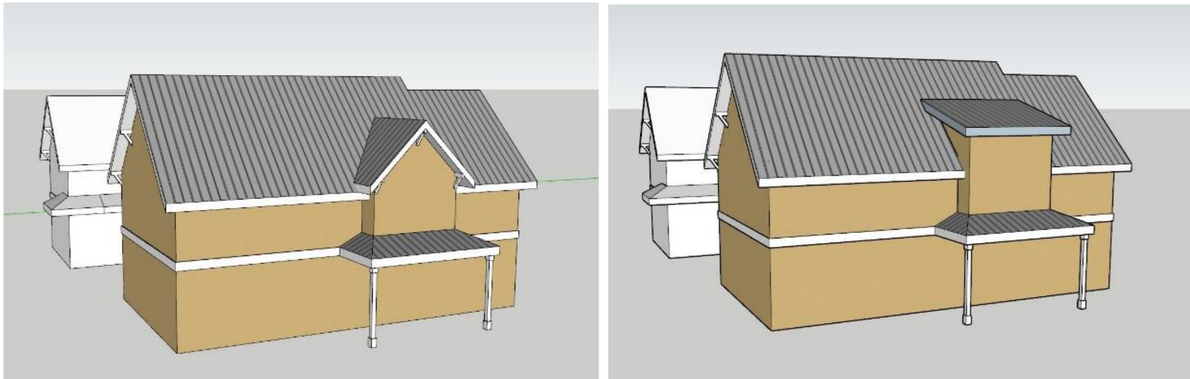

Figure 5.11. Alternative SFR designs

The images below show two different design explorations by an architect. In the early stage, the architect tries to find the best option for the roof above a house's entry. One design has a shed roof, while the other has a gable roof.

These two designs are distinguished by the differences in front wall and roof. Square-foot CE method cannot help in this case as both schemes have the same building square footage. Therefore detailed assembly analysis on the differentiated front facade becomes necessary.

Unlike the previous 2nd scenario where a whole building is analyzed, in this case, the user needs only a quick estimate on the two designs of the building's front facade. This is a common situation in schematic design – architects explore alternations on a certain part of the design. In this case, knowing the cost differences between design schemes can help the architect choose between different design directions.

In Cost Guru, the assembly-cost-estimate function can quickly perform scoped cost analysis on altered design elements. As the first step of this function, Cost Guru provides a handy paint method that lets the user quickly paint the subject geometries.

This function sets the scope and specifies building system at the same time. Then the tool focus on the painted geometry and provide QTO and estimate.

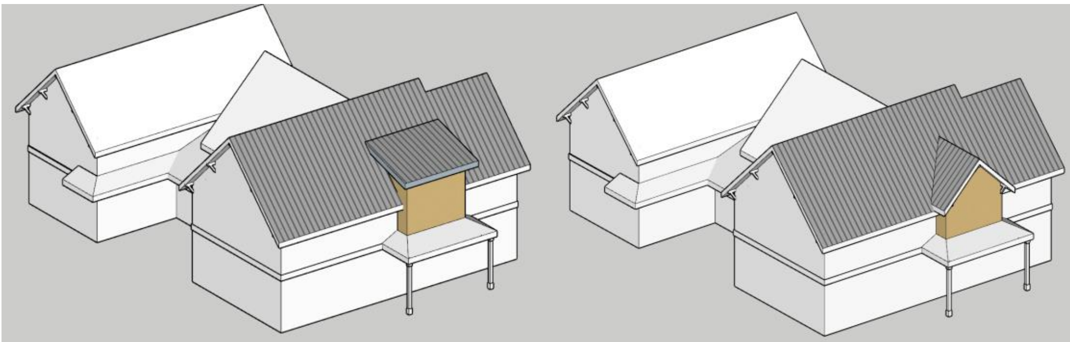

Figure 5.12. User paint subject geometries

As the results show, the building on the left would cost slightly less than the design on the right. The paint-estimate function allows architects to focus their cost inquiry on key design features and this quick cost feedback helps them quantitatively evaluate the design moves or find better cost-saving solutions.

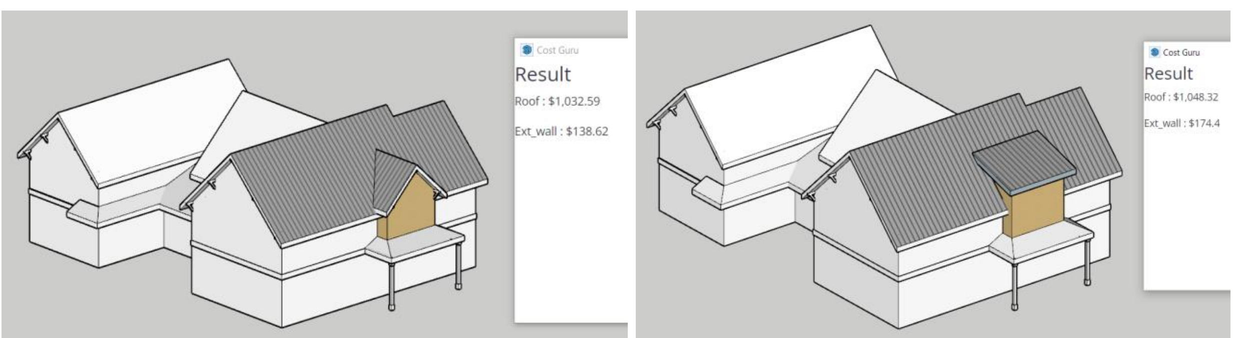

Figure 5.13. Cost Guru provides estimate results for designated geometry

Chapter 6 Conclusion

In this research, the author develops a tool to perform SFR cost estimates in the early design stage using the BIM tool Sketchup. Three cases of cost scenarios were demonstrated. Cost Guru improves this existing BIM tool by providing a simple and quick estimating tool. With geometry algorithm, it automates the traditional manual QTO process. Additionally this pre-built building knowledge provides default assumptions and handles specification scarcity in early design. Finally, the tool's cost database makes up for designer's inexperience in estimating construction cost. It promptly delivers cost advice to the user in the schematic design phase.

However, the limitations of the tool is also worth noting. It is solely for use with SFR projects in Pacific Northwest region. The tool also only considers the SFR structure and building envelop. With this limited scope, the author considers major cost factors that significantly determine final project costs. The accuracy of the tool is similar to existing schematic estimate methods but its values is in speed and convenience.

For further development, there are several research areas that would extend the tool's capability:

- Due to the limited type of SFR projects studied, the tool's knowledge framework is solely capable of estimating for SFR types in the Pacific Northwest. More project types can be studied to enlarge the tool's assembly knowledge. For a larger scope, the tool should include the assemblies of SFR in a broader spectrum, such as luxury custom homes, larger multifamily projects etc.
- The geometry-reading algorithm can also be improved. Currently the tool can read the building's footprint from a generic Sketchup model. Further research

work can focus on developing graphic algorithm that can automatically recognize other building features such as floor levels, roofs, etc. Those improvements on algorithm will make the automatic QTO more accurate.

- The tool references data from RS Means and The Guide. Their data is the most current because of the process of publications however it may still lag market conditions. Future research on building a current cost database to include real time market conditions could improve the tool's accuracy with more reliable cost data.

Bibliography

AESP "From Standard Estimating Practice" Sixth Edition, American Society of Professional Estimators, Bni Publications, Inc, 2004, ISBN 1557014817

Aram, Beetz, J., & Eastman, C. (2014). "Qualitative and Quantitative Cost Estimation: A Methodology Analysis." In *Computing in Civil and Building Engineering (2014)* (pp. 381–389). https://doi.org/10.1061/9780784413616.048

Gordian. "RSMeans Residential Cost Data, 2017." (2017).

Konchar, Mark, and Victor Sanvido. "Comparison of US project delivery systems." Journal of construction engineering and management 124, no. 6 (1998): 435-444.

Kulkarni, Aditi, Zofia K. Rybkowski, and James Smith. "Cost comparison of collaborative and IPD-like project delivery methods versus competitive non-collaborative project delivery methods." PhD diss., Texas A & M University, 2012.

Monteiro, A., & Martins, J. P. (2013). "A survey on modeling guidelines for quantity takeofforiented BIM-based design." Automation in Construction, 35, 238-253.

Niazi, Adnan, Jian S. Dai, Stavroula Balabani, and Lakmal Seneviratne. "Product cost estimation: Technique classification and methodology review." (2006): 563-575.

Rojas, Eddy M., and Ian Kell. "Comparative analysis of project delivery systems cost performance in Pacific Northwest public schools." Journal of Construction Engineering and Management 134, no. 6 (2008): 387-397.

Poli, C., Escudero, J., and Fermandez, R., 1988, “How Part Design Affects Injection-Moulding Tool Costs,” Mach. Des., 601, pp. 101–104.

Project Management Institute. (2019). "Practice standard for project estimating" (Second edition.). Project Management Institute, Inc.

Staub French, M.Fischer,e.a.JohnKunz, "A generic feature-driven activity-based cost estimation process, Advanced Engineering Informatics 17 (1) (2003) 23–39, (http://www.angelfire.com/ak4/ad5/escom/ac/lectura2.pdf).

Standard Estimating Practice Sixth Edition, American Society of Professional Estimators, Bni Publications, Inc, 2004, ISBN 1557014817

The Guide© Building Construction Material Prices 2021, https://www.rsmeans.com/products/books/2022-cost-data-books

Wang, Xin-Zheng, et al. “Application of Neural Network in the Cost Estimation of Highway Engineering.” *Journal of Computers*, vol. 5, no. 11, 2010, https://doi.org/10.4304/jcp.5.11.1762-1766.

Appendix – Source Code of Cost Guru

The source code of the app, Cost Guru, can be found in the GitHub repository:

https://github.com/wencheasin/Cost-Guru