

**Design Change Management in Construction Projects Using Building Information  
Modeling (BIM)**

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## **ABSTRACT**

### **Design Change Management in Construction Projects Using Building Information Modeling (BIM)**

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Scope changes in construction can vary, and among all types of changes, design change by owner is the type that most often threatens a project with failure. Design changes requested by owners include additions, deletions and/or modifications to the original scope of the work. Design changes frequently impact project cost and time and have the potential to increase the possibility of conflicts between owners and contractors. Project time and cost change impact can become severe if owners do not consider the fact that a change in one part of the project may cause a series of changes in other parts of the project, which is known as the “change ripple effect.” Therefore, for the well-organized delivery of construction projects, it is essential to have an efficient design change management system. The fundamental objective of any change management system is to eliminate any unnecessary extra costs and time delays to the original contract. Therefore, there are two main factors to effectively manage design change: first, identifying the ripple effect of the design change on other project components, and second, quantifying the ripple effect of a change on project cost and time. Limited work has been conducted in this area and no integrated model has been developed that would be able to visualize, identifies and quantifies the above-mentioned factors. This thesis presents an automated model named BIM-Change for design professionals and owners that make it possible to visualize the ripple effects of owners’ design changes. The developed model calculates

the impact of design changes and their ripple effect on a project's total duration and updates the project schedule accordingly. It then estimates the impact of design changes, and their ripple effect, on project cost. The cost data provided by the developed model would be the updated project total cost including direct cost, indirect cost and impact cost. As result of the proposed model, the computer program called BIM-Change was developed using the "Visual C#. Net" programming language. This program consists of six add-ins: Check Change, Ripple Effect, Room Grouping, Time Impact, and Cost Impact, Data Filtering. The model has been applied to a case study to demonstrate its usefulness, illustrate its essential features, and facilitate its evaluation. The result validated the advantages of the BIM-Change over the available software such as Vico, Innovaya, Autodesk Navisworks, Synchro and Assemble.

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*This Thesis Is Dedicated To*  
*Gender Equality and Women's Empowerment*

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# Nomenclature

AEC	Architecture, Engineering and Construction
EPC	Engineering, Procurement and Construction
BIM	Building Information Modeling
CAD	Computer Aided Design
IFC	Industry Foundation Classes
2D	Two Dimensions: x, y
3D	Three Dimensions: x, y, z
4D	Fourth Dimensions
5D	Fifth Dimensions
WBS	Work Breakdown Structure
B/C	Benefit-to-Cost
REP	Request for Proposal
PMBOK	Project Management Body of Knowledge
DPM	Dynamic Planning and Control Methodology
DSM	Dependency Structure Matrix
EWS	Early Warning System
CBR	Case Base Reasoning
CCT	Change Control Tool
CCS	Change Control System
KNN	K Nearest Neighbor
CBR	Case Base Reasoning
KBDS	Knowledge-based Decision Support System

NBIMS	National BIM Standard
QTO	Quantity Takeoff
LP	Loss of Productivity
API	Application Programming Interface
Q	Quantity
LH	Labor hours
MPP	MS Project Program
CSV	Comma Separated Values
DES	Discrete Event Simulation
PI	Process Interaction
AS	Activity Scanning
EPPMS	Electronic Product and Process Management

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# Chapter 1: Introduction

## 1.1 Background

It is general knowledge that construction project owners have become more and more demanding, continuously changing their project's design. Responding to market demands, they request changes at any phase of a project (Ibbs, 2012). Even years ago, studies revealed that 20-25% of the construction period is lost as a result of inadequate design (Undurraga, 1996). Also, lower quality level construction projects could be 78% attributable to design change requests (Koskela, 1992). Change is considered as any addition, deletion or modification to the scope of a project that may cause the project to incur delays and adds extra costs to the original contract. As such, it can take many forms; however, it is the owner-acknowledged change that must receive more attention than the other types of change since this type can present a risk to owners and contractors. In the mind of owners, a change could be something very simple, but that perspective (most likely) does not consider the multiple effects one change may have on many other areas of the project. Each change could add to the cost of the original contract and cause delays in the project execution, while there could also be cases where a change requested would not add to the project's cost and time. Some changes can even be beneficial to owners and contractors, but that situation is rather rare.

Therefore, a system that can evaluate changes concerning time and cost would be a valuable tool in the construction industry. Owners should be involved in their project, and the role and responsibility of an AEC team are to provide guidance, giving owners assessments of each requested change and its impacts on the project. If this system could support visualization capabilities to illustrate the impact of the contemplated change, then



the owner would be able to see the big picture and make better and well-informed decisions. This system could also help avoid unnecessary conflicts and disputes between owners and contractors, and greatly reduce recourse to lawsuits.

Having a successful management system for applying, visualizing, analyzing, and organizing changes requested by owners would be a clear advantage. Dealing with changes in traditional fashion, namely using paper-based printouts of 2D drawings is no longer sufficient, as it is not possible to discover all ramifications of a contemplated change. This problem is addressed by the development of Building Information Models (BIM) by providing dynamic databases. BIM makes it possible to apply a change to a model and to get new information about the impacts of that change in the design model in every view. In other words, it can self-adjust the model's database whenever a new change is applied to the model. However, the problem is that the user is only able to see a change, and the newly-affected model, but not the ripple effect of that change. Current BIMs only visualize the new model design, but do not highlight the components affected by the changed components.

In order to understand the impact of change on time and cost, there must be a link between the 3D model, project cost estimation and time scheduling databases. BIM represents that link with a 4D model (scheduling) and a 5D model (cost estimation). It takes considerable skill to create a link among different software interfaces and to provide a BIM all of these dimensions. As such, a more user-friendly software program is needed, one with the ability to generate all of these dimensions, 3D/4D and 5D, under one domain. This would make it possible to visualize the change ripple effect and analyze the cost and time impacts in a quantitative manner, before starting the construction phase.

Therefore, an integrated BIM-based change management system is needed to assist effective management of a multi-disciplinary model through the dynamic procedure of building design.

## **1.2 Problem Statement and Research Motivation**

The construction industry is well known for a high number, scale, and variety of serious conflicts due to owner-requested design changes. Changes are the major cause of project failure (Arain F. M., 2008). Most of the time, owners do not realize the consequences of the changes they are requesting from the contractors, and they invariably blame contractors if a project is faced with any disputes or claims. Hallock (2006) states that changes in the construction process causes difficulties among all the parties involved in the project and increases the probability of contractual disputes. Project changes have visible impacts on the project construction process; they affect the project schedule, cost, productivity, overall project performance, as well as cause ripple effects. Time and cost are of critical importance in today's construction market. Hallock (2006) states that changes to project drawings affect project contract price and/or schedule. Upon receiving any owner-requested design changes, designers should give prompt feedback about the ripple effect of design changes on the project cost and schedule. This action is needed before the project owner makes any final decisions regarding the requested changes to the project's design. However, present-day change management methods are usually more focused on managing the change impact on project's labor productivity, and less on considering their impact on project time and cost. It is even less likely for current methods to consider the ripple effect of change in other parameters of the project.

Current approaches that rely on 2D project drawings are not sufficient enough to evaluate and analyze the impact of requested changes. With projects becoming increasingly complex, the impact analysis of design changes is also becoming much more challenging and time-consuming. These challenges have served to enhance the role of Building Information Modeling (BIM) in today's construction industry. BIM allows real-time coordination of information in every view by combining a design model with a behavioral model (Autodesk, 2010). The design model consists of the project geometry and data. A behavioral model can be a change-management model since BIM has the potential to control changes through its dynamic process of building design. However, as Langroodi (2012) observed, "dynamic data are processed reasonably well in a single BIM, with all the necessary parameters explicitly defined. Changes across inter-related multidisciplinary designs that reside in a federated environment are significantly more challenging to manage." However, many BIM projects still rely on paper-based printouts of 2D drawings that make it very difficult to see what is being changed in the model. An effective project change management system is needed to control and manage these changes. This system should be able to trace and visualize project changes, along with an analysis of their impacts on project cost and time. The growing popularity of using BIM in the construction industry while still lacking a cumulative change management system underscores the need to improve BIM-based change management systems. Effective management of multi-disciplinary models is needed throughout the dynamic process of building design and construction. This thesis presents an integrated BIM-based automated model for design professionals and owners. The goal is to visualize the ripple effect of design changes on other project systems, along with the analysis and estimation

of a design change's impact on project cost and time, to assist owners and designers in making appropriate decisions. The motivations for conducting this research are lack of an automated and quantitative BIM-based change management model for construction projects that can automate the process of owner-requested design change impacts' analysis on the project cost and time, lack of visualization for analyzing the design changes' ripple effect and tracking of the consequences; and lack of communication between project owners and designers, in selecting beneficial changes that respond to the owners' desired criteria.

### **1.3 Research Objectives**

This research aims to develop an integrated automated BIM-based model for visualizing the ripple effect of design changes originating from project owners and then analyzing these changes impacts on project time and cost to support more informed management decisions. A set of tools and techniques are integrated into a model to provide this capability in a user-friendly manner. This will be achieved through the following objectives:

- To study the ripple effect of design changes and develop a system for managing these changes in construction projects using BIM;
- To provide and improve the visualization capabilities of design change ripple effects;
- To automate the quantification of design changes' impacts on project time and update project schedules; accounting for the impact of design changes; and
- To automate the quantification of design changes impact on project cost.

## 1.4 Research Organization

Figure 1-1 illustrates the methodology to be followed in order to achieve the above-mentioned objectives. The methodology is summarized in five stages: analysis, design, computer implementation, validation, and conclusion stage. The analysis stage begins with a problem statement and the definition of the objectives (Chapter 1). It then focuses on performing a comprehensive literature review in the following domains (Chapter 2):

- Construction changes; and
- Building information modeling.

After the analysis stage, the gaps and limitations in the current literature are identified (Chapter 2), and the design phase (Chapter 3) is developed to respond to these limitations. The proposed model consists of four frameworks:

1. Data acquisition framework;
2. Data analysis framework;
3. Reporting and highlighting framework; and
4. Data filtering framework.

These frameworks are elaborated in detail in the development stage. After data collection has been conducted in the implementation stage, the model framework can be designed and validated through its application in a case study (Chapter 4). Finally, highlighting the conclusions, the research contributions and recommendation for future work (Chapter 5).

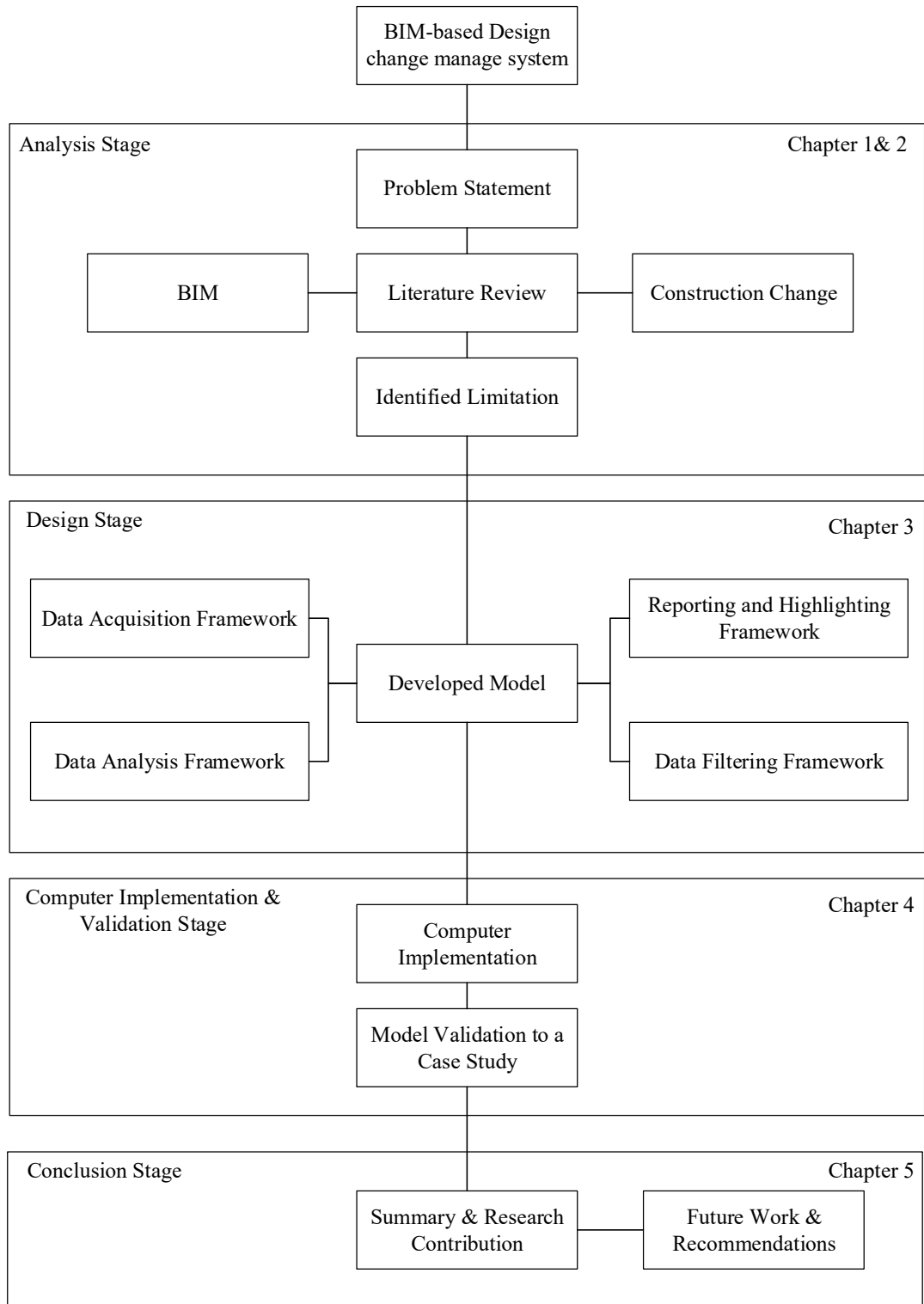


Figure 1-1: Research Methodology

## **Chapter 2: Literature Review**

In this chapter, a comprehensive literature review is performed on domains of construction changes and Building information modeling. Changes occur in all construction projects and cannot be avoided or disregarded. Changes are mostly initiated from the owner's side during the design and construction phases of the project since they drive the project to be up-dated according to market demand and new technologies. When a change is initiated, some modifications are required to the project design and specifications. Therefore, AEC teams should start doing revisions on project plans and specification and try to apply the change and see its consequences. Any misunderstanding at this stage may face the project with failure concerning meeting the project constraints, such as cost, time, and quality. In 2006, a group of professional engineers conducted a survey and identified change as the major cause of project failure (Hallock, 2006). Change should be considered as a primary source of construction projects' cost overrun. It may cause delays and lack of quality, and this can be the case in any different phases or areas of the construction project (Burati J.L, 1992). Any added cost to project contract and any delay to the project might become the main cause of conflict between project parties. Vandenberg (1996) observed that knowing the cost impact of changes reduces disputes between owner and contractors.

### **2.1 Definition of Change in the Construction Industry**

In the construction industry dealing with changes is not only a matter of applying and accepting the changes; any change might bring about many losses to the project, and as the project gets bigger, the more complex the effect of the change. Many authors have come out with different definitions regarding construction change.

Until 1990, the construction industry described changes as modifications, differences, subtractions, additions, or exclusions of work (Antill, 1990). Ibbs et al. (1995) stated that change is described as any event that results in an alteration of the project's original scope, and that also may impact a project's time, cost, and/or quality of work. Coffman (1996) added that a change to the project might cause additions, deletions or revisions in the project that lead to adjustments in the project's contract sum and time. CII 2000 defines change as any action initiated by the owner, owner's agent or design engineer that result in a project's adjustment. Hanna et al. (2002) stated that change is an event that may modify the original scope of the project and affect project's time and/or cost. Mokbel (2003) described change as an action that indicates and aligns a change to the project's scope that modifies the original time and total cost needed for the project's completion. Later, Ibbs (2005) defined change as any variation to the original scope of work that can be classified as a physical or unphysical (less tangible) change. Physical change is related to the project unit of work, while unphysical change belongs to a reporting requirement or adjusting the project schedule. Change is a request to the contractor, initiated by the owner, that modifies the project work, leading to an adjustment in the project cost and/or time (Hallock, 2006). Meanwhile, Sun and Meng (2009) declared that change in construction projects indicates to any variation to the projects' design, database, scope of work, project and any other project characteristic caused by the requested change. In this research, change is considered as any addition, deletion or modification on the original design drawings, plans, and documentation requested by the project's owner.



## 2.2 Cause of Changes in a Construction Project

All the participants of a project, such as owners, designers, and contractors, can be the cause of the changes by requesting any modifications after signing the contracts. Cox et al. (1999) investigated several successful projects' requested changes, analyzing historical data as case studies and discovered the reasons of change as follow:

- Designer's omission in tender documents;
- Coordination defects in tender documents;
- Forced upon project from shop drawing coordination;
- Employer has changed his requirements; or
- New information on existing site conditions.

According to Arian et al. (2006), changes happen due to several predictable and unpredictable causes. They identified four origin agents for the changes in the construction project, including:

1. Owner-related changes: changed that is requested by the owner of the project with the purpose of achieving the project objectives that they have in their mind;
2. Consultant-related changes: originating from consultants whenever they have a request out of the scope of the original contract;
3. Contractor-related changes: changes requested by contractors when they cannot deliver the project requirements according to the original plans; and
4. Any other changes that do not come directly from project contributors.

Based on the above classifications, Arian et al. (2006) have also categorized "Change Causes"; Table 2-1 illustrates this classification.

Table 2–1: Change Origin and Causes (Arain and Low Sui Pheng, 2006)

Change Origin				
Change Cause	Client Generated Changes	Consultant Generated Changes	Contractor Generated Changes	Other Changes
	Change of scope	Change in design Errors and omissions in design	Lack of contractor's involvement in the design	Change in government regulations
	Change of the project schedule	Conflicts between contract documents	Unavailability of equipment	Weather changes
	Owner's financial problems	Inadequate scope of work for a contractor	Unavailability of skills manpower	Change in economic conditions
	Inadequate project objectives	Design complexity	Contractor's financial difficulties	Unforeseen problems
	Replacement of materials	Inadequate shop drawing details	Defective workmanship	
	Change in specifications	Lack of consultant's knowledge of available materials and equipment		

Based on various literature and questionnaires conducted through the course of their research, Mohammad et al. (2010) ranked the major causes of the change, the results of which are shown below:

1. Change of plan by owner;
2. Substitution of materials;
3. Change in design by consultant;
4. Errors and omissions in design;
5. The scope of work for a contractor is not well defined;
6. Conflict between contract documents;
7. Differing site conditions;
8. Change of plan by client;

9. The lack of coordination between contractor and consultant;
10. The contractor's financial difficulties;
11. Owner's financial problems;
12. Workmanship or material is not meeting the specification;
13. Contractor's desire to improve his financial situation;
14. The required labor skills are not available;
15. The required equipment and tools are not available;
16. New government regulations; and
17. Weather conditions.

After a cumulative investigation of causes of change in public construction projects in Oman, Alnuaimi et al. (2010) came up with 24 items:

1. Owner instructs additional work;
2. Owner instructs modification to design;
3. Non-availability of construction manuals and procedures for project construction in Oman;
4. Non-availability of engineering licensing for engineers in Oman to maintain the quality of consultancy services;
5. Poor communication between relevant governmental units and the owner;
6. Non-availability of overall project planning;
7. Unrealistic design periods;
8. Unrealistic construction schedule;
9. Owner fails to make decisions or review documents at the right time;
10. Low consultancy fee or less experienced designers;

11. Non-availability of records of similar projects in Oman;
12. Failure by the consultant to provide adequate and clear information in the tender documents;
13. Natural growth of the project was not anticipated at the design stage;
14. Owner's needs during the design stage are unclear or not well-defined;
15. The contractor uses the gray areas in general conditions and request variations to the contract;
16. Design errors;
17. The design and construction criteria are outdated and do not suit the present construction technology;
18. The contractor misses variations instructions;
19. Non-availability of qualified engineers from the owner side;
20. Consultant not familiar with the regulations and construction permits in Oman;
21. Unilateral decisions made by the owner without proper considerations to the contract;
22. Consultant's supervisors do not have collective experience about construction projects in Oman;
23. Failure by the consultant to perform design and supervision effectively; and
24. Poor project management by contractor.

Throughout their research, Alnuaimi et al. (2010) also found that major causes of changes were:

- The client's additional works;
- Modifications to design; and

- Non-availability of construction manuals and procedures.

According to the literature above, if the cause of change is classified according to the parties involved in the project, in other words by those responsible, the owners and their requests are the primary cause of changes in construction projects. Owner-initiated changes can lead the project to massive failure and losses since any change to original plans by owners may bring up scope change and lead to additional work. Changes to the original scope of work and design are responsible for 50% of changes reported (Pruitt, W. Bruce, 1999; Weston Hester, 1991). Design changes are a contributing factor to redoing work (Han et al., 2013; Zhang et al., 2012). This study considers owner-initiated design changes to the project, since according to the literature; they are the most common major cause of change in construction projects.

### **2.3 Type of change**

Knowing the type of the change is important in determining which change should receive an action first, and is a way of prioritizing changes in construction projects. According to the engineering, procurement and construction (EPC) contractor, there are two types of changes in detailed design: a “design development” initiated by the engineering team, and a “design change” initiated by the client (AkerKvaerner, 2005). Hunt (2005) categorized change into three different types:

- Actual change: any change to the scope of work directed by the owner of the project;
- Constructive change: any action and/or inaction directed by the owner that modifies the design scope, but the owner does not recognize it as a change; and

- Cardinal change: it will be recognized in the federal sector of the contract (Hunt, 2005).

Mirshekarlou (2012), on the other hand, classified changes into whole other four types:

- Beneficial or Detrimental Changes: “beneficial” changes are those that improve the quality of the job, decrease the cost and time, and sometimes the level of complexity in the project design. In contrast, “detrimental” changes are those that decrease owner benefits. However, sometimes one change can be “beneficial” for the owner but be a “detrimental” change for the contractors, or vice versa. In general, the “beneficial” changes must be supported, and the “detrimental” changes must be avoided. The timing of the change is the only way to help the project team to distinguish the “beneficial” change from “detrimental” change. If a change occurs in the early stage of the project, it might be considered “beneficial.” The same change, when it occurs closer to the end of the project, might be “detrimental,” since it can face the project with an additional cost, time, or both.
- Required or Elective changes: “required” change is obligatory due to the nature of the problem and should be evaluated and processed. For instance, matching the design variations with building codes needs an instant action. On the other hand, “elective” changes are not compulsory. When the project team has many alternatives for change management, the change is considered “elective.” These alternatives differ regarding their impacts on the contract cost and time. In order to select the best “elective” change, a benefit-to-cost (B/C) ratio scale is applied.

- Compensable, Excusable or Non-excusable changes: the project's owner in response to its needs or required modifications in the project suggest "Compensable" changes. For example, design changes by the owner caused by market demand. The consultant proposes "Excusable" changes in reply to technical problems or possible document errors. For instance, the implementation of the structure for controlling the landslides is "excusable" change, which has to be paid to the contractor, and there is no payment for a consultant. "Non-excusable" changes are entirely the responsibility of the contractor and there would not be any payment for them. An example of this change would be construction errors that lead to redoing work or demolition.
- Controllable or Uncontrollable changes: "Controllable" changes are those where the source of their cause is under the control of the contractor, such as labor productivity or material procurement. The contractor is the only person responsible for "controllable" changes and cannot ask for extra funds. "Uncontrollable" changes are those where the contractor has no effective control of them, such as weather conditions, inflation, and unforeseen ground conditions.

This study uses owner-requested actual and elective design changes in order to aid owners to choose the most beneficial design changes to the project, which have the lowest impact on project parameters such as cost, time and productivity.

## **2.4 Time of Change**

Any above-mentioned type of change could happen during any phase of the construction project and impact the project, but not all in the same way. A construction project is divided into several phases, and together these phases define the project life

cycle. In general, a construction project has three phases, namely project conception, project design, and project construction. The conception phase is the time when designers put in the effort to get to know the owner's desires, demands, and what they expect to see at the end of the project. The design phase is the phase when designers start to find a way to satisfy the owner and reply to all their requests by creating drawings. The construction phase is when the project design and concept become a reality.

According to Ibbs (1994), later change requests in the project will affect the project's overall performance in comparison to changes applied earlier in the project. If the problem is reviewed as early as possible, CII (1994) states that changes can be reduced due to problem identification, resulting in beneficial changes. After investigating 104 projects from 35 contractors, Ibbs (1995) found that late project changes are implemented less effectively than early project changes. Ibbs (1997) also deduced that it is considerably more beneficial to identify changes in the early stages of the project and manage them immediately after initiation. After collecting numerous data and statistical relationships from 14-page questionnaires, Ibbs (1997) validated the hypothesis that a late change is more disruptive to labor productivity than an early change. Similarly, Hanna (1999), after interviewing the industry, concluded that changes suggested late could lead to greater losses. Therefore, the timing of the change request makes all the difference in change impact analysis. Understanding the impacts of the change in any phase of the project is the only key to help the project participant choose the most beneficial changes to the project and avoid all the detrimental changes.



## **2.5 Impact of Change**

A change can have impacts on any part of the project and leads to scheduling conflicts, cost overruns, or both at the same time. It can also affect the quality of work, labor productivity, cause legal disputes, and in general affect the overall project performance. According to Arian (2005), changes have impacts “on the cost, time, productivity, quality, health and safety, hiring new professionals, delay in payment, rework and demolition, tarnish a firm’s reputation, poor professional relations and disputes among professionals.” For Mirshekarlou (2012), some of these impacts can be “measurable” effects like direct costs or time overruns, while some of them can be “immeasurable,” like moral effects of change or quality defects.

Changes can have positive or negative impacts on a project, depending on the level of the change, but mostly it has negative effects. The main idea, however, is that these impacts should be known before approving and applying any changes to the project. In current practices, the impact of a change is usually classified as a “direct” or “indirect” impact. According to Mirshekarlou (2012), direct impacts are the first and main effects of change, such as additional costs due to design changes. An indirect impact exists on the condition of the existence of a “direct impact.” In other words, the indirect impact is contingent on the direct impact. For instance, the direct impact of a design change is an additional cost to the project. This cost may result in a claim between the owner and the contractor, which would be the indirect impact of a design change. Some of the direct and indirect impacts of changes are summarized in table 2-2.

Table 2–2: Impacts of the Change (Mirshekarlou, 2012)

Impacts of the Change	Direct	Indirect	Direct & Indirect
	Addition or deletion of work	Ripple Effect Impact	Revisions to project reports and documents
	Direct costs of resources and administration	Loss of productivity	Rework and lost effort on work already done
	Time extension and delays	Change in cash flow	Reprogramming
	Quality changes	Overhead costs	Loss of earnings
	Re-scheduling and re-organizing	Acceleration	Loss of rhythm
		Inefficient use of resources	
Time lost in stopping and restarting current tasks in order to make the variation			
Financing costs			

Some of the direct and indirect impacts mentioned are measurable, and some are not or hardly possible to estimate. Out of all of the above factors, change impact on project cost, time, and quality is the most important ones that should be forecasted in every type of change. Apart from the direct impact of the change on cost and time, there is significant indirect impact created by changes, and this impact is called the ripple effect. A ripple effect happens when a single change in an action or event spreads the impact of that change and escalates it to a series of consequences. In other words, a small change in one part of the project causes a series of the changes in other parts of the project. Change ripple effect is also known as the cumulative impact. Change in any item, activity, or event might have an impact on another item, activity, or event, which is in its direct connection.

Mirshekarlou (2012) describes how a change might have a “single” or a “cumulative” (ripple) effect on the project features. A change single effect has an independent impact on a specific project characteristic without affecting other project characteristics. Conversely, a change cumulative (ripple) effect has several impacts on the project, affecting numerous parts of the project. Ibbs (1995) stated a change cumulative effect increases proportionately to the number of project changes. According to CII (2000), the problem intensifies when multiple changes are initiated into the project. In addition to identifying the ripple effect of the requested change, knowing its impact on project time and cost is also necessary for the change impact analysis process. Change impact on time is also known as a delay to project schedule. It means time overrun beyond the completion date, which is signed to the original contract by all parties. Delays bring modification to the project schedule and require specialized experience and knowledge to change the schedule according to days added. Some changes may add more days to the schedule, and some may deduct some days. The time impact may be beneficial to the project and causes it to end sooner than the date expected. However, in the opposite scenario where the project does not finish on time according to the contract date signed before the construction phase, severe conflicts and disputes may arise between project parties. Mirshekarlou (2012) states that delay is “major variation to the project planned schedule which is very common in construction projects. Delay causes the owner faced with financial losses due to the project late operation and contractor loaded with a delay due to higher overhead costs and potential inflation of material, equipment and labor prices.”

Some researchers have put in the effort to demonstrate that changes are the main cause of project delays and support their claim by investigating real projects. After reviewing Hong Kong's various construction projects, Kumaraswamy et al. (1998) found that 50 percent of the projects surveyed suffered delays that originated from changes. Assaf et al. (2006), after studying construction projects in Saudi Arabia, found that 70% of the construction projects faced time overruns. As such, they concluded that changes were the most frequent source of delay. When a change impacts the time, it also impacts the cost. Cost and time impacts of change are directly and mutually co-related. The change impact on project cost could be positive or negative to both the owner and contractor. In addition to the type of project contract in some cases, it is a win-win situation for both, and sometimes only one side gets all the benefits, and one side has to deal with the losses that result from the change. Another scenario could be that the change does not have any cost impact to either the owner or the contractor.

This is usually not the case since almost always most construction projects are at risk of cost overruns during every phase of the project. Change is considered as a kind of risk to all project participants including owners and contractors; the contractors consider a markup in the case of change contingency to cover cost overruns, and the challenge begins when the cost overruns exceed the markup. Many disputes between owners and contractors arise during negotiations regarding the price for a change. The owners almost always assume the contractor just wants to benefit from change request, and the contractors think the owner wants to apply changes without accepting new costs. Therefore, to reduce the negative impact of change on project, an applicable change management system or guideline is required to protect the project and to avoid facing

irrecoverable damages and losses. As such, to have a successful project, a system for managing the diverse consequences of change requests is fundamental.

## 2.6 Change Management Process

The construction industry should understand the necessity of having an organized change management process. Streamlining the change management process can reduce the time and cost of processing changes (Du, El-Gafy, & Zhao, 2015). For Tiong (1990), “a change management process should be established for the ultimate benefit of owners.” According to Sun et al. (2006), the purpose of project change management is not to remove project changes but to reduce the undesirable impact of essential changes and to prevent redundant ones. Mirshekarlou (2012) stated that having a change management process throughout the project development helps the efficient establishment of the presented change events and minimization of future changes. Also, it aids project participants to be able to decrease detrimental changes and reassure constructive changes, which also increase the project work performance and the chance of project success. Managing change is required in every phase of the project, and it differs from one stage of the construction project to another. CII (1990) and Arian (2005) provided change control tools for every stage of the project. The summary is shown in Table 2-3.

Table 2–3: Change Management for Different Project Stages (CII 1990, Arain 2005)

	Design Stage	Construction stage	Design-Construction interface stage
Change	Review of contract documents	Clarity of change procedures	Prompt approval procedures
	Freezing design	Written approvals	Ability to negotiate change
	Value engineering at conceptual phase	Change scope	Valuation of indirect effects
	Involvement of	Change logic and	Team effort to control

management	professionals at initial stages of the project	justification	changes and coordination
	Owners involvement at planning and design phase	Project manager from an independent firm to manage the project	Utilize work breakdown structure
	Contractor's involvement at planning and scheduling process	Restricted pre-qualification system for awarding projects	Control the potential for changes arising through contractual clauses
	Thorough detailing of the design	Owner's involvement during the construction phase	Comprehensive site investigation
	Clear and thorough project brief	Avoiding the use of open tendering	Use of collected and data compiled by owner, consultant and contractor
	Reducing contingency sum	Use of project scheduling/management techniques	Knowledge-base of previous similar projects
		Comprehensive documentation of change	

Many authors have tried to understand how this system can be more practical so that project participants can get the best out of it. McCally (1997) introduced nine keys for effective change management for use by both contractor and owner. With the benefit of reducing the impact of changes:

1. A clearly defined processing methods;
2. Supervision of processing methods;
3. Clear instruction regarding the scope of changes;
4. Timely issuance of a request for proposal (RFP) to the contractor or owner;
5. Timely response by the contractor or owner to RFPs;
6. Timely review of the contractor's or owner's proposals;
7. Timely issuance of work authorization;

8. Timely performance of the changed work; and
9. Prompt payment for change work.

McCally (1997) also added four other points that contractors and owners should pay attention to:

1. Evaluation of change time impact: owner and contractor should be aware of the possible amount of extra time that might add to the project due to the change;
2. Having a documented scope of change: modified work must be clearly defined and reviewed carefully by all parties in order to prevent potential disputes;
3. Evaluation of change costs impact: the cost of change should be discussed between all parties and in this way, conflict can be reduced. The change cost includes direct cost and indirect cost as well as mark-ups in the change proposal; and
4. Forward pricing on changes: this technique helps the owner and contractors to reach an agreement on any potential cost and schedule impact and plays the role of insurance.

At the end, McCally (1997) recommends four guidelines for efficient change management:

1. An organized process for dealing with changes;
2. A process that considers all the steps, and all the participants involved;
3. A process that is executed timely; and
4. A process to provide equitable treatment for both owner and contractor (McCally, Bob M., 1997).

Conversely, Doran (2002) introduced six steps towards good change management:

1. Gathering historical change data;
2. Gathering supplier feedback;
3. Sorting and preliminary analysis of data;
4. Statistical analysis of finding data;
5. System revisions formulation and report; and
6. Implementation

By having these key guidelines, a professional would be able to create an effective change management process to manage change and control its impacts. There are a number of publications and guidelines available to support change management. Voropajev (1997) defined change management as “an integral process related to all project internal and external factors, influencing project changes; to possible change forecast; to the identification of already occurred changes; to planning preventive impacts; to coordination of changes across the entire project.” According to Sun et al. (2006), the objective of change management is to predict possible changes, recognize changes that have already happened, plan preventive impacts and manage changes throughout the entire project. Similarly, AkerKvaerner (2005) defined change management as an overall work process that includes the proactive measures required to reduce the volume of changes, and to ensure that the cost, schedule, and quality are under control, as well as the evaluation and implementation process. A change management process is a combination of several qualitative steps that all together make the process work and guide the user how to process changes once they happen. These steps guide the



change management process from the time the change is initiated to the completion of the project. For Mirshekarlou (2012), the main concept of any qualitative change management process is to predict, identify, assess, resolve, record, and learn from changes and conflicts in a way that supports the overall project priorities. CII (1994) introduced the change management process principle:

- “Promoting a balanced change culture”: this means agreeing on ‘beneficial’ changes to proceed and meanwhile preventing ‘detrimental’ changes;
- “Recognize Change”: all the parties in the project should be in a good communication and relationship and try to identify the potential changes;
- “Evaluate Change”: project participants should try to figure out that the requested change could be classified as a required change or elective change. Required change should get an immediate action, and elective change is possible to be omitted;
- “Implement Change”: project participants must implement changes on the schedule and have a procedure for the changes’ documentation (to follow the change impacts) and authorization. “Authorization assures that all parties have been communicated with regarding the change”; and
- “Continuously improve from the lessons learned”: this means learning from the lessons achieved by the previous projects. “From the outset, project strategies and philosophies should take advantage of lessons learned from past similar projects.”

Based on the author’s experiences of project changes in Russia’s unstable environment, Voropajev (1997) introduced the function of Change Management in Project Management Body of Knowledge (PMBOK). The author insists that “Change

Management” should be presented as a “Key Integrative PM function.” Table 2-4 shows the overview of the author’s proposed change management system.

Later, PMBOK created the “Integrated Change Control Process,” shown in Figure 2-1. It includes the following change management procedures:

1. Identifying that a change is likely to occur or has occurred;
2. Influencing the factors that circumvent integrated change control to ensure that only authorized changes are executed;
3. Reviewing and approving the requested changes;
4. Managing the approved changes when they occur, by regulating the flow of requested changes;
5. Maintaining the integrity of baselines by releasing only approved changes for incorporation into project products or services, and maintaining their related configuration and planning documentation; and
6. Reviewing and approving all recommended corrective and preventive actions.

Table 2-4: Overview of Change Management (Voropajev, 1997)

Change Management			
Change Forecast and Detection	Project Protection Plan Development	Plan Execution	Change Control and Result estimation

<p>1. Project context changes Political factors Legal aspects Social factors Economic factors Finance. Tax. Tariffs Ecology Institutional aspect Other external factors</p> <p>2. Project parent organization changes Property relations Development concept Status and structure Behavior and cultures Production systems Infrastructure Management and communication systems Other</p> <p>3. Change of project Scope Quality Time Cost Contract/ procurement Risk Human resources Communications</p> <p>4. Project process changes Project plan system Overall change control Project plan execution Project documentation</p>	<p>1. Current status and tendencies monitoring Data gathering Status analysis Change probability evaluation Impact evaluation</p> <p>2. Preventive measures Cooperation with governmental bodies Public relations Forming demands Other</p> <p>3. Internal protection measures Guarantees Insurance Liabilities Inventory Other</p> <p>4. Project change plan Objectives configuration Quality specification Schedule Budget Contract/ procurement Project team System of information and documentation Risk events Other changes</p>	<p>1. Change procedures Requirements Discussion Approval Responsibilities</p> <p>2. Change introduction system</p> <p>3. System of change informational support</p> <p>4. Corrective action</p>	<p>1. Change monitoring Change control system Progress measurement Progress reports</p> <p>2. Current change and results estimation</p> <p>3. Correction proposal</p> <p>4. Change database</p> <p>5. Archive forming</p> <p>6. Post project analysis, change and result evaluation</p> <p>7. Lesson learned and strategy correction</p>
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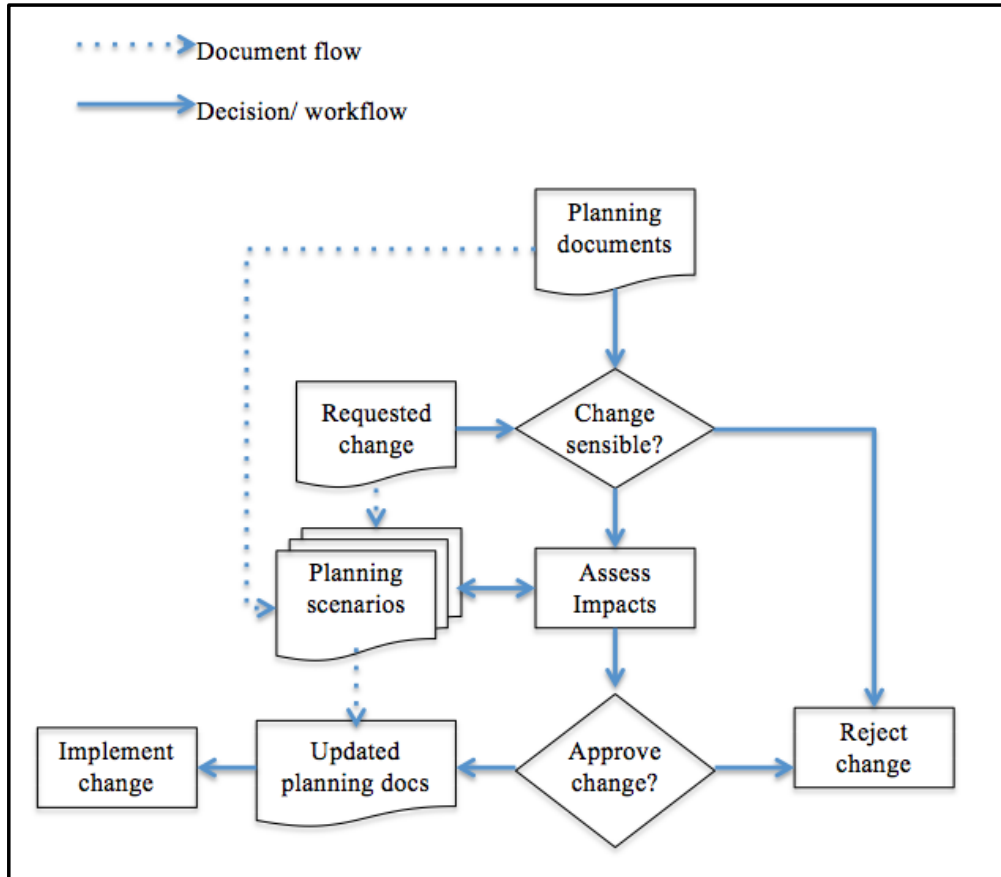


Figure 2–1: Change Control Process (PMBOK)

Ibbs et al. (2001) also recommended a comprehensive two-level process model for qualitative change management, as shown in Figure 2-2. It includes:

1. Principle level; and
2. Management processes level.

The first level includes five principles:

1. Promote a balanced change culture;
2. Recognize change;
3. Evaluate change;
4. Implement the change; and
5. Continuously improve from lessons learned.



Figure 2–2: Change Management System (C. William Ibbs C. K., 2001)

In order to capture “iterative cycles” and their impacts during simultaneous design and construction and fast track contracts, Lee et al. (2003) presented another framework for qualitative change management. Sun et al. (2006) presented a prototype change management toolkit (MCD) as standard framework and tool for supporting change management in construction projects by focusing on forecasting the changes and responding by rescheduling the workflow. Price et al. (2006) contributed to the discussion by identifying the critical methods that could improve the management of change. Based on a review of the literature and interviews with experts, they applied the critical methods and developed a strategic framework for change management that consists of six steps:

1. Preparing the organization;
2. Developing a vision and implementation plan;
3. Checking;
4. Communications and workforce engagement;
5. Implementation; and
6. Evaluation.

A change management process can qualitatively manage a change from implementation to the completion. Therefore, some research has attempted to improve the process by developing some quantitative models to calculate the impact of change since one of the main steps in every change management process is evaluating the change and identifying its impact on project parameters such as cost, time, productivity and project overall performance.

## **2.7 Quantitative Methods and Models for Change Impact Analysis**

When a change happens, impact analysis is an essential step that should be applied in order to figure out the direct and indirect impact of the change. Quantitative models concentrate on the impacts of the change on time, cost, quality or productivity, and calculate everything numerically. All the theoretical models and information models for the change can be under the quantitative change management system banner. In order to quantify the impact of change on project cost, Ibbs (2003) proposed that the difference between the project cost at the end of the project and the project original budgeted is needed. This is reflected in Equation 2-1:

$$\text{Change in cost (\%)} = \frac{\text{final cost} - \text{original cost}}{\text{original budget}} \times 100 \quad 2-1$$

Serag (2007) built a model to calculate the change impact on the project cost, based on Equation 2-2:

$$\% \text{ inc. due to change} = \frac{\text{cumulative cost of the change order to date (\$)}}{\text{original cost of the project (\$)}} \times 100 \quad 2-2$$

Lee (2008) defined the concept of “cost overrun” as the differentiation of project actual and budgeted costs as a percentage of the calculated cost, with all costs estimated in constant amounts. Another addition was proved by Lee (2008) about actual costs and estimated costs, as follows:

- Actual costs: The amount of cost spent which is calculated by the time the project is get completed; and
- Estimated costs: The budgeted or forecasted costs at the time of project approval.

Ibbs (2003) generated an equation to calculate the percentage of change in schedule, defined as the difference between the time used to complete the whole project and the estimated time to complete the project, as shown in Equation 2-3:

$$\text{Change in schedule (\%)} = \frac{\text{total time used} - \text{original estimated time}}{\text{original estimated time}} \times 100 \quad 2-3$$

By using the data from 57 different construction projects, Leonard et al. (1991) developed a regression model in order to quantify the impact of changes on productivity. Mokhtar et al. (1998) implemented an information model with the objective to help project participants coordinate design information when design changes happen by having a central database that consist of active building components. The model can transit design changes, track past changes, plan and schedule future changes, and improve design change management. Hanna et al. (1999) developed a statistical model called “%Delta,” which is a linear regression equation intended to quantify the effects of changes on labor efficiency in electrical and mechanical construction. The model was



made to assist both the owners and contractors on change management and understanding of how changes affect labor efficiency. Mokhtar et al. (2000) proposed a “computer-assisted” methodology for managing design changes and to support planning and scheduling of the interrelated design changes by linking knowledge to collect and organize the data related to the design changes.

Hanna et al. (2002) also developed another statistical model to quantify whether an electrical or mechanical project is impacted by a change by using regression techniques. The model aids the owner or contractor to find the probability of whether a project has been impacted by changes and acts as a forecasting tool. It classifies projects as either impacted or not impacted by changes, and the impact is also classified either as productivity losses or  $\Delta$ . Hanna et al. (2002) presented a new methodology, which is the integration of statistical regression and fuzzy logic in order to quantify the cumulative impact of changes on construction projects. The output of fuzzy membership function would be the expected loss of labor productivity and its standard deviation.

Kettlewell (2003) recommended a framework for calculating changes in price. The detailed costing structure can be used for providing bidding documents with the intention of helping contractors establish change pricing and also aids owners in the selecting of a contractor. Lee et al. (2004) developed a decision tree model for electrical and mechanical projects in order to classify and quantify the labor productivity losses due to the cumulative impact of changes. The model will support the owner and the contractor to understand how changes affect labor efficiency. Moselhi et al. (2005) developed a neural network model for quantifying the impact of changes on labor productivity. The model is integrated with four other models developed by others in order

to make a prototype software system to evaluate the percentage loss of labor productivity due to changes. In order to estimate the adverse impacts of changes on construction performance, Lee (2003) proposed a framework incorporated into a system dynamics model of dynamic planning and control methodology (DPM).

Chen (2005) developed a model called Early Warning System (EWS) with the use of the Case Base Reasoning (CBR) method. EWS can resolve the changes with the potential of recourse to lawsuits by using the previous resolutions that are saved in the model database. The model gives a warning any time a new change case is similar to past cases. To quantify the impact of changes on cost and time, Yitmen et al. (2006) presented a prototype expert system named QUICOPP. To minimize disputes, QUICOPP also provides recommendations to the parties involved in the project and helps prevent the project from becoming a claim case. In order to analyze the negative impacts of changes on different project parameters and to discover the “cause-and-effect relationships” of the change events, Motawa et al. (2007) developed a change management system that integrates a fuzzy logic-based change prediction model with the system dynamics model of the Dynamic Planning and Control Methodology (DPM). Based on time and compliance metrics, Karimidorabati (2008) developed a simulation model for change management, arguing that the automated way is better than all the other electronic and paper-based processes. In order to examine the impact of changes and to involve the project participants in the decision-making process, Isaac (2008) proposed a new approach for managing changes in construction projects named Change Control Tool (CCT). By using a Knowledge-Based Decision Support System (KBDSS), Arian (2008) presented a change management system for reducing variations and to increase overall

the level of productivity in the construction industry. In order to avoid disputes between project parties and prevent unnecessary expense and loss by providing similar litigation cases from its established comprehensive database, Chen (2008) developed a K Nearest Neighbor (KNN) knowledge sharing model. Serag et al. (2010) demonstrated two regression models to quantify the impact of change on a contract price in heavy construction projects in Florida. It aids the owners to do forward pricing of changes.

Zhao et al. (2010) developed a change prediction model as a beneficial tool for project management teams to manage changes proactively and efficiently. The model is used activity-based dependency structure matrix (DSM) to identify the ripple effect of the changes. Also, it used Monte Carlo simulation to analyze the change probability of activities involved in construction projects. Nahod (2011) proposed a theoretical system based on a Dynamic Planning and Control Methodology (DPM) for reducing the time it takes to get change approval. For better quantification, Ibbs (2012) quantitatively studied 226 projects collected by Leonard in (1991) and Ibbs (2005). The result is “a set of curves and reference points that contrast the amount and likelihood of change with the amount and nature of its impact.” Heravi et al. (2014) developed a framework to predict the change in construction projects and its impact on project objectives. The predicted changes are inserted into the change implementation process in the form of change request and subdivided into change implementation paths based on general possible scenarios of conflicts/non-conflicts, followed by scenarios of request/non-request. A risk index is developed using the event tree analysis to evaluate the developed change implementation paths separately and analyze the occurrence of change and arising conflicts due to the change implementation process. Du et al. (2015) developed an object-

oriented discrete event simulation (DES) model to simplify and support change management process by using the process interaction (PI) model instead of activity scanning (AS) model, since the PI model can capture project changes in real-time. Taghi Zadeh (2016) developed a predictive model to identify the impacts of design changes on project cost and schedule in oil and gas industry projects by using a number of quantitative techniques, including Pearson correlation and multiple regression analysis methods. The current change quantitative models are categorized in Table 2-5 based on the type of model used, with some of their limitations highlighted.

Table 2–5: Current Change Quantitative Models and Their Limitations

Model Type	Author	Model Functions	Model Limitations
Regression/ Statistical Models	Leonard et al. (1991) (CSCE)	The effects of COs on productivity	Not considering the timing of CO, lack of visualization, lack of integration, no Computer implementation
	Hanna et al. (1999, 2002) (ASCE)	Quantify productivity loss (labor efficiency) /percent Delta	Only applicable in mechanical and electrical project, lack of visualization, lack of integration
	Hanna et al. (2002) (ASCE)	Quantify the cumulative impact of CO	Lack of visualization, lack of integration, no computer implementation
	Chen (2008) (Automation in Construction)	Share knowledge of past court resolved disputes by court	Limited litigation cases, no quantitative models, lack of visualization, lack of integration
	Serag et al. (2010) (ASCE)	Quantify the increase of the contract price due to COs in heavy construction projects in Florida	Limited to projects in Florida, limited database, Only applicable for heavy construction (Highways and roads), no quantitative models, lack of visualization, lack of integration
	bbs (2012)	Forecast the probability of	Limited projects in the

	(ASCE)	impacts that change has on cost, schedule, and productivity	database, no quantitative models, lack of visualization
	Taghi Zadeh (2016)	Predict the impacts of design changes on project cost and time	Only applicable in oil and gas project, limited projects in the database, no quantitative models, lack of visualization
Artificial Intelligence Models	Moselhi et al. (2005) (ASCE)	Quantifying the impact of change orders on labor productivity	Lack of visualization, lack of integration
	Yitmen et al. (2006)	Quantify the impact of change orders on cost and time	Lack of the visualization, database limited to North Cyprus project
System dynamics model	Lee et al. (2005) (ASCE)	Evaluate the negative impacts of changes on construction performance (protect the planned performance against changes)	No quantitative models, lack of visualization, lack of integration
	Nahod (2011) ARCOM Conference	Decision analysis, (reduce the time for getting the change order approval)	Carried out only in Croatia, only applicable in the phase of execution, lack of visualization, lack of integration
	Motawa et al. (2007) (Automation in Construction)	Evaluating change effects depending on the available information at the early stages of projects	No realistic implementation based on few cases, lack of visualization, No quantitative models
Decision tree model	Lee et al. (2004) (ASCE)	Identify & quantify the cumulative impact of COs on productivity	Only applicable in mechanical and electrical project, lack of visualization, lack of integration
	Heravi et al. (2014)	Predict occurrence of change and arising conflicts	No quantitative models, lack of visualization, lack of integration
Case Base Reasoning (CBR) Model	Chen (2005) (ASCE)	Early Warning System (EWS) able to solve the COs that have the potential of lawsuits	No quantitative models, lack of visualization, lack of integration, limited database from past projects, only litigation cases

Simulation Model	Karimidorabati et al. (2008)	Automated process-based management of change	No quantitative models, lack of visualization, lack of integration
	Du et al. (2015)	Simplify and support change management process	No quantitative models, lack of visualization, lack of integration
Activity-Based Dependency Structure Matrix Model (DSM)	Zhao et al. (2010) (ASCE)	Identify the activities with a high risk of causing changes	Limited case studies have been done, no quantitative models, lack of visualization

Reviewing the literature aids in the recognition of current practices and their limitations. Based on the literature review of project changes and change management systems, it can be concluded that most of the research has focused on identifying the change management processes. In order to have a successful change management system, lessons learned and best practice recommendations are necessary, and all these methods can manage project changes qualitatively. On the other hand, some researchers have focused on how to analyze the impact of changes on cost, time, productivity or overall project performance quantitatively to help change decision-making. The quantification models were mainly developed based on statistical regression, fuzzy-logic theory, case based reasoning (CBR) and knowledge-based decision support system (KBDSS). As shown in Table 2-5 the common limitations of these models are lack of integration, lack of computer implementation and lack of visualization. As stated throughout, the main impacts of change are on cost, time, and productivity, but most of the research to date has been on productivity impact analysis. Some researchers have developed a model for cost and time impacts analysis, but it is less likely a model can quantify both cost and time

impacts. As a result, a model is needed that can analyze more impacts simultaneously. However, not enough focus has been paid on evaluating cause-and-effect relationships or dependencies within the change process, which are essential to realizing how changes happen and how causes influence effects. These dependencies deliver the foundation for change evaluation within the overall change process. Most of the time, the causes of change are not easy to identify due to lack of information. In construction projects, experts try to make decisions based on their assumptions and previous experience in order to figure out these relations. Also, it is hard to trace the impacts of the change in other components or disciplines such as mechanical, electrical, HVAC, piping and plumbing from the 2D drawings or even 3D drawings. What is missing is a model with the ability to visualize the impact of change both qualitatively and quantitatively, and this limitation can be addressed by taking advantage of BIM. As such, below is a review of the literature on BIM, which is necessary to understand its definition, abilities, benefits and its current adoption in architectural, engineering and construction industry (AEC) for the purpose of change management.

## **2.8 Building Information Modeling (BIM)**

Building Information Modeling (BIM) is a developing technology used all over the world in the Architecture, Engineering, and Construction (AEC) industries because of its ability to provide accurate building data and information. BIM allows architects and engineers to use digital design information to analyze and understand how their projects will perform before they are built. It has been increasingly applied by owners, designers, and engineers during the life cycle of a project. Edgar (2007) defines BIM as “a complete 3D database that can be used for cost estimating, scheduling, detailing, advance bill

production, automated shop drawing and construction planning are provided by a BIM model.” Based on the BIM Project Execution Planning Guide, BIM is defined as: “A process focused on the development, use and transfer of a digital information model of a building project to improve the design, construction and operations of a project or portfolio of facilities” (CIC research group, 2009). Autodesk (2010) argued, “Developing and evaluating multiple alternatives at the same time enables easy comparison and informs better sustainable design decisions.” BIM is made by combining all the project data including, cost and schedule information and allowing users access to them without obstruction. The BIM Handbook presents BIM as a modeling tool to produce, communicate, and analyze building models. Building models are recognized as “Building components that are represented with digital representations (objects) that carry computable graphic and data attributes that identify them to software applications. As well as parametric rules that allow them to be manipulated in an intelligent fashion” (Eastman, 2011). In BIM, a project can be viewed as 3-dimensional or 2-dimensional from any direction, and a user can define the scale according to need. A user can also generate more information for the model, such as construction scheduling (4D BIM) and cost estimating (5D BIM). In addition to the 3D rendering of the building, BIM is a combination of design technologies to make a virtual environment for building components (Eastman, 2011). BIM upgrades the traditional 2D model to a 3D model and further to a 4D model (scheduling) and a 5D model (cost estimating). Eastman et al. (2011) argued, “further extended to incorporate additional management parameters to nD CAD are already being undertaken by various solution providers.” This research attempts to add another dimension: 6D (change management). BIM provides several types of 3D



models such as architectural, structural, HVAC, mechanical, electrical, plumbing, and piping. In general, a 3D model introduces any three-dimensional surface of an object mathematically, including parameters such as width, height, and length. A 4D model is a 3D model with the project schedule linked to it; the fourth dimension in the BIM environment is the time and scheduling of the project. It provides a virtual simulation of the project to the user in the 4D environment. A 5D model is a 3D model with a project cost data with the Quantity Takeoff (QTO) linked to it; the fifth dimension in the BIM environment is the project cost. 5D provides more accurate project cost estimation. BIM is used in all phases of the project from planning and design to construction and operations. The main disciplines in each category and the different areas where BIM tools are used are shown in Table 2-6 (IBC, 2011).

Table 2–6: BIM Tool Purpose by Category (IBC, 2011)

Total Category	User	Areas of Use
Planning and Design	Architect Engineer	Site Modeling
		Spatial Programming
		Design Authoring
		Design Review
		Engineering Analyses
		Code Evaluation
		Cost Estimation
Construction	Contractor Sub-contractor	Sequential Planning
		Construction Site Utilization
		Temporary Structure Design
		3D Coordination
		Site Analysis & Phase Planning
Operation	Owner Building Manager	Building Record
		Building Performance
		Space and Asset Management
		Disaster Planning

Various researchers considering the different uses of BIM in the construction industry have highlighted many benefits. The Stanford University Center for Integrated Facilities Engineering (CIFE) summarized the benefits of BIM based on 32 major projects as follows:

- Up to 40% elimination of the unbudgeted change;
- Cost estimation accuracy within 3%;
- Up to 80% reduction in time taken to generate a cost estimate;
- A saving up to 10% of the contract value through clash detection; and
- Up to 7% reduction in project time.

Azhar, et al., (2008), on the other hand, lists the benefits of BIM as follows:

- Quicker processes aid to easier information sharing;
- Enhanced analyzing of design alternatives allows to have innovative solutions;
- Controlled whole-life costs and environmental data for better understanding of project lifecycle costs;
- Better production quality; documentation output is flexible and applies automation;
- Automated assembly;
- Better customer service by providing accurate visualization that helps the understanding of alternatives; and
- Aid to facilities management by providing design, construction and operational information (Azhar, 2008).

For Kymmell (2009), the benefits of BIM are that it decreases struggles during construction by enhancing the mutual understanding of design, overall project quality, and reduces construction changes and number of RFIs. The BIM Handbook summarizes BIM's benefits as:

- Better management of the design documentation;
- Simulate construction process and operation activities prior to physical implementation;
- Solve problems and forecast performance;
- Coordinate the construction to reduce construction time and eliminate changes;
- Facilitate data entry as part of the construction business process and then re-uses it throughout the whole project lifecycle and beyond (Eastman, 2011).

There are eleven common “early” benefits that most contractors experience in their use of BIM, as follows:

1. Visualization;
2. Scope Clarification;
3. Partial Trade Coordination;
4. Collision Detection/Avoidance;
5. Design Validation;
6. Construction Sequencing Planning/Phasing Plans/Site Logistics;
7. Marketing Presentation;
8. Options Analysis (Value Engineering Analysis);
9. Walk-through and Fly-through;
10. Virtual Mock-ups; and

## 11. Sight Line Studies.

One of the main benefit of BIM Visualization is the reason that this study chooses BIM as the main platform for its developed model. When any data visualized, it can help project participants to communicate better and more effectively, and the data will be more understandable. Price (2006) stated that most change processes faced with failure due to poor communications. Shneiderman (2004) stated that the visualization tools could accelerate human thinking and strengthen human brainpower. IEEE (2005) argued that visualization systems help quick insight to compound data; these systems are comparable to power tools for analytical reasoning.

From the literature, when it comes to any visualization system, two values are always discussed. The first is the usability of the system, and the other is usefulness that is considered in this study for developing a practical visualization model. ISO (1998) defines usability as the product extension help for specified users to accomplish specified targets with efficiency and satisfaction in a specified framework. Nielsen (1993) describes usability as the group of factors such as learnability, productivity, impressiveness, few serious inaccuracies, and satisfaction and usefulness as the matter of whether the system can be used to reach some anticipated objective. Allendoerfer (2009) states that usability means the effort needed to use a system and usability observes how easily the tool gets used to complete a task. For Allendoerfer (2009), usefulness is system extension to encounter the users' desires and provide profits. In this case, usefulness refers to the quality of the tool output results. Table 2-7 summarizes the characteristics of highly usable and useful information visualization systems, as outlined by Allendoerfer (2009).

Table 2–7: Characteristics of Highly Usable and Useful Information Visualization Systems

	Highly Usable	Highly Useful
Information Visualization System	Users can know what next actions is (Polson, P. G., Lewis, C., Rieman, J., & Wilson, C, 1992).	Users can formulate goals related to using the system (Norman, 2002).
	Users can learn to use system with minimal training (Lam, 2008; Nielsen, 1993).	Users can formulate objectives for actions (Norman, 2002).
	The number of steps or amount of time needed to complete an action, such as create a visualization, is small (Nielsen, 1993; Norman, 2002; Lam, 2008).	Users understand presented data correctly (Chen C. , 2005; Lam, 2008).
	Users trace information simply (Nielsen, 1993; Shneiderman, B., 1996).	Users realize an accurate and relevant understanding of the visualized data (North, 2006).
	Users can manipulate a visualization (e.g., zoom, apply filters) without errors (Lam, 2008; Shneiderman, B., 1996).	Users achieve a complex understanding of the data (North, 2006).
	Users enjoy interacting with the system (Nielsen, 1993; Shneiderman, 2004; Wattenberg, 2005).	Users achieve a deep or sophisticated understanding of the data (North, 2006).
	Users can perceive the effects of their actions (Norman, 2002).	Users achieve an innovative or unexpected understanding of the data (North, 2006).
	Users can develop action sequences easily (Norman, 2002).	Users achieve a better understanding (Hornbæk K. , 2006; Hornbæk K. &., 2003).
	Users always understand where they “are” in the visualization (Gwizdka, J., & Spence, I., 2007).	Users can determine when their goals have been achieved (Norman, 2002).

## **2.9 Role of BIM in Enhancing Project Change Management**

BIM is in the process of continuous development and plays an important role in the construction industry. Considering this evolving role there is a need to improve the understanding of change management systems in the context of a BIM environment. The issue of managing design changes using BIM has not received much attention in the current literature. For example, to discover changes between two versions of the same data model, Wang et al. (2007) developed an accurate semi-automated method for finding the differences between versions of a data model precisely and efficiently. This approach includes a taxonomy for defining feasible differences between two versions of a data model and provides a way to classify these differences. The method can benefit AEC-related software developers implement data models in their software systems.

Akcamete et al. (2009) presented results from an analysis of changes found in case studies conducted during construction and operation phases and highlighted some initial patterns of changes occurring throughout the life cycle of a facility. They discussed some challenges related to managing such changes and updating building information models accordingly. They also investigated how well commercially available BIM tools are capable of addressing these challenges, such as capturing the changes and storing them in the BIM change history. This stored data will help users' decision-making when they need to analyze the changes over time for effective maintenance.

Navon and Isaac (2009) developed computer-based tools to automate the change management process. Nour and Beucke (2010) presented an approach to integrate object versioning (as a change management concept) and the IFC model (as a BIM) in an open, multidisciplinary collaborative environment to address the necessity of design change

management in early design. Koch and Firmenich (2011) presented a modeling approach that integrates current version-oriented information (i.e., state-oriented descriptions of virtual buildings) with change-oriented information (i.e., moving a wall, modifying its thickness and material) using processing-oriented modeling. The developed model contains both the design states and design changes, and it automatically records design changes by using a new operative modeling language.

Langroodi et al. (2012) investigated different challenges with regards to change management in fast-tracked construction projects and looked at the abilities of available BIM tools to overcome these challenges. In order to aid project participants who use BIM for change management to understand change characteristics, they developed a change ontology. Isaac and Navon (2013) presented the possible use of graph-based algorithms that get input from BIM and other information sources to track the consequences of design changes throughout the project, from one element to others. These algorithms can considerably decrease the amounts of time project team members spend manually browsing through project information and the large volume of data to evaluate the impact of a projected change.

Liu et al. (2014) developed a new model to manage project changes by integrating change management with BIM. The developed model is able to reduce the negative impacts of changes on energy efficiency purposes by taking the change data and automatically updating changes in BIM models. The automated model updating facilitates information collection and the coordination process among team members. Pilehchian et al. (2015) presented a method to identify, manage, and track changes in a collaborative multi-disciplinary BIM environment. An ontology was developed to

characterize design changes based on the changed component attributes, dependencies between components, and change impacts. A graph-based and dependency matrix approach was used to determine different types of dependencies amongst different design changes and their impact in a BIM-based project delivery process.

Karimidorabati et al. (2016) developed an automated workflow-based change management process model for the execution of megaprojects as part of an Electronic Product and Process Management (EPPMS). The developed automated workflow-based process was then compared with two other change management processes in terms of time reduction and compliance, namely: A fully paper-based process (hard copy documentation, faxes and snail mails), and an email-based process with PDF softcopy documentation. The results of comparison showed that the workflow-based process improved compliance by reducing the rate of rework and the automated notice to all project team members. Mejlaender-Larsen (2016) presented a change management process and a corresponding change control system (CCS) for managing changes in detailed design, evaluating how BIM can be used to identify the impact of changes.

In the construction industry, before the development of any change management system, the project participant used to review the changes on paper by laying two versions of plans side by side and manually locating and clouding the areas of changes. Also, they had to switch between sets to review previous and current versions in order to estimate the impact of changes on cost and time. Later on, this traditional setting got easier with the development of models that allow users to review changes by overlaying and aligning plan revisions and finding the differences in 2D. Then the user can cloud the



area of changes and isolate versions, and sometimes these models are able to quantify items that are removed and added.

## **2.10 BIM Software**

Some of the available BIM tools on the market that can be used to develop a BIM platform for the purpose of project change management are introduced below, such as Vico, Innovaya, Navisworks, Synchro, BIMestiMate and Assemble. These models' capabilities are discussed later on in chapter 4, and in section 4.4 they are compared with this study developed model. The first model is Vico Office Document Controller, which allows users to compare versions of 2D drawings and 3D models to locate the changes between versions. It can examine PDFs and DWGs using an overlay technique to find out which drawings have changed, and documents these changes in the comprehensive report. A color-code system is used to demonstrate the type of changes available between the drawing's versions. The user can cloud, annotate and log the located changes in Vico Office Issue Manager. Then the estimator can use the results of a comparison to analyze the impact of the changes. However, Vico is not accurate if the scales or the pages are slightly shifted, and it becomes very difficult to see what has changed. Also, it is not able to quantify the changes' impacts on project cost and time (VICO, 2016).

The second software is the Innovaya system, which works like a bridge to transfer the model components to an estimating database like Sage Timberline to provide an automated visual estimation of a project by eliminating the manual mappings between the objects and cost assemblies. For the purposes of change management, Innovaya visual estimating can present changed, new, and deleted components using different colors, and the new quantities can be automatically updated in the estimate. Therefore, the estimated

cost can be adjusted since the changed components are identified and quantified. Innovaya also has the ability to run a 4D simulation of a project by linking the model to its schedule. However, it is not able to update the schedule based on the requested project changes, nor can it quantify the impact of changes (Innovaya, 2014).

The third software is Navisworks, which is able to compare two versions of a model, and track, visualize and quantify changes. It compares two 3D versions of a model in terms of type, unique ID, name, properties and geometry by overlaying them on top of each other. It hides everything that is the same in both models and highlights the modified, deleted and added items with different colors. The user can export the comparison data to estimating Sage Timberline software. Therefore, in terms of calculating the impact of changes on project cost the model is able to calculate only the components' direct cost, not the other aspects related to the cost impact estimation such as impact cost, indirect cost, and change cost. The system also is able to do 4D scheduling; it shows 4D construction simulations of a project model by associating tasks straight to the 3D geometry. As with Innovaya, Navisworks links the available schedule, but cannot update the schedule based on the changes ((Navisworks, 2016).

The fourth model is Synchro, a construction project management system that has the capability to visualize project scheduling in 4D by auto-matching a BIM model to its schedule. The user is also able to add changes such as the number of resources into the 4D scheduling to see their impact as they are made. Having a look ahead to the changed reports reduces the project's schedule and cost variances. However, this model cannot visualize the project changes and also calculate the impact of changes on project cost (Synchro, 2017).

The fifth is BIMestiMate, which allows users to compare two or more versions of a model and then visualize the available changes that exist between them and uses color codes to define the change types. Also, the system uses the information about the changes to analyse the cost impact (Michal Juszczka, 2016). Finally, the sixth model, Assemble, is a cloud-based platform used for viewing models, estimating, scheduling, and project control, and letting a project's AEC team advance project collaboration and communicate changes. The system compares the latest two versions of the model and tracks both the graphical and cost differences between them. Then, the system highlights and visualizes the model's components change types: addition, deletion and modification. However, it cannot visualize the changes' ripple effect. The Assemble platform also provides the components' quantities report that the user can add to the component unit cost in order to calculate the cost impact due to design changes which allows users to see the effect of changes on a project's cost (Assemble, 2015).

Investigating 424 construction firms, Burcin et al. (2010) found that "Autodesk BIM tools are the most widely used BIM solutions in the U.S., with 54% of those construction companies using them; Graphisoft ArchiCAD follows with 10.7% and Bentley BIM tools with 8%. 6.5% and 5.8% of the construction companies based on the survey uses Tekla and Vico BIM tools. The other software tools such as Innovaya, Dprofiler, Vectorworks, etc. are also being used by a small portion of the construction firms," as summarized in Figure 2-3. Eastman et al. (2011) noted that any tools that create building models and contain parametric objects are considered BIM tools.

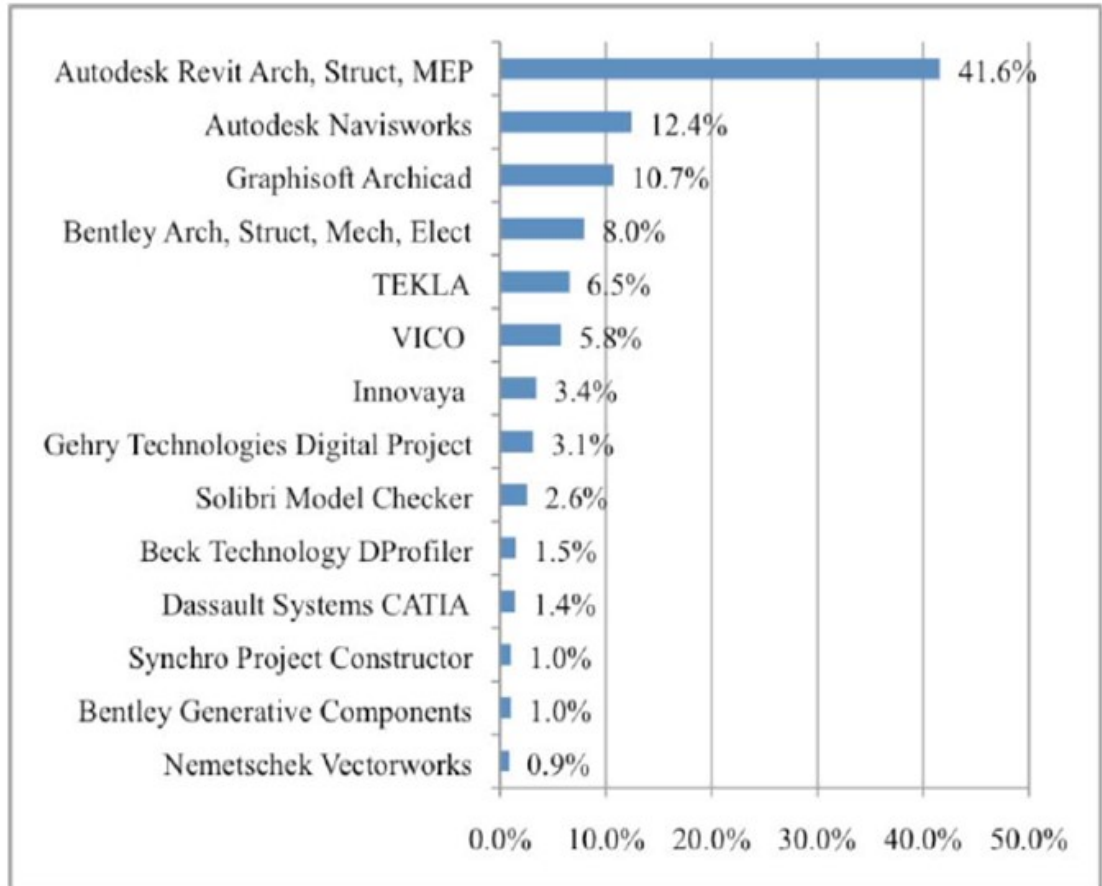


Figure 2–3: Percentages of market share of BIM tools that are used by construction firms (Burcin, B.G. and Samara, R., 2010)

### 2.11 Research Gaps and Limitations

The comprehensive literature review above was intended to aid the reader in understanding that some effort has been made in order to improve the process of change management in the construction industry. As such, different techniques and procedures have been used for developing a model, which are able to evaluate the change impacts quantitatively. The developed models can be categorized in two categories: BIM models and non-BIM models. As classified in section 2.7, the available developed non-BIM quantitative models and methods (see, for example, Leonard et al., 1991; Hanna et al., 1999, 2002; Ibbs, 2003; Moselhi et al., 2005; Yitmen et al., 2006; and Serag et al., 2010) use numerical calculations to estimate the impact of changes on project schedule, cost,

productivity, and overall project performance. They only calculate the probability of a change's impact on these project parameters, and in doing so, render users unable to update specific project activities' duration and component cost in order to generate a new project schedule and cost estimation based on requested changes. In addition, identifying change consequences (ripple effect) and impacted components is often required after detecting the change, which the current non-BIM models are not capable of doing; project participants thus mostly depend on expert opinions, manual analyses and project drawings to determine these effects. Navon and Isaac (2009) identified three common limitations of the existing non-BIM computer models of building projects:

1. Project data are not fully integrated and stored in different sub-models.
2. Current building models do not allow continuous modification of data, so the updating and propagation of changes throughout the project is not happening automatically.
3. Building models that identify sources of changes and their impact on project cost and duration of the planned activities should incorporate uncertainties and link the project components explicitly.

Therefore, the common limitations of current non-BIM models are: lack of computer implementation, a limited number of variables, lack of visualization, lack of integration, and they mostly consider only the impact a change has on project productivity. Also they are not accurate since their analysis is based on experts' knowledge. This is due to the lack of BIM software for tracking changes among different building information models versions and presenting the results effectively (Pilehchian, Staub-French, & Nepal, 2015). Therefore, BIM-based project management is beginning

to get more attention, but is also a contentious topic in the construction industry. Various studies on BIM have addressed the challenges related to managing changes and updating building information models, and investigated the capabilities of commercially available BIM tools that can be used in a way to overcome these challenges, but no actual BIM model has yet been developed.

For the purpose of determining the ripple effect of changes, as well as cost and time analyses, some studies developed an ontology that can be used to characterize design changes based on the changed component attributes, dependencies between components, and change impacts. Some studies have developed a BIM model able to find differences between versions of a data model, and they classify and visualize the change types (addition, deletion, modification), quantify the variances and automatically record these differences using a new operative modeling language (see, for example, Assemble, Vico and Innovaya). However, in terms of ripple effect visualization, not enough research has been conducted on evaluating cause-and-effect relationships or dependencies within the change process, which are essential to realizing how changes happen and how the causes influence the effects.

Some developed models, such as Innovaya, Navisworks and Synchro, are only capable of visual 4D simulation of a project and not able to estimate the impacted components duration and update the overall project schedule after quantifying changes; updating the project schedule and receiving the change-impact analysis causes additional work for project schedule developers. This means an optimized system is needed that is able to calculate the impact of changes on the duration of each project component and the overall project duration; the newly calculated durations can then be used to update the

project schedule. In terms of estimating the impact of changes on project cost, the available BIM models such as Assemble and Innovaya is only capable of quickly generating an automated cost estimate. Their estimation is based on calculating the project component cost without considering the project changes' impact costs (productivity and time-related costs) or indirect costs. However, in this research review of the literature, a powerful method was found that could be used for efficient cost estimation of change: Moselhi's framework is a strong method for cost estimation of change. However, this method would be more powerful when combined with BIM as an automated platform.

The literature review confirms that the existing developed BIM models are incapable of updating the overall project cost and schedule after quantifying changes. Therefore, updating project budget and schedule after receiving the change-impact analysis causes additional work for project schedule developers. Additionally, previous research did not develop an integrated BIM model able to visualize the change ripple effect of design changes throughout the project, from one element to others, nor one with a quantitative system that can estimate the cost and time impact of change. So there is a need for an integrative, adaptive and stochastic model. Therefore, after analyzing the gaps revealed above, and building on the foundation of previous research, the present study aims to bridge some existing knowledge gaps by proposing an integrated BIM-based model for change ripple effect recognition, visualization, and estimation of the impact of design changes on project cost and time.

Integrating the currently available systems and methods can provide enough data in order to make a cumulative and quantitative system for change visualization. With this

proposed model, owners remain involved in the project, and are able to see the results of their request in a way that can help them make better decisions, as dealing with changes in the traditional way (applying all the changes to the project after starting the construction phase of the project) is not that easy and recognizing the impacts on all systems is very time-consuming.

Using the proposed model to quantify the impact of change allows the project team to save a significant number of man-hours that would be traditionally spent on this task. So, the proposed model decreases the back-and-forth negotiations among project participants by increasing the owner's knowledge about changes and their impacts on project cost and time. Since time and cost are the main factors for all parties involved, not considering which side would be on the losing side of any proposed design changes may cause conflict between the parties involved. This is when claims can arise, and the parties involved may eventually need to resort to the court for arbitration. In the next chapter, the ideas behind this proposed system are explained in detail.



# Chapter 3: Proposed Model

## 3.1 Introduction

This chapter presents a comprehensive description of the proposed model and an explanation of the steps required for its development. The model was developed to support design change management, in particular to visualize the ripple effect of design change and to analyze the time and cost impact of each change. The main purpose of this model is to provide decision makers with a tool to visualize the ripple effect of owner-requested design changes, including analysis of the change's impacts on time and cost. Having easy access to this information is expected to improve, the decision makeup process and, accordingly, lead to fewer delays and reduction in cost overruns, and minimize conflicts among the project stakeholders and related legal fees. The process of project design change management begins when the owner requests design changes, and it can be divided into four different categories: adding, removing and/or modifying one or more component in the original model. These types of changes have their unique impact on the project. In the proposed model, work breakdown structure (WBS) is defined at a micro level, which means every component in the model has its data information regarding its associated ID, location, system, time (schedule) and cost, as shown in Figure 3-1.

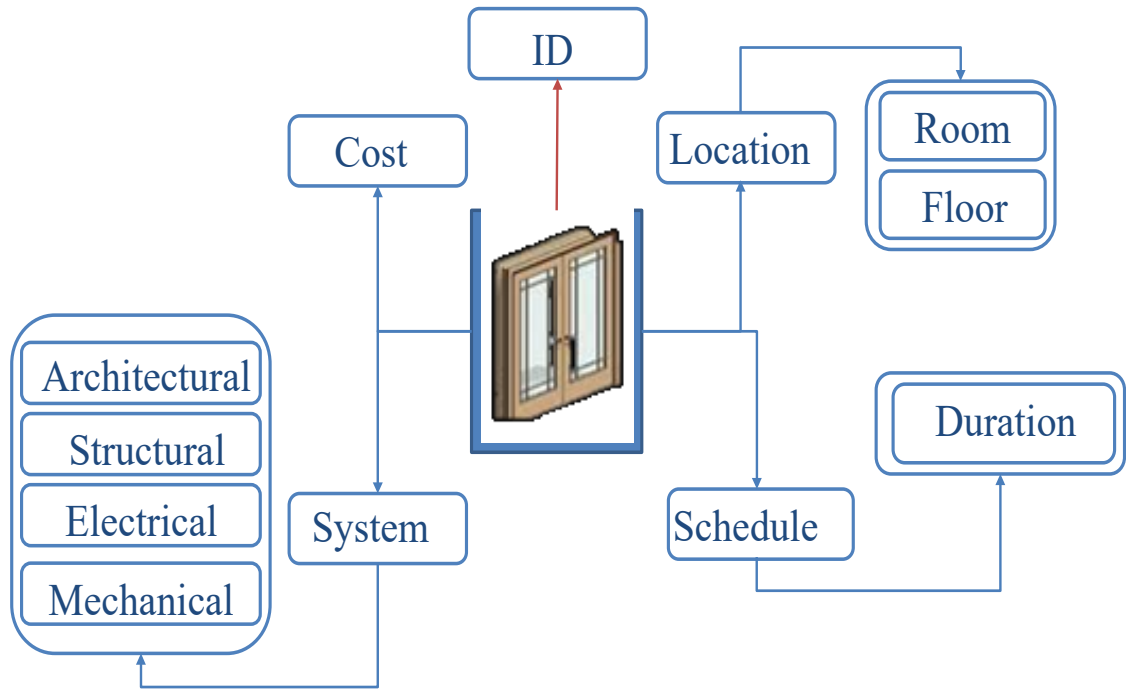


Figure 3–1: Model Component’s Information

In the construction industry, the combination of time and cost is associated with particular project activities or tasks, and not with the components within that activity. That policy makes it more difficult to determine the ripple effect of the changed component on the other components within the same activity. For example, if the dimension of the wall in an activity is changed, the project management model will be able only to identify the impact of that wall change on cost and time. However, this cannot be completely accurate, since the wall is connected to another component, such as a window, door, ceiling, etc. and these may change as a result and lead additional cost and time. For that reason, the proposed model breaks the schedule down to a more detailed, later on referred to micro-level scheduling. The following set of characteristics have been identified and deemed necessary to make this model more useful to project managers.

- The model should be user-friendly with the minimum need of training;
- The model should be able to integrate the cost and schedule data at component and project levels;
- The model should be able to compute and update cost and schedule data to each component and to the project after the change is applied;
- The model should automate the process of identifying the change ripple effect;
- The model should automate the process of change impact analysis on project cost;
- The model should have the capability of extracting and exchanging data from/with visualization information technologies such as BIM, Revit and MS-Project;
- The model should be multi-user and allow them access to the project captured data and reports; and
- The model should be flexible for facilitating future extensions.

### **3.2 Overview of the Proposed Model**

The proposed model consists of four main frameworks utilized in change management and owner decision-making process. The first framework is data acquisition; the second is data analysis; the third is reporting and highlighting, and the last is data filtering. The data acquisition framework captures four types of data. First is the developed 3D model of the project from project 2D construction drawings. The second is the schedule data of the project to aid in the building a project 4D BIM model for the project. The third is the project cost estimation data in order to build the project 5D BIM model, and the final data acquisition process is applying the owner-requested change to the model. The change data analysis framework consists of three modules,

namely the change ripple effect visualization module, the change time impact analysis model, and change cost impact analysis module. The reporting and highlighting framework generated a comparison report between the original (as-planned) and modified (as-changed) models in terms of cost and time. The data filtering framework allows the user to define constraints for the comparison report regarding available parameters such as project cost and time, and get an updated report. At this stage, the quantitative model is done after the change impact analysis and reporting. The owner is responsible for accepting and rejecting the changes being analyzed. The proposed model is illustrated in Figure 3-2.

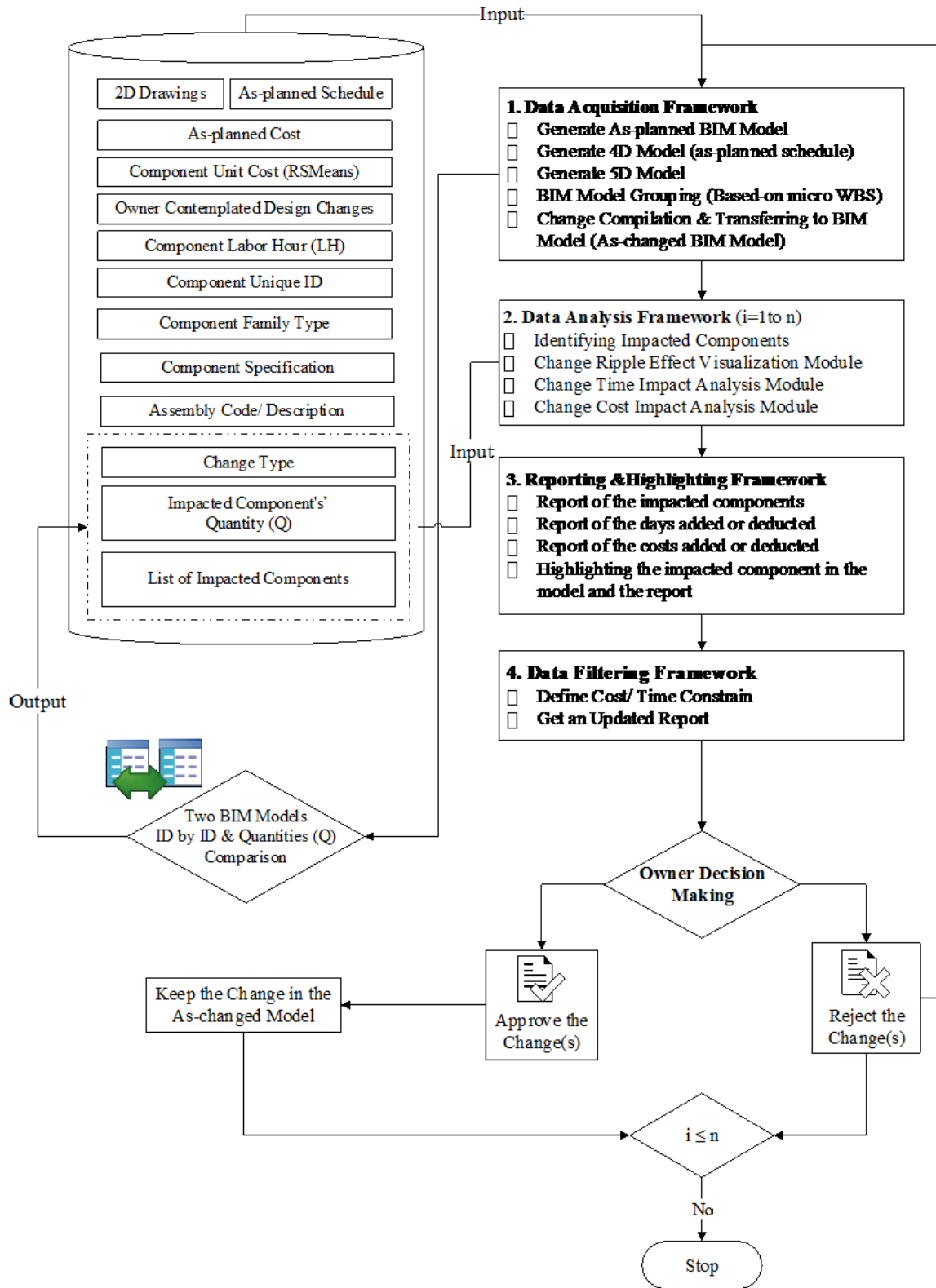


Figure 3-2: Overview of the Proposed Model

### 3.3 Data Acquisition Framework

The Data Acquisition Framework consists of four main sources of data required to run the proposed model: 1) generating BIM model, 2) building BIM-based micro scheduling model (4D), 3) building BIM-based micro cost data model (5D), and 4) changes compilation and transferring to the project BIM model, as shown in Figure 3-3. The main input to the model is comprised of the above-said information.

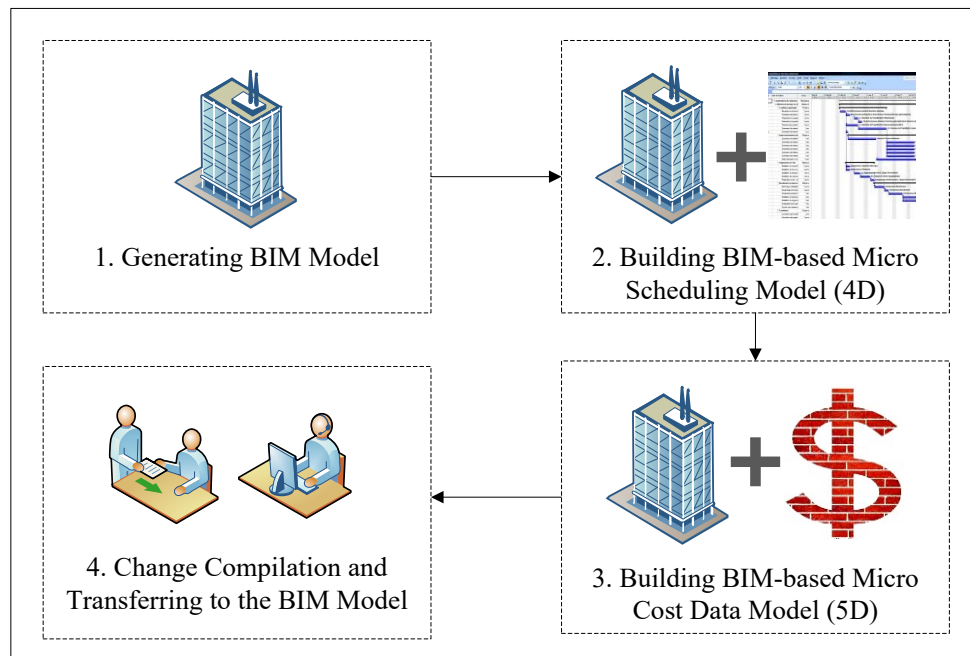


Figure 3–3: Data Acquisition Framework Steps

Some modifications to the provided drawings, data, and documentation might be needed in order to generate the project BIM model. The data pertinent connects to each component of the model is captured in the BIM model. Each component has its own characteristic and data in terms of design specifications, cost, and schedule. Therefore, it is important that the project drawings, specifications, cost and time data be accurate and complete for constructing the BIM model. Any mistake or defect can result in failure of

the BIM general model, and will corrupt the results of the ripple effect of the introduced change and its impact on time and cost.

### **3.3.1 Generating BIM Model (3D)**

The BIM model is generated as the first step of model development and consists of all the project components and specifications. For the purpose of change impact analysis, in this project all project systems—such as architectural, structural, electrical, mechanical, plumbing, and HVAC (building systems)—should be part of the BIM model. If a BIM model of the project exists, the system applies the second steps of data acquisition framework. Otherwise, the user must generate a BIM model. The user first selects a building system category and collects related 2D drawings from project database to generate the BIM model for the selected category directly from the 2D drawings, as shown in Figure 3-4. Then, the generated BIM model is saved in the project database.

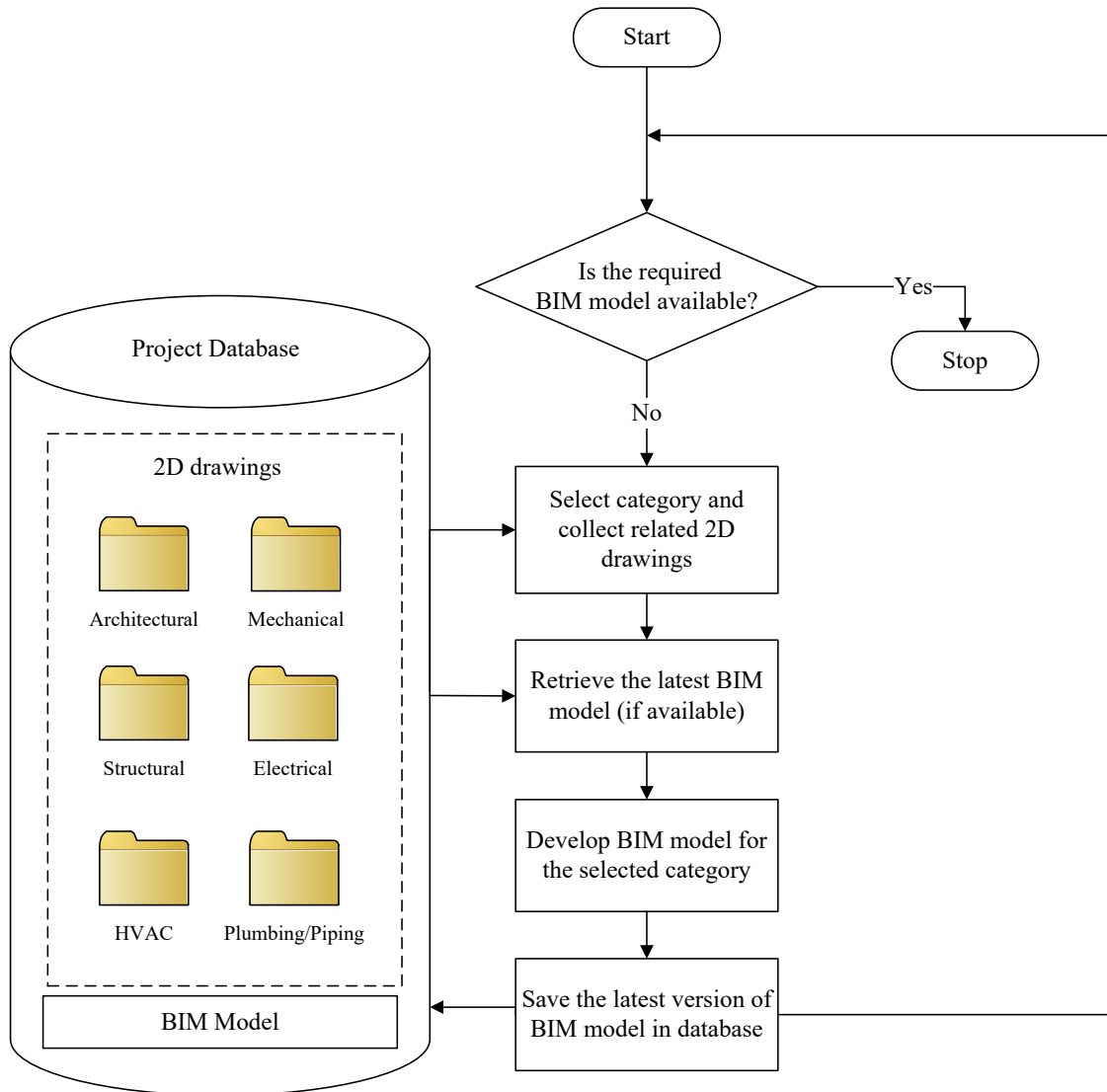


Figure 3–4: Generating BIM Model (3D)

### 3.3.2 Building BIM-based Micro Scheduling Model (4D)

After generating the BIM model, the project schedule must be linked to the model as the fourth dimension. The schedule based on the project WBS includes the project milestones and activities with a start and finish dates. In this research, the project schedule is extended to account for details needed for the application of the developed model. This is achieved by generating the project micro-level WBS. It starts from the project activity (floor), sub-activity (area), work packages (system), and ends with the



parts (component). In this case, constructing project floor slabs would be at the activity level, building the areas or rooms on each floor is at the sub-activity level, constructing the systems such the architectural, mechanical, electrical, piping, plumbing, and HVAC in each area is the work package level, and building every component in each of these systems would be at the part level. The proposed micro-level WBS is illustrated in the Figure 3-5. The model is flexible if the user wants to add more levels to the schedule, like defining activities per component in both BIM model and schedule. This means that in the BIM model for every component the user can define activities and general specifications related to that component.

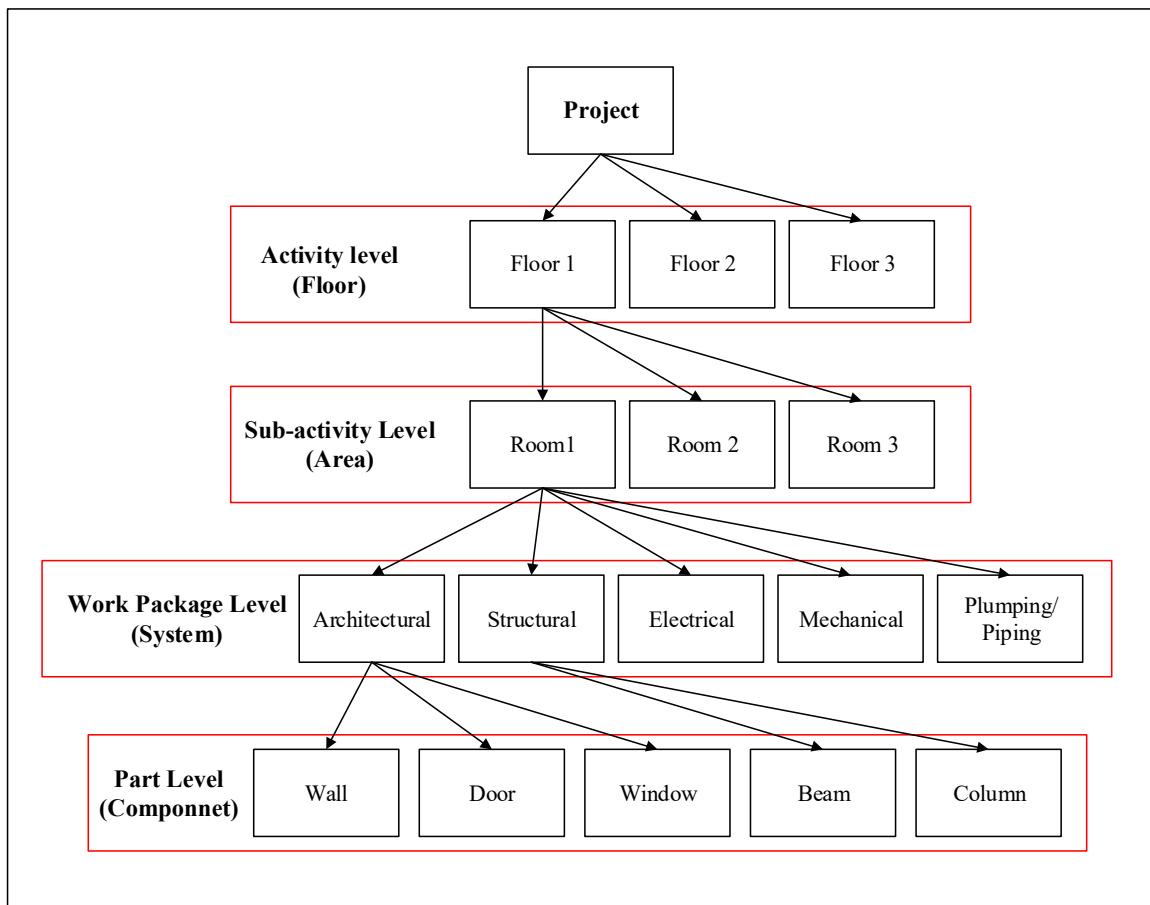


Figure 3–5: Proposed Micro-level Work Breakdown Structure (WBS)

Therefore, after generating the project BIM model, the model components are grouped based on the generated micro WBS structure, and each group receives a unique ID. Then, the proposed model uses these BIM model groups' ID to map them to the project schedule, which is available in the project database. The BIM model grouping is shown in Figure 3-6. Then, these group IDs are used to find and read the corresponding task in the as-planned project schedule, and after entering the as-planned tasks' information into the BIM model, the 4D as-planned schedule is generated, as shown in Figure 3-7. What differs the developed model from work of others (see, for example, Montaser et al., 2013) is that grouping only used to map schedule data to a group of components in a BIM model. So it only solves the problem of mapping, but the grouping does not follow a particular rule like the proposed model that has a hierarchical structure for mapping the schedule, and it is flexible based on the owner needs.

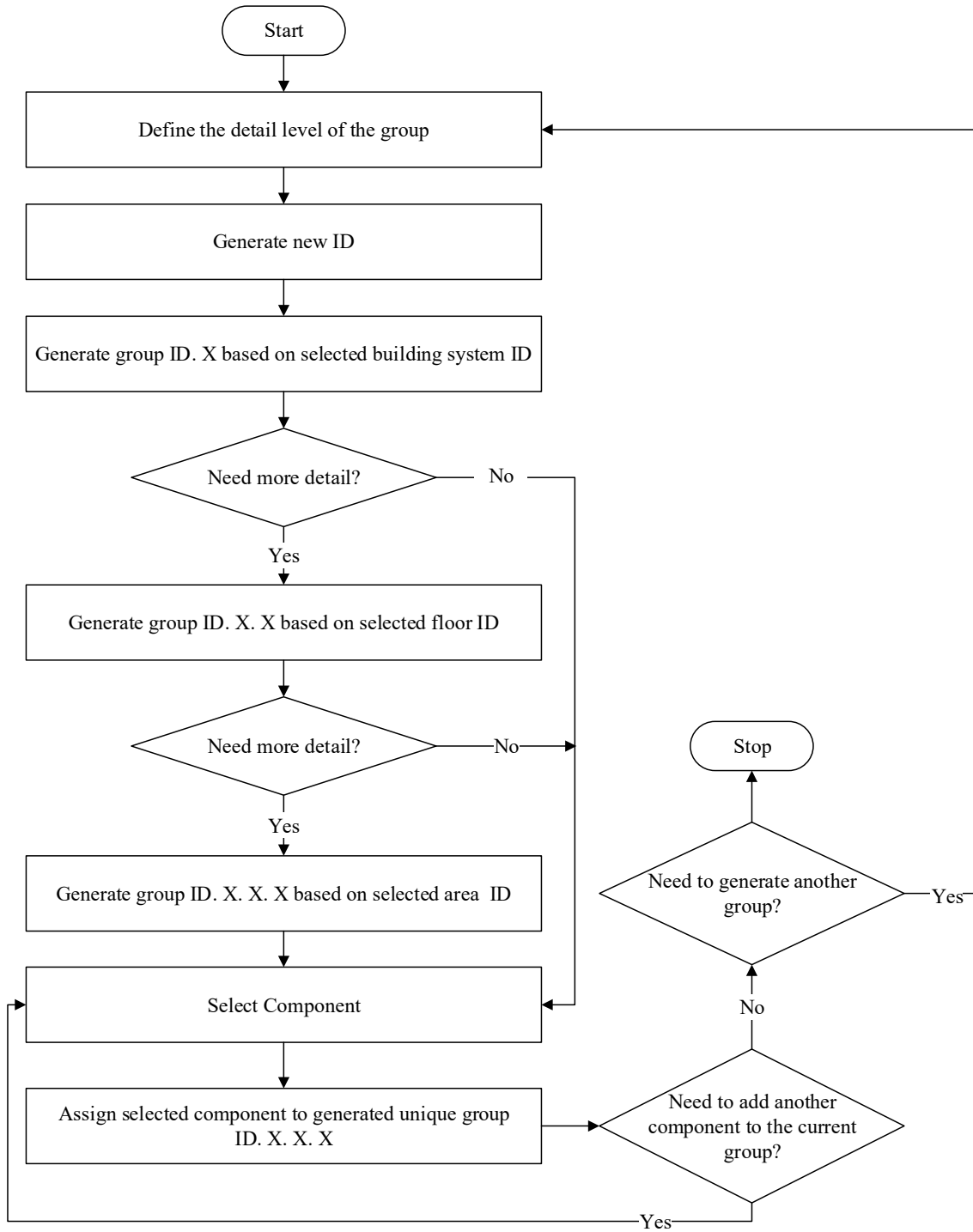


Figure 3–6: BIM Model Grouping

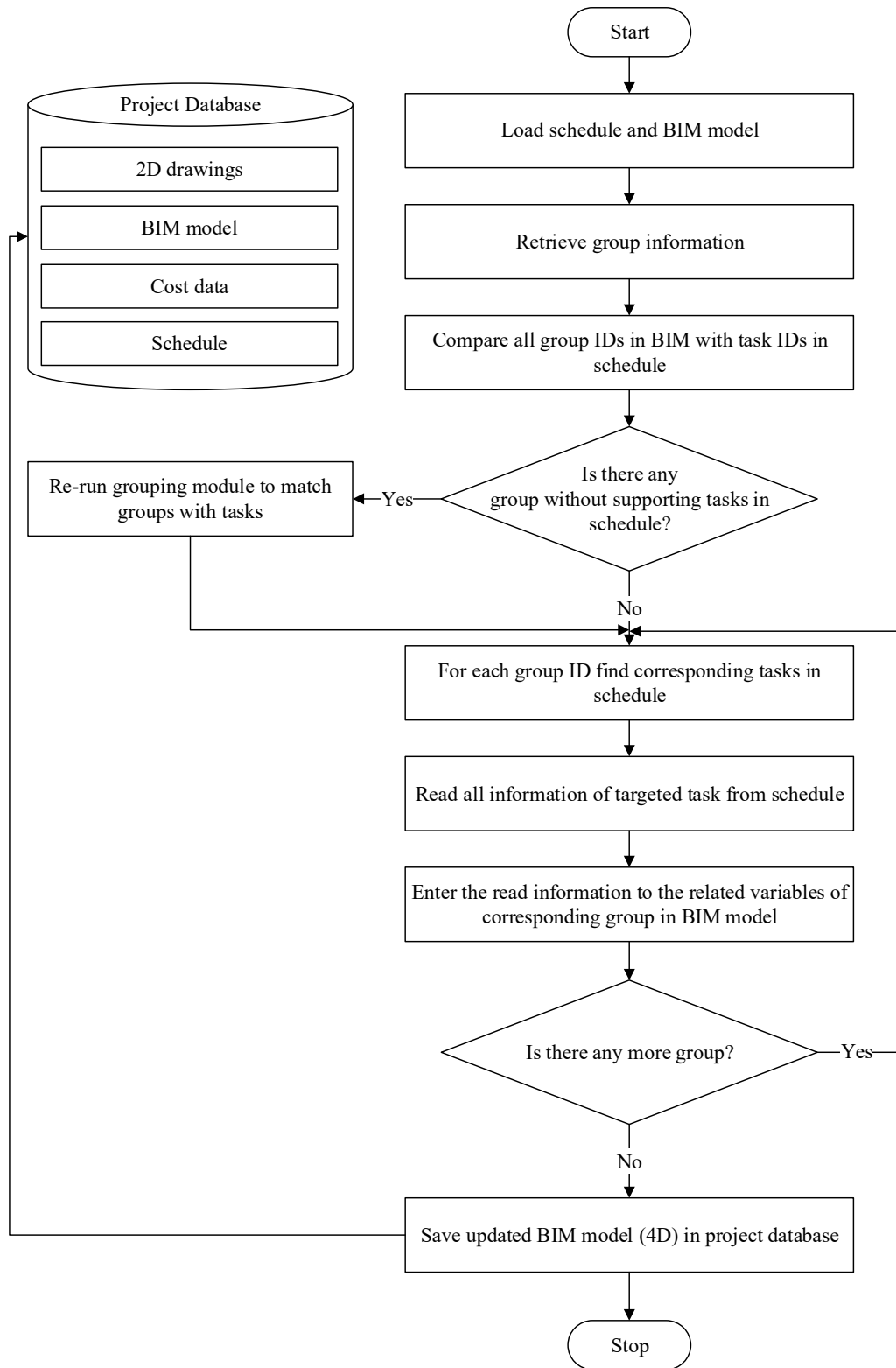


Figure 3–7: BIM-based As-planned Schedule Data Model (4D)

### **3.3.3 Building BIM-based Micro Cost Data Model (5D)**

Considering time and schedule for change management is critical. Change management processes that do not pay attention to impact cost are not practical. Both time and cost impact should be part of any change management system. Fortunately, a BIM model can create a list of the components and related materials. In this case, a cost estimate can be calculated easily by introducing a cost for every component in the model, and a BIM model can be used to generate quantity and support in the formation need to cost estimation as the fifth dimension of the project BIM model.

According to Autodesk, BIM model Quantity takeoffs can aid project participants to generate quick cost estimates. It can also provide alternative cost information to owners in every phase of the project (Autodesk, 2010). Therefore, this helps the project team to show the cost impact of contemplated design changes, in order to make better decisions and decrease unnecessary cost overruns. Moreover, Autodesk 2010 states: “Having this cost feedback available at every state of design enables project teams to:

1. Compare cost plans to the original project budget at any point in time.
2. Stakeholders can easily see what has changed and make a proper decision on adjusting the scope as necessary;
3. Understand and focus on design decisions having the largest impact on the project cost;
4. Evaluate the cost impact of proposed design enhancements and what-if scenarios; and
5. Compare the impact of using sustainable design strategies in terms of installation time, cost, and projected energy savings.”

Upon generating the project 5D BIM model (cost), the user can evaluate design changes and see which design change options have less impact on project cost. Eastman et al. (2011), managing costs with BIM applications provides owners with:

1. More reliable estimates early in the process with conceptual BIM estimating; and
2. Faster, better-detailed, and more accurate estimates with BIM quantity takeoff tools.

In this research, the impact of change on cost is shown in a different cost table since cost analysis is based on micro level scheduling. The cost estimate is shown at the part level, with the component in that part. The proposed model first calculates the quantity takeoff from the generated BIM model, which consists of the entire model components. Then, it loads the components unit cost from a provided cost database (RSMeans) and links the cost database to the components that are listed in the project quantity takeoff by matching and finding similar assembly IDs, as shown in Figure 3-8. What differs the developed model from work of others (see for example, Ranjbaran et al., 2014) is the capability of calculating the cost of any contemplated change dynamically on top of finding the total cost of a project.

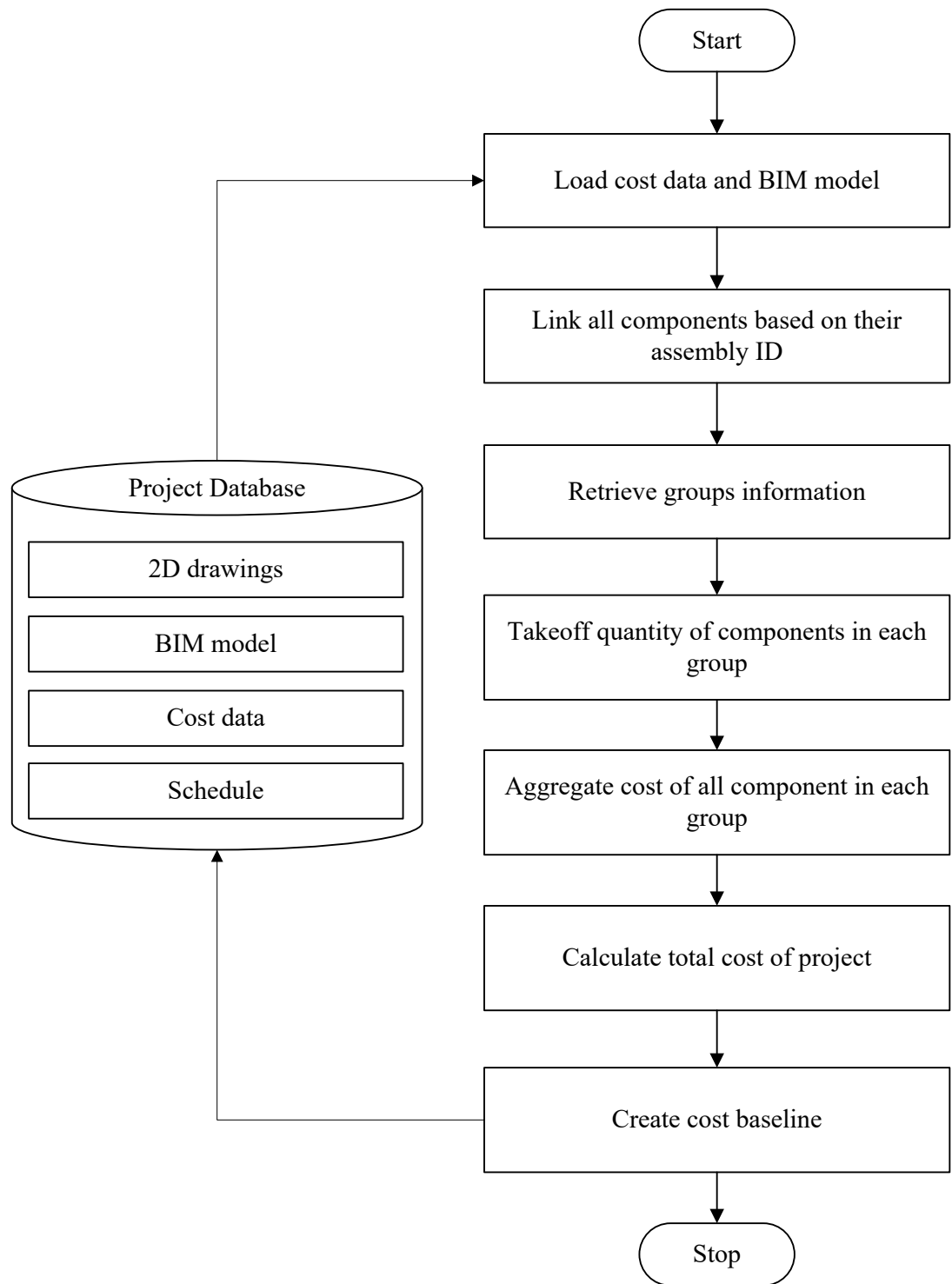


Figure 3–8: BIM-based Micro Cost Data Model (5D)

### **3.3.4 Change Compilation and Transferring to the BIM Model**

This research focuses on design change, as it is ranked as the most common type of change in the construction industry (Motawa et al., 2007). It is defined as any change requested by owner before starting or during the construction phase of the project. The owner either provides a list of contemplated changes and submits it to the designer, and the designer then applies them to the architectural model in order to visualize them for the owner, as shown in Figure 3-9. Then the architect, after receiving this list, ensures that the changes are only applied to the architectural system of the project, and filters out the non-architectural changes. Then the architect introduces these changes to the BIM model and sends the model to other project system experts for review, and they adjust and modify the other project's building systems model in case that change impacts other systems. Then, the new building system adjusted BIM model is sent back to the architect, and the architect starts integrating the new building systems design into the architectural system. Then, the architect saves the developed integrated model as a new as-changed version of the as-planned BIM models. The developed as-planned BIM model and as-changed BIM model then input for data analysis in order to begin the process of tracing the ripple effect of the changes on other systems of the project including architectural. Impact analysis is then performed decision. This is accomplished by keeping the beneficial changes and removing the undesirable changes that might not comply with the budget limitations.



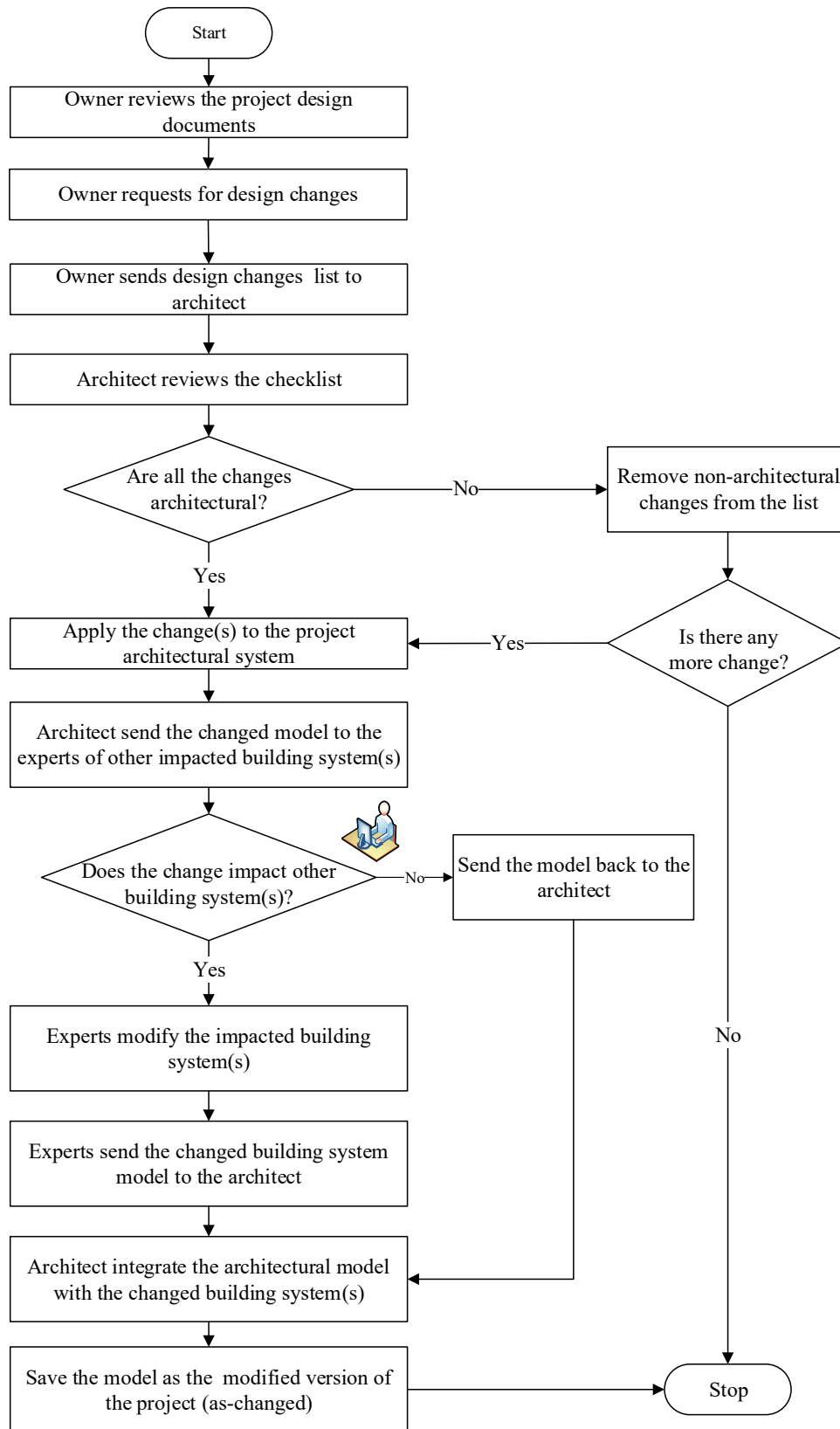


Figure 3–9: Change Compilation and Transferring to the BIM Model

### **3.4 Data Analysis Framework**

The data analysis framework consists of three main modules: a) ripple effect visualization, b) time impact analysis, and c) cost impact analysis. The proposed model begins the analysis of these impacts by a comparison method, which means the model starts to compare the as-planned BIM model with the as-changed BIM model. This analysis procedure is based on a component-by-component comparison between the two BIM models, as shown in Figure 3-10, which provides a list of impacted components along with their change type and quantity. Each component in both models has an ID that eases the comparison part and timely generation of analysis results. By matching both BIM models, components' ID and quantities, the comparison model will detect the following change types:

- If the components are found in the as-planned model but not the as-changed model (deleted components). This applies to the types of design changes where the owner decides to remove one or more component from the as-planned model;
- If the components are found in the as-planned model but not in the as-changed model (added components). This applies to the types of design changes where the owner decides to add one or more components to the as-planned model;

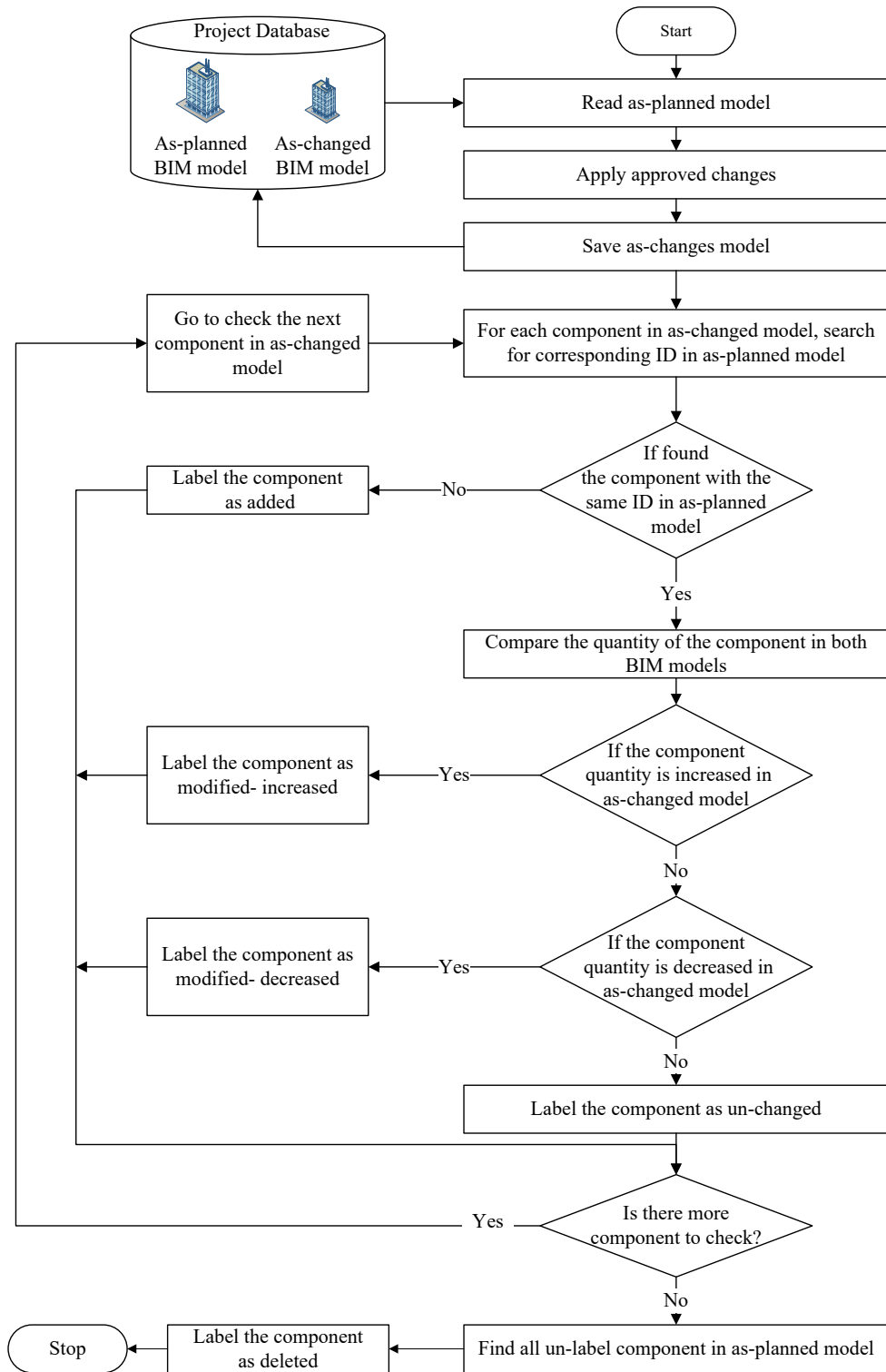


Figure 3–10: Identifying the Impacted Component, its Change Type and Quantity

- If the components are found in both models, but the component's specifications have changed in the as-changed model (modified-increased or modified-decrease components). This type covers the design changes where the owner changes the specifications of one or more components in the as-planned model. For instance, the component's modification could be material and/or geometrical, such as, length, width, and height; and
- If the components are found in both as-planned and as-changed models identical these components are marked as "un-changed components".

A simple example is given in Figure 3-11, which shows different types of comparisons. This example shows the four types of changes that can be applied to the windows of a small office. After the comparison of the two models, the proposed model recognizes and traces the differences between the two models. As demonstrated in Figure (3-11-a), the user has deleted one of the windows in the room, and in Figure (3-11-b) the user has added new windows to existing ones in the room. In Figure (3-11-c), the user modified the specifications of the two existing windows by decreasing their height, and Figure (3-11-d) shows no difference between the two models, which means the user did not apply any changes to the windows. The proposed model stores the comparison analysis between the as-planned and as-changed models in its database. The stored data can provide the list of the entire direct and indirect impacted components along with their change type and quantity.

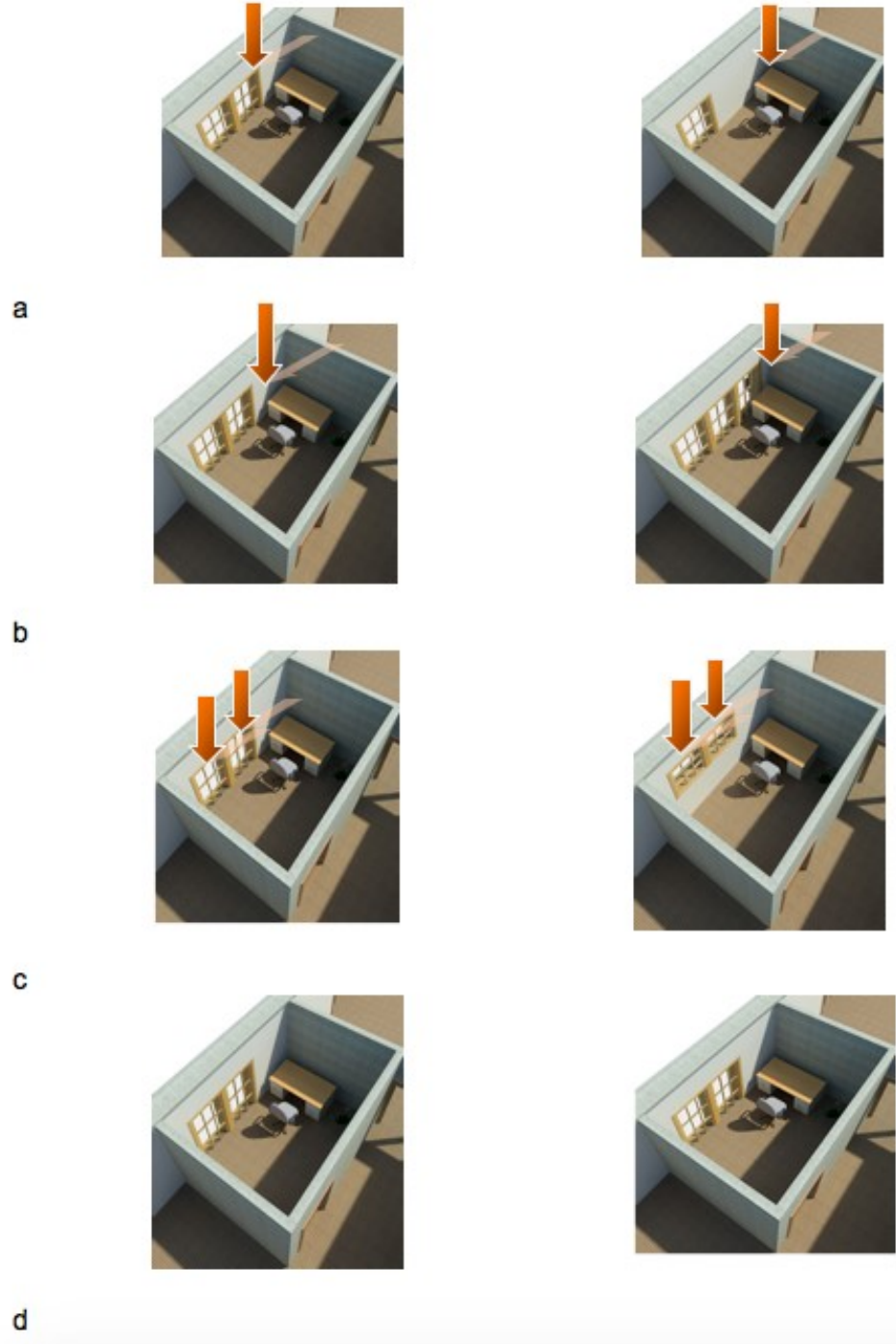


Figure 3–11: Proposed Model: Detection Types

### 3.4.1 Change Ripple Effect Visualization Module

A direct change in one part of the project may cause several indirect changes in other part(s) of the project. Figure 3-12-a demonstrates an example of a change in the ceiling height of a room. Since the ceiling of the room is connected to the room's surrounding walls (Figure 3-12-b), these walls also need to increase in height because they are connected to the ceiling (Figure 3-12-c). In this case, the revised height of the walls is considered an indirect part of the design change, which means that the height of the walls changes only if the height of the ceiling is changed (Figure 3-12-d). In other words, an indirect impact exists in the condition when a “direct impact” exists due to the contingent relationship between the direct impact and indirect impact. Therefore, due to the interdependency between all components of the project BIM model, that change may have an impact on other components, such as those of the HVAC system.

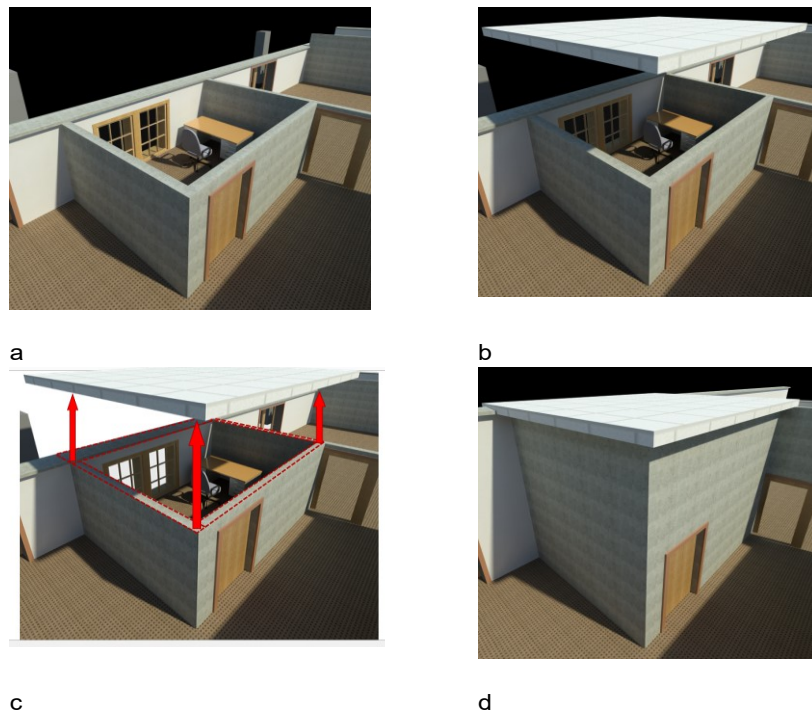


Figure 3–12: Direct and Indirect Impacts

Current BIM tools are able to update the entire model according to the first change. By the time a change happens in the attributes of a component, all the other components' attributes related or connected to the first-changed component adjust automatically. The automated changes in the BIM environment happen according to the existing connectivity and defined relationships between the components of the BIM model. Therefore, when the user changes a component, all other components connected to it correspondingly change. Two types of connectivity can exist between the BIM's components: physical connections and logical connections. For example, the user changes the height of a wall in the BIM model, and the column attached to that wall is automatically impacted. As a result, the height of the column is changed due to the physical connectivity between the wall and the column. Besides the height of the column, the other specifications of the column stay unchanged because they are unique to the column, like the column diameter, width, and material. Unless the change does not meet the structure analysis requirement provided by the engineering team. For example, by changing the column's height, its slenderness ratio is exceeded then its width must get adjusted relatively.

The user can provide some constraints in BIM during the model development stage, which establishes logical relations between the components of the BIM model. For example, the user can define a constraint between the height of the column and its width, which means that whenever the column's height is changed, its width changes according to the proposition defined by the user between the column's height and width. Therefore, these constraints define the logical connections between one component and another. In other words, there is a physical connection between the BIM components; it does not

mean if a change happens in one component, all the other connected components to the changed-components will get changed too.

In order to trace the relationships between the changed component and the other components, the first step is to determine the relationships and connections between the changed-components and the other project components. For the ripple effect analysis of the change, tracing is used, which means finding the indirect changes that occur due to the direct changes requested by the owner of the project. The problem with this automated process is that tracing and finding changes that happen in response to the main requested design change is very time-consuming and challenging. Also, if the system happens to deal with more complex projects involving many components and attributes, this process becomes even more complicated.

For example, a wall is attached to a window, a door, the roof, floor, etc. The component not only has a connection to other architectural components, but it also has a connection to the components of non-architectural systems. Therefore, finding this relationship and connections is the primary step in modeling the ripple effect of the change. The micro-level WBS will ease this process. By using the model comparison database and micro-level WBS, the proposed model is able to trace the relationships between the changed component and the other components connected to it, which means finding the design change path or the change sequence and visualizing the change path in the project's model.

The proposed model traces indirect impacted components (via the ripple effect) by first finding the level (e.g. 1<sup>st</sup> floor) at which the selected direct change is located. The model then checks the components that are connected to the direct change in other levels,



searching level by level until every floor level is scanned. The model starts at the first level and finds connected components to the components receiving direct change, identifying all found components and matching component IDs with the component IDs in the impacted component database. Then it selects all the impacted components one by one and identifies the connected components in the next level (2<sup>nd</sup> floor).

This process continued up from one level to the next and from the components found in the next level, the model identifies the impacted components using the same matching process. Then it selects the first impacted component in the 2<sup>nd</sup> level and finds the components that are connected to it to the next level (3<sup>rd</sup> floor). When the proposed model gets to the last component in the last level it saves this path. Then it follows the saved path to return to the first impacted component in the first level. Then it selects the next impacted component in the first level, and performs the same procedure to get to the last level and again get back to the first level by using the second saved path.

This process is respected until there are no more impacted components left on the first level, which is connected to the component receiving the direct change. The proposed model uses the generated paths to visualize the indirect impacted components by highlighting them in the BIM model. The process is shown in Figure 3-13 as (K), representing direct change, (i) project levels, (j) project components, and (n) is the number of components exists in each level.

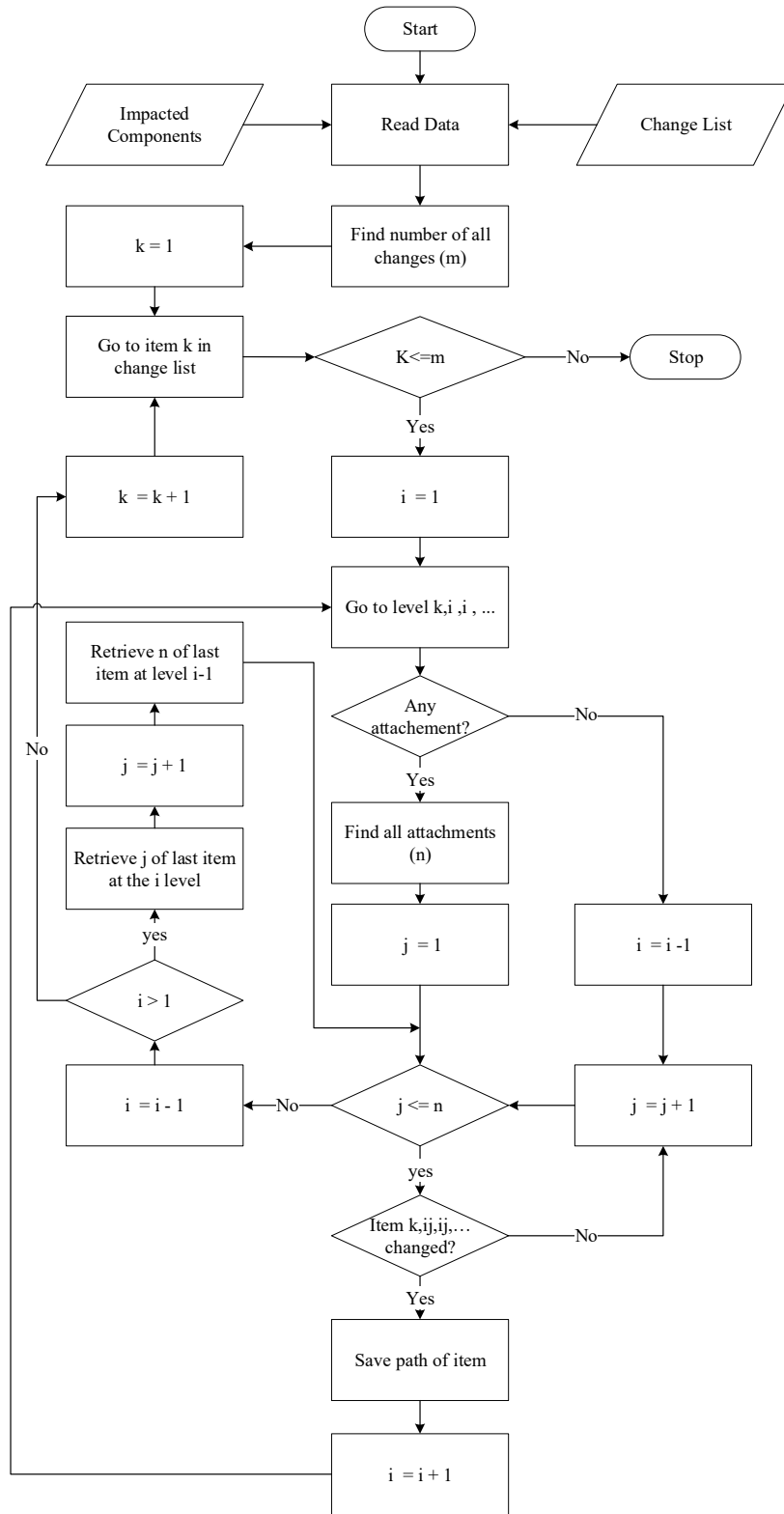


Figure 3–13: Change Ripple Effect Analysis

The proposed change ripple effect analysis procedure is explained in the simple example shown in Figure 3-14. In this example, there are four levels (i) (1 to 4) and three direct changes (k=1,2 and 3) located in level (i=1). The proposed model starts with change k=1 and by scanning the other levels (i) is able to find out the impacted components that are connected to the direct change in other levels (i=1 to 3). The number of components (n) identifies at this level (i=1) is three (n=3). The proposed model for every level by searching for each levels components in the impacted components database identifies the components that get impacted indirectly by the direct change (K). If the levels' components are found in the database list, it considered as an indirect impacted component. In level (i=2), among components (j=1 to 3) (roof, door, slab), (j=2) (door) and (j=3) (slab) are get impacted indirectly by (k=1). Then, the proposed model starts with each impacted components one by one and apply the same procedure, in this example it starts with j=2 and goes to the next level (i=3). In level (i=3) there are four components (n=4) that are connected to the component (j=2) and (j=2), (j=3) and (j=4) are found in the impacted components database. The ripple effect for (j=2) and (j=4) in level (i=3) is stopped here since there are no components connected to them in level (i=4). So, the proposed model from (j=3) goes to the next level (i=4) that has connected components which are (j=1) and (j=2). From the two components in level (i=4) only component (j=1) is impacted.

The ripple effect of (k=1) is stopped at this level (i=4) since there is no more level and components left. It means the change paths (k, ij) at this level generated here for (k=1) are: (k<sub>1</sub>, 22), (k<sub>1</sub>, 22, 32), (k<sub>1</sub>, 22, 33), (k<sub>1</sub>, 22, 34), (k<sub>1</sub>, 22, 33, 41). Then, the proposed model follows the above-mentioned change path backward to get to the (k=1)

in level ( $i=1$ ) and then it starts to identify the second impacted components in level ( $i=2$ ) which is ( $j=3$ ). The second change path for ( $k=1$ ) is ( $k_1, 23$ ) since there is no more connectivity between  $j=3$  and other the next level's components. Also, the ripple effect analysis of direct changed component ( $k=1$ ) is stopped here since there are no more impacted components in the level ( $i=2$ ). Then, the proposed model does the same procedure for the next direct changes ( $k=2$  to  $m$ ) that exist in level ( $i=1$ ).

To summarize, the proposed model for each individual direct change traces all the related components in the horizontal level and in then in the vertical level. It starts with one of the impacted components in the first horizontal level and it goes vertically down levels till there are no more levels left, and it finds the path of impacted component throughout all the levels; then it goes backward to get to the first level. Then, the same process is enacted for the all impacted components in the first horizontal level till there are no more impacted components left in that level. The ripple effect works as a tree diagram: on top of the tree the individual direct change is located, and in the other levels are all the other components connected to the direct change.

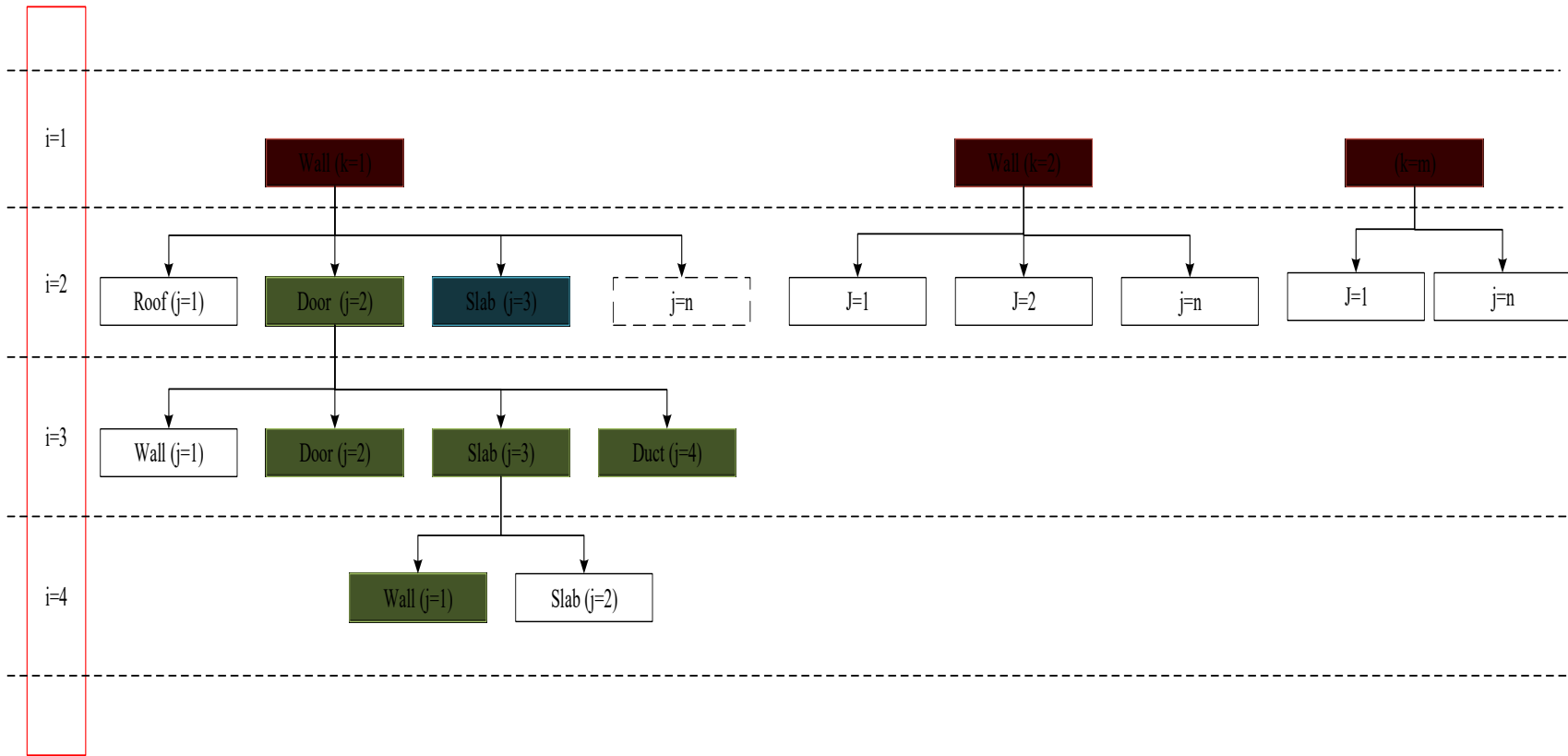


Figure 3–14: Change Ripple Effect Analysis Model Example

### **3.4.2 Change Time Impact Analysis Module**

The purpose of the change time impact analysis module is to develop a BIM-based model capable of calculating the number of days that need to be added or deducted from the project's total duration due to change impact. By calculating the total number of days needed for each of the project's impacted components, the proposed model is able to estimate the change impact on the total duration of the project.

As shown in Figure 3-15, in order to evaluate the impact of change on project schedule, a database that includes the list of all components impacted due to the applied changes to the project's as-planned model along with their change type (addition, deletion, and modification) and quantity is necessary as a main input to run change time impact analysis. The development of that database is explained in Figure 3-9. Then, the proposed model for every direct and indirect change type determines the number of days needed to complete each impacted component.

The proposed model uses labor hours and component quantity, which both are available in the model's database to calculate the duration of the impacted components from change 1 to n to find out the number of days needed to complete each of the impacted components. The user can use the proposed model for different change scenarios to calculate the change impact on project time. The time impact can be calculated for a change, combine some changes or for the entire design changes.

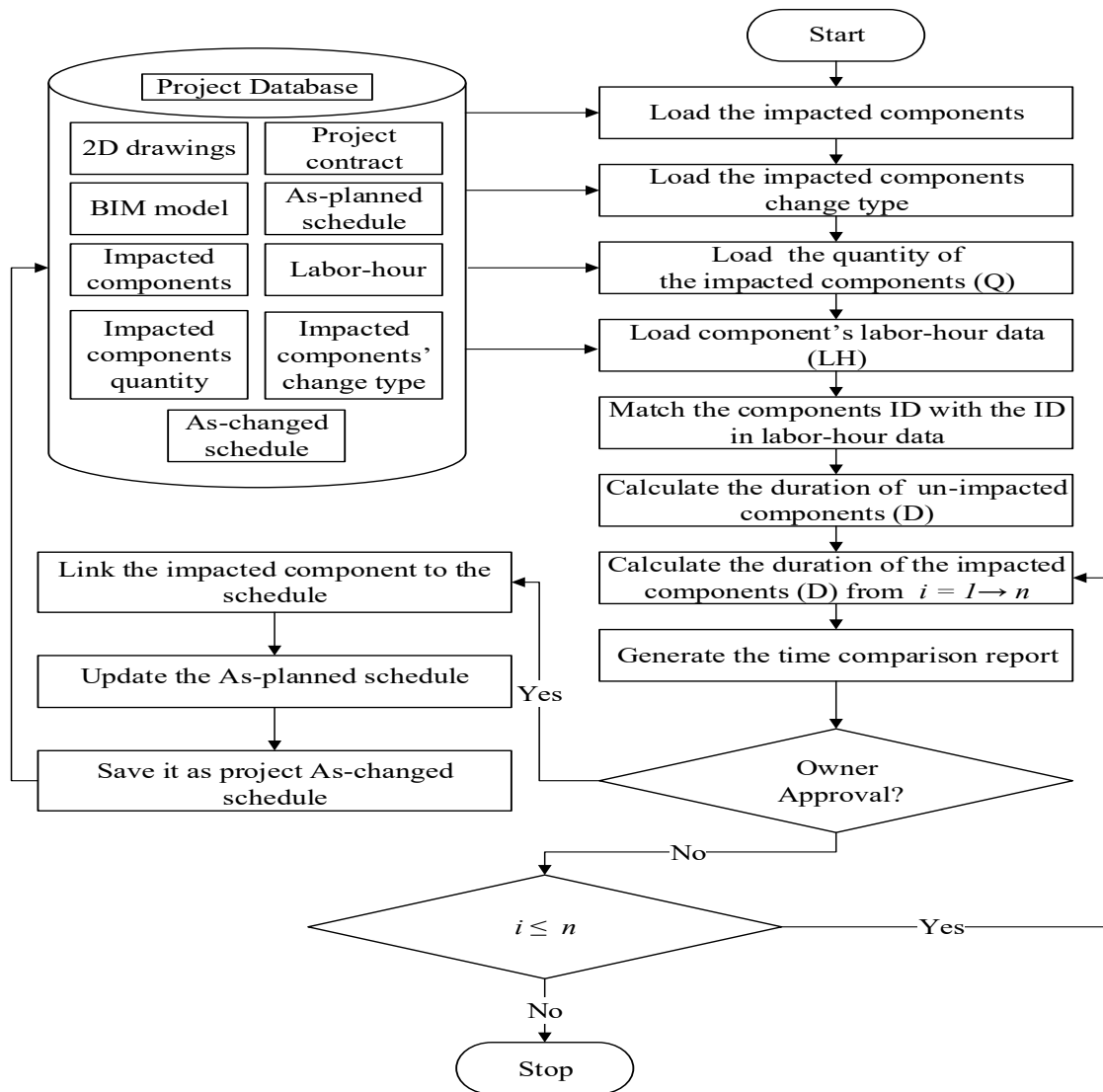


Figure 3–15: Change Time Impact Analysis Module and Schedule Linking

Different responses are needed to assign duration for each change type. An addition means that a new component is added to the project, so there is no duration time available for the newly added components. Therefore, new duration data is needed. To do this, the proposed model uses Equation 3-1 (Leonard et al. 1991), where  $D$  is the component's duration,  $P$  represents productivity which calculated by dividing labor hour (LH) by unit of work, and  $Q$  shows the component's quantity. Also, Equation 3-1 is used to calculate the un-impacted components' duration for the entire model, which is

common to both as-planned and as-changed BIM models. When the change is a deletion of a component, the duration time for that component is available, and the only action that needs to be done is changing that duration to zero days.

$$D = P \times Q \quad \text{where,} \quad P = \frac{\text{Labor hour (LH)}}{\text{Unit of work}} \quad 3-1$$

For modification changes, the component is already part of the model, and its specification is changed. Therefore, the duration for the changed component is available and needs to be modified based on the components' new quantity. The proposed model uses Equation 3-2 (Leonard et al. 1991) to calculate the component's duration, where  $\Delta Q$  represents the component's quantity differences between the as-planned and as-changed projects, as given in Equation 3-3 (Leonard et al. 1991).

$$D = P \times \Delta Q \quad 3-2$$

$$\Delta Q = Q_{as-planned} - Q_{as-changed} \quad 3-3$$

The result of the duration estimation for modification changes can either be negative or positive, which means that days may be added to, or deducted from, the as-planned model. The proposed model's database consists of labor-hour data used to identify the labor-hour for the project's impacted components, so for this matter, the impacted components' IDs are matched to the components IDs in the labor-hour database. After assigning the updated duration for every changed component in the as-changed version of the project, the next step is to link the estimated duration to the as-planned schedule in order to update the as-planned schedule and provide an as-changed version. In other words, the duration of the project's 4D as-planned schedule is replaced with the estimated duration of the impacted components, and an updated project schedule is generated. The grouping, as explained in section 3.3.2, eases the process of linking the



impacted components to the as-planned schedule and getting the update. The updated schedule provides the number of days needed in order to complete the entire project, or the project's new total duration.

The project owner can use the newly updated project schedule in order to see the quantification of the ripple effect of all design changes. The owner can then compare the total duration of the updated project schedule with the as-planned project schedule to determine whether the changes are going to save or add more time to the project duration. In addition to total duration, the duration needed to complete each activity is given in the schedule. In this research it is assumed the project's new added activities have no overlap and their duration is additive and calculated by the summation of all the impacted components' number of days within that activity so that the owner can see the components' duration in the updated project schedule on a smaller scale. If the owner approves the changes, the as-changed schedule is then created. If not, the owner uses the as-planned schedule.

### **3.4.3 Change Cost Impact Analysis Module**

One of the main reasons for change management is to have control over the cost of the project and respect owner's budget constraints. From the owner's point of view, knowing the cost of a change assists in making better decision-making. The cost of change consists of different parts, which should be considered in estimating the cost of that change. In this study, the proposed model uses Moselhi's (1998) change cost estimation framework in order to calculate the cost of change, as shown in Figure 3-16.

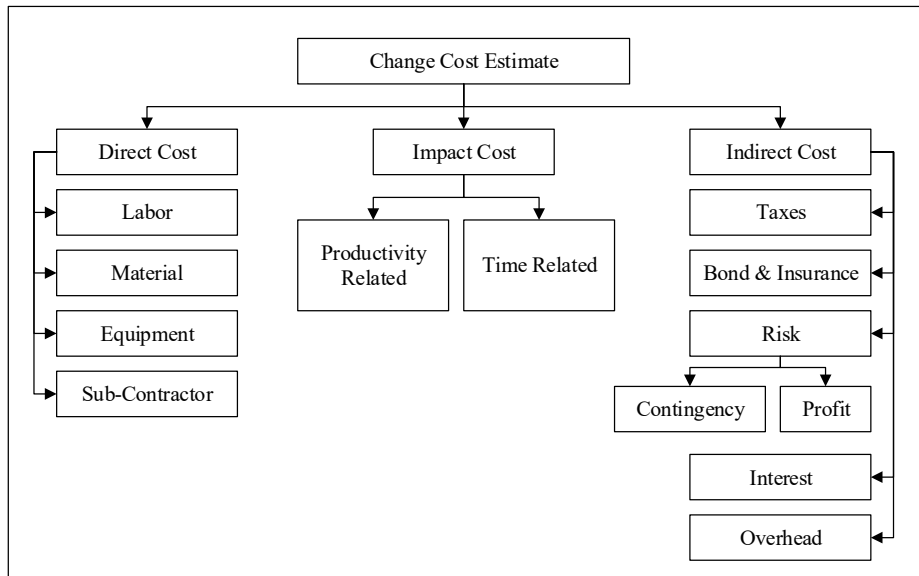


Figure 3–16: Change Cost Estimate (Moselhi, 1998)

This framework consists of three main categories: direct, indirect, and impact cost. Direct costs include project labor, material, equipment, and sub-contractor cost, while indirect costs include project taxes, bond, insurance, risk (contingency and profit), interest, and overhead. The project’s impact costs consist of productivity- and time-related costs. Therefore, the summation of project’s direct, indirect, and impact cost results in the project’s total cost.

As shown in Figure 3-17, a database similar to the time impact one is used for calculating the impact of change on project cost, including the list of all components impacted due to the applied changes to the project’s as-planned model, along with their change type (addition, deletion, and modification) and quantity. The development of the mentioned database is explained in Figure 3-9.

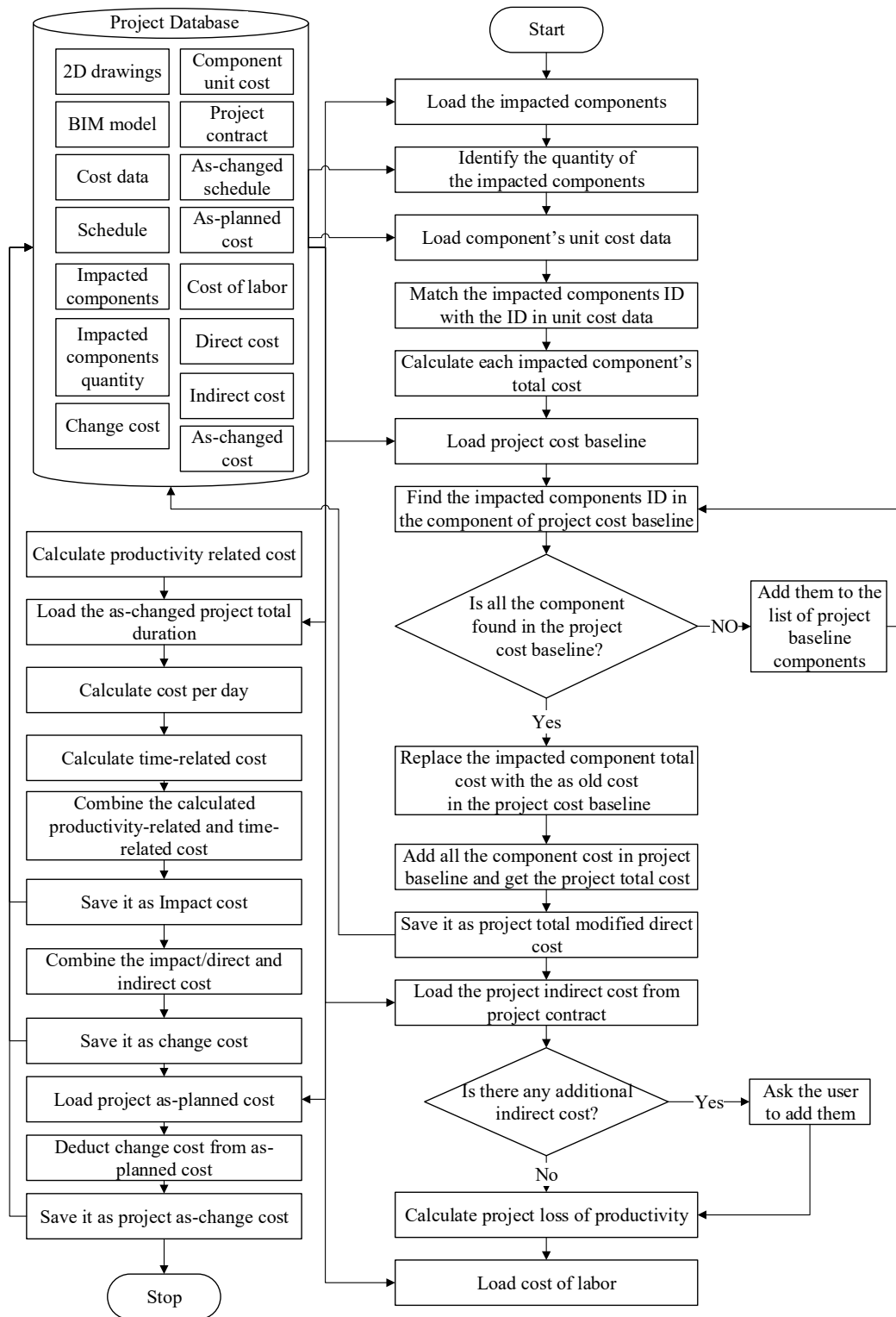


Figure 3–17: Change Cost Impact Analysis Module

The proposed model for each type of change uses different responses to determine the costs needed to complete the impacted components. When the change type is a deletion, the cost data for the deleted components are available, and zero cost should replace the component cost. When the change type is an addition, a new component is added, and there is no cost data available for the newly added component, which means it needs to be assigned. The proposed model uses Equation 3-4 (Moselhi, 1998) in order to calculate the added component's cost, where  $Q$  is the component's quantity, and  $C$  is the component's unit cost:

$$\text{Estimate component's cost} = Q \times C \quad 3-4$$

When the change type is modification, the components unit cost is available, but needs to be adjusted based on the component's new quantity. The proposed model for the modification change type uses Equation 3-5 (Moselhi, 1998) to estimate the component's cost, where  $\Delta Q$  represents the component's quantity differences between the as-planned and as-changed project's components, as given in Equation 3-6.

$$\text{Estimate component's cost} = \Delta Q \times C \quad 3-5$$

$$\Delta Q = Q_{as-planned} - Q_{as-changed} \quad 3-6$$

The result of estimating the modified component's cost might be negative or positive; therefore, the modified components may increase or decrease the total cost of the project. The proposed model's database consists of component unit cost data extracted from RSMMeans cost data, and it is used to identify the unit cost for the project's impacted/un-impacted components, so for this matter, the project impacted components' ID is matched to the components IDs in the unit cost database.

After estimating the cost for every impacted component being added, deleted, or modified, the proposed model updates the project cost estimation document and calculates the total modified direct cost. The proposed model combines all the newly estimated costs for the impacted components with the un-impacted components available in the project's model and provides a modified version of the project direct cost estimation. Therefore, the proposed model generates the project's modified direct cost estimation by assigning a cost to the components, replacing the deleted components cost with zero and the modified components with the calculated adjusted cost. The project's modified direct cost estimation provides data related to the amount of direct cost required to construct the entire project.

After estimating the direct cost, the proposed model estimates the project's changes in cost. As shown in Figure 3-16, the total change cost is calculated by adding the direct cost, indirect cost, and change impact cost. For indirect costs, project taxes, bonds, insurance, risk (contingency and profit), interest, and overhead are needed, reflected in the form of input by the user from the project's as-planned contract. The project's impact cost, consisting of productivity and time-related costs, is calculated by the proposed model, as shown in Equation 3-7 (Leonard et al., 1991):

$$\text{Impact cost} = \text{Productivity Related} + \text{Time Related} \quad 3-7$$

Equation 3-8 (Leonard et al., 1991) is used to estimate the productivity-related costs (LP), representing the loss of productivity on a percentage change, and Equation 3-9 (Leonard et al., 1991) is used to estimate time-related costs:

$$\text{Productivity related} = \text{LP} \times \text{Cost of Labor} \quad 3-8$$

Time related Cost

3-9

$$\begin{aligned} &= \text{Extension from original duration of the project day} \\ &\times \text{Cost (per day)} \end{aligned}$$

The factors needed to calculate the productivity-related impact cost are the loss of productivity on percentage change (LP) and cost of labor. Cost of labor is direct input data provided by the user based on the agreed-on contract price. For calculating the loss of productivity on percentage change (LP), this study uses the (Leonard, 1991) model. The latter model calculates impact cost for both civil/architectural and electrical/mechanical works based on (Equation 3-10), where (a) is y-axis intercept, and (b) is the slope of a line, and x presents the change percentage:

$$LP = a + bx \quad 3-10$$

Parameters (a) and (b) are taken from Table 3-1, where the type of work is divided between A and C. A denotes electrical and mechanical building construction, and C denotes civil and architectural work and type of impact is divided into 1, 2 and 3. One (1) means the project has only changes, two (2) and three (3) apply to change plus one major and change plus two major causes of impact respectively. Acceleration, congestion, staking of trades, inadequate scheduling, and inadequate coordination is examples of these major causes of impact. Parameter (X) presents change percentage, calculated by Equation 3-11.

$$\text{Change percentage (x)} = (\text{change hours} / \text{planned contract hour}) \times 100\% \quad 3-11$$

Table 3–1: Linear regression of percentage loss of productivity on percentage change (Leonard, 1991)

Category		Linear regression	
Type of work	Type of impact	y-axis intercept (a)	Slope of line (b)
A	1	6.3	0.25
A	2	21.5	0.48

A	3	35.6	0.16
C	1	9.8	0.27
C	2	17.4	0.28
C	3	23	0.28

Then, to calculate change cost and cost variance caused by these contemplated changes, the proposed model adds up the indirect cost, direct cost and change impact cost. The result aids project owners in design change decision-making process. Owners can see if their requested design changes are worth doing or not.

### 3.5 Reporting and Highlighting Framework

By identifying and calculating the cost and time impact of owner-requested design changes, the proposed model is able to provide a comparison report to the user in order to assist the change decision-making process. The report shows all the affected components with their newly assigned unit costs and durations. The report also includes information about as-planned components, so that the user can see the differences between the as-planned model and as-changed model components. Table 3-2 is a sample of the reporting module.

Table 3–2: Proposed Report Module

Project Impacted Components Data							
As-Planned Model				As-changed Model			
ID#	System	Unit Cost	Duration	ID#	System	Unit Cost	Duration

At the same time, the compared model visualizes the differences between the two models by highlighting the changes in the two models in the report by using different

color codes for the different results of the comparison. For instance, components that exist in both models but their specifications are changed in the as-changed model are indicated in yellow in both as-planned and as-changed model report. Components that are in the as-planned model but not in the as-changed model are visualized in red in the as-planned model report. Components that are in the as-changed model and not in the as-planned model are visualized in green in the as-changed model report. The components that stay the same in both models after the owner applies design changes appear as is in both sides of the report. Therefore, the user can receive the report from the proposed model, which provides all the information with regards to a changed component and the impact of those changes at the total project cost and total duration. Having all of this information allows users to make the best decision about accepting, modifying, or refusing the contemplated design change(s).

The proposed model provides another type of report to the user for the ripple effect of the requested changes. The report provides the changed path based on the project building system for each change by selecting the direct change in the model. In the ripple effect analysis report, a highlighting ability is designed in order to link the ripple effect report to the model when the user wants to see a changed component in the model. It is available by simply clicking on the component ID in the report, and immediately the clicked component is highlighted in the project's model view. The proposed model provides this highlighting in all model views, such as 3D, plan, section, and elevation views. In other words, the report table and project model view are integrated to give better visualization ability to the owner. This process is summarized in Figure 3-18.



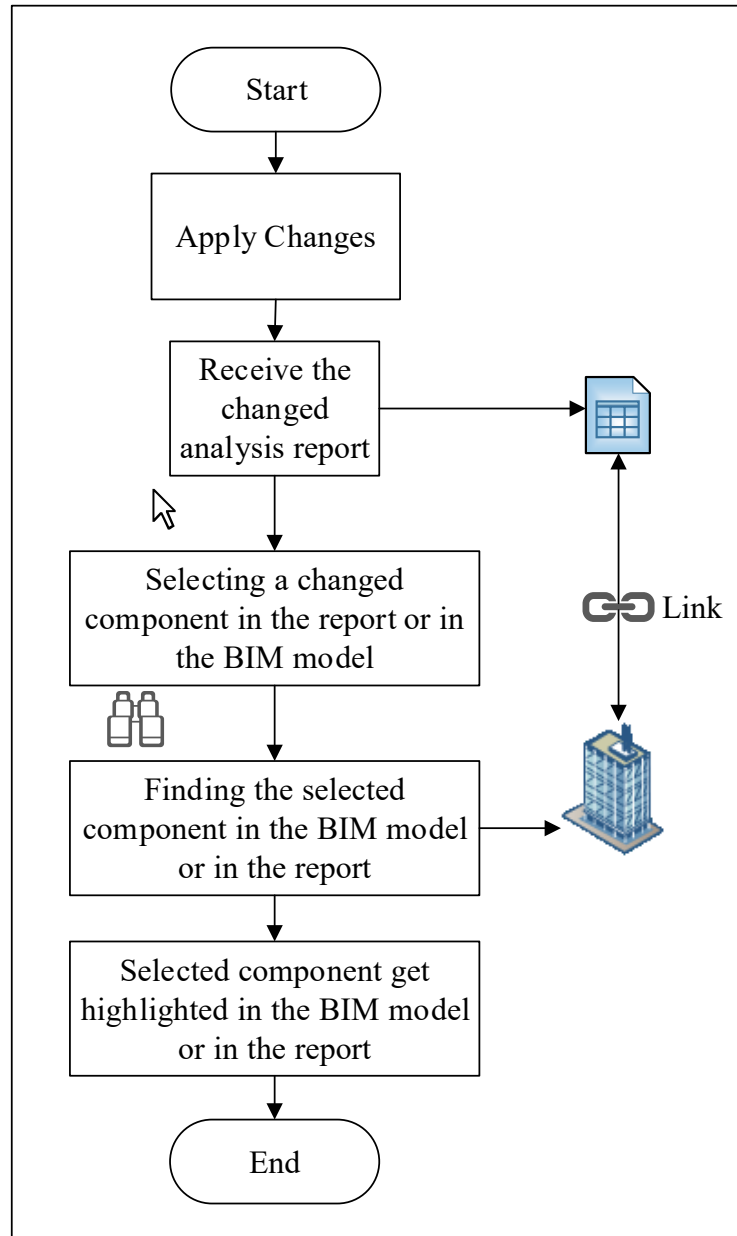


Figure 3–18: Reporting and Highlighting Framework

### 3.6 Data Filtering Framework

The filtering option in the proposed model gives users the ability to easily filter out some of the requested changes from the report by defining the constraints of the project. This allows each user to determine which of the changed components are more costly and/or which will cause more delays to the project and increase the total project

duration. For example, the user can limit the cost and duration of the changed components, and the report will be updated by highlighting only the changes that are within the defined constraints. Then, the user may prefer to omit some of those changes that result in over budget or get behind schedule, and these decisions could very well be based on the degree of impact. The user can also define different scenarios and view the related time and cost results.

The filtering portion of the model will introduce several alternatives to the users that can be used to assist them in choosing the most beneficial and acceptable changes. The final report has additional beneficial changes that will be saved to the project database and can be used for change monitoring and process control when construction begins. The filtering module is shown in Figure 3-19.

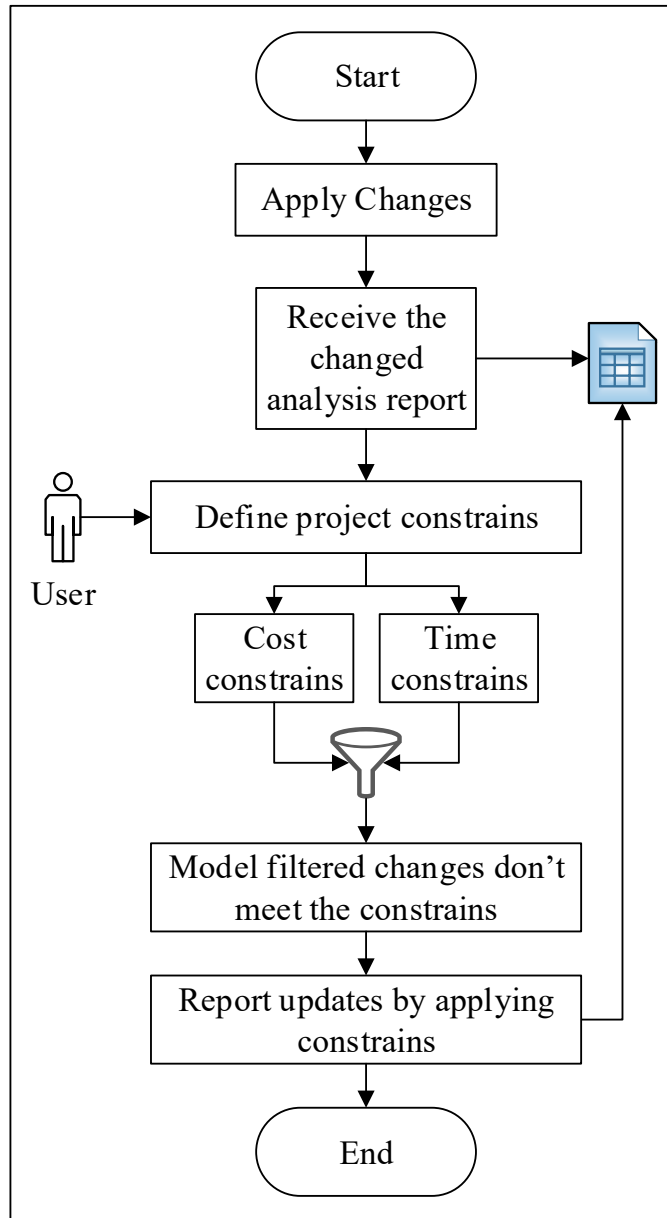


Figure 3–19: Data Filtering Framework

### 3.7 Summary

An overview of the proposed model has been presented, and its components, frameworks, modules, and procedures are described. The model consists of integration and automation processes, utilizing BIM in an adaptive way to facilitate change management application. The proposed model integrates project visualization

information aspects in 3D, automated time change impact analysis for 4D analysis, and automated change cost impact analysis as 5D.

The proposed model is flexible and can be used to evaluate three different change scenarios based on the owner request:

1. Evaluate each change individually and generate separate impact analysis report for each change;
2. Evaluate all contemplated design changes and generate one cumulative impact analysis report; and
3. Evaluate group of changes that are selected or prioritized by the owner from the list of contemplated changes.

The flexibility of the proposed model can assist owners in selecting the most beneficial changes by understanding the full ramifications of the changes through the generated analysis reports.

# Chapter 4: Computer Implementation and Validation

## 4.1 Introduction

This chapter presents the computer implementation of the developed model. It includes the data acquisition framework and the change ripple effect visualization, change time and cost impact analysis from the data analysis framework and the analysis report of the impacted components from a reporting and highlighting framework, and report filtering from the data filtering framework.

## 4.2 Developed System

The main BIM platform of the developed model was implemented with Autodesk Revit Architecture 2014, which allows for the auto-adjusting of building components by the time they are affected by design changes. Revit Application Programming Interface (API) was then used to develop the following six add-ins in a C# environment:

1. Check Change: this add-in is designed to automatically detect the changes between the as-planned and as-changed BIM models and visualize the type of change utilizing a color-coded algorithm;
2. Ripple Effect: this add-in automatically detects the cause and effect relationship between the direct and indirect changed components. It can also analyze and visualize the ripple effect of the design change on other components of the model;
3. Room Grouping: this add-in is designed to help users to manually develop a micro-level WBS by selecting the components that belong to the same room (area), floor or building systems and generates a unique ID for the selected group;

4. Time Impact: this add-in is developed to automatically calculate and quantify the ripple effect of owner-requested design changes on a project schedule and link the impacted components duration to project as-planned schedule;
5. Cost Impact: this add-in automates the quantification of owner-requested design changes ripple effect on project cost; and
6. Data Filtering: this add-in enables users to narrow down the data in the project as-planned and as-changed model report, allowing the users to view only the information needed.

The development of each add-in is explained in the following subsection. These add-ins are categorized based on the four frameworks of the developed model: data acquisition, data analysis, reporting and highlighting, and data filtering.

#### 1. Data Acquisition Framework

There is no add-in developed for the data acquisition framework, but the data generated in this framework is the main input of the data analysis framework add-ins (Check Change, Time Impact, Cost Impact). In this framework, the as-planned and as-changed BIM models are developed, which provide data to the above-mentioned add-ins such as component specification, family, type, assembly code, assembly description, and unique ID. The family represents the main description of objects, such as a wall, door, window, column, etc., and the type represents a specific kind of a family object, such as a 450mm round column, or a 600mm rectangular column. The assembly code represents a type of component, and the unique ID represents the individual components. After the generation of both as-planned and as-changed BIM models, the components of both BIM

models are saved to a central database including the above-mentioned characteristics of each component.

## 2. Data Analysis Framework

The add-in belong to data analysis framework are Check Change, Time Impact and Cost Impact, which are explained here in following subsections. In order to run the add-ins the user has to open the two BIM models in Revit and select the as-planned BIM model as the base model; the other is automatically saved in the system as the as-changed model. The user can alter the as-changed model even after opening it in the interface, but the system does not allow any changes to the as-planned base model. Then, the user can run the data analysis framework add-ins one by one.

### 4.2.1 Check Change Add-in

The developed Revit add-in Check Change provides the user with 3D BIM visualization and color-code highlighting of the all impacted components due to the contemplated design change. The developed add-in uses the data captured in the generated central database to identify the differences between the two BIM models by running a component-by-component comparison. The add-in compares the quantity of the component with the matched IDs to identify their change types. Therefore, the result of this comparison provides a list of all components that are added to, deducted from, or modified in the as-changed BIM model. The add-in highlight the list of impacted components in the BIM models and also provides a color-code report to aid the understanding the three change types in both report and models. The Check Change add-in report has two sides, one for the components of the project as-planned, and the other for the components of the project as-changed. The report lists all the added components

on the as-changed side, all the deleted components on the as-planned side, and all the modified components on both sides.

The developed add-in also highlights the types of changes by a different color code in both BIM models and the report: red for deletion, green for addition, yellow for modification. The same color-coding is used through all the developed model add-ins to differentiate the impacted components' change types (addition, deletion and modification); this feature is used to visually represent the proposed changes in the developed model. The list of changed components and the report, and components' quantity are then used to identify the ripple effect, time impact and cost impact of each contemplated design change. The next add-in, Room Grouping, is developed to ease the application of the Ripple Effect and Time Impact add-ins introduced in the following subsections.

#### **4.2.2 Room Grouping Add-in**

The developed Room Grouping Revit add-in is based on the developed micro-level WBS, which groups the project's floor in designated areas and gives the same ID to components that are located in the same area as in the as-changed model. So, all the components that belong to the same group (area) carry the same group ID. The group ID is used to run the ripple effect analysis for each changed component of the as-changed model. The user can also define the group based on the components that are located on the same floor, and do the selection based on project building systems.

#### **4.2.3 Ripple Effect Add-in**

This developed Revit add-in does the ripple effect analysis on two bases: by finding the components that the direct change is connected to (same group ID) or



surrounded by (different group ID) throughout the building, horizontally and vertically, and then identifies which of those components are impacted indirectly. As a result, the developed model provides the user with the change's path, which means the direct change and its consequences. The ripple effect add-in is only applicable after the grouping of all the components of the as-planned and as-changed model, after grouping the user selects the individual direct changed components in the as-changed (if the change type is addition and modification) or as-planned (if the change type is deletion) model's architectural system based on the owner's requested design changes. Then, the system lists the components that are impacted due to the connection with the selected direct change and belong to the same group. The generated list of components is only the ripple effect of the selected individual direct change and does not include the rest of the impacted components that exist in the project. The add-in is able to trace the change path for one selected individual direct change at a time.

The developed add-in provides the result of the change's ripple effect analysis in two different modes, and the user has access to both modes at the same time. The first mode is to provide the analysis of the change's ripple effect in report format, in a Revit interface. In the report, the user can see the direct change along with the list of its impacted components. The report consists of two parts; the first part belongs to the as-planned model and the second part belongs to as-changed model. The report for both BIM models provides the type of discipline for each component, change type (modification, addition, or deletion), component ID, and location of components. The report also shows the component's virtual information such as family type, assembly code, and assembly description. By reporting the information of as-planned and as-

changed BIM models side by side, it eases the understanding and recognition of changed components' location and the building systems that they belong to. Color code highlighting of BIM models is used in the second mode to visualize the result of the ripple effect analysis and highlights the types of changes by a different color code in both BIM models. To find the cause and effect relationship, the user first selects a component as the direct change and the ripple effect of the selected change shows the BIM as-changed model. Therefore, the change path of the selected changed components gets highlighted in the as-changed BIM model. The developed add-in links the report and the BIM model; the user can select a component in the model and get the component's data in the report, and vice versa.

#### **4.2.4 Time Impact Add-in**

The developed Revit Time Impact add-in provides the user with a calculation of the ripple effect of the owner-requested design change(s) on project time and schedule. The add-in provides a report that consists of changed/new durations for all the components that get impacted due to each contemplated change and/or group of approved changes. Moreover, the add-in is capable of color-coding, highlighting, and differentiating the impacted components based on their change types (addition, deletion, or modification); this feature is used to visually represent the proposed changes in the proposed model. The developed add-in first needs input data, which should consist of a list of a project's components impacted by owner-requested design changes. In order to provide the required list of impacted components for time-impact analysis, the data needed is exported from the developed Check Change add-in. Therefore, by using a component-by-component comparison between components of the two as-planned BIM

models generates, a list of all impacted components caused by each contemplated design change is generated.

The Check Change add-in provides a report of all the impacted components from all project systems, which is used as the main input database for the developed Time Impact add-in. The Check Change add-in's report includes all added, deleted, and modified components that exist in the project's as-changed BIM model. The developed Time Impact add-in is coded in a way to be able to extract the impacted components change types from Check Change add-in's report and the components' quantity ( $Q$ ) from the Check Change add-in database, which is generated during the ID-by-ID comparison between components of the two BIM models to determine the type of changes. For deletion, the new quantity is considered zero; for addition and modification, the quantities are taken from the report developed in the Check Change add-in. This means that the difference between the old ( $Q_1$ ) and the new ( $Q_2$ ) quantity value of the component to be modified is calculated as ( $\Delta Q$ ) and the data used in Time Impact add-in.

The component's quantity ( $Q$ ) is used to calculate the duration of the impacted components; since the two main factors required for calculating the impacted component's duration are a component's quantity ( $Q$ ) and labor hours ( $LH$ ). Labor hours ( $LH$ ) are provided by an external database in format of Excel spreadsheet for Time Impact add-in is included in Appendix A. The LH database is generated based on RSMeans assembly data, since the components in the RSMeans assembly database follow the same format as Autodesk Revit, which define the components' family type, assembly number, and assembly description. However, in the RSMeans assembly database, a component's labor hour data is not provided. This study uses Al-Mashta's

(2010) technique to map RSMean assembly type into RSMean Unit Type (UNIFORMAT II) in order to generate the labor hour (LH) data (included in Appendix B). The Time Impact add-in links the generated list of impacted components with the labor hour (*LH*) database based on their assembly number and determines the labor hour value for each impacted component. After providing components' quantity and its related LH, the developed add-in uses the coded equations for a duration to estimate the duration needed for each component in the generated list of impacted components. First, the add-in divides components' labor hour value by unit of work to estimate productivity and it multiplies the calculated productivity by components' quantity to get its duration. The relationship between the quantity and labor hours corresponding to each component is linear in the proposed model by default. However, the system provides flexibility for the user to introducing a multiplying productivity factor. Therefore, the labor hours could multiply by a productivity-related factor in the BIM model, depending on the user's needs.

After calculating the impacted component's duration, the developed add-in provides a two-sided color-coded report that shows the components of the as-planned and as-changed models along with their duration on a component or project level. If the owner approves the changes proposed in the Time Impact add-in report, the developed add-in generates the as-changed schedule.

In order to generate this schedule, the developed add-in links the impacted components with the project 4D as-planned schedule by matching the impacted components' group IDs (generated by Room Grouping add-in) with project schedule activities that have the same group IDs. By linking the impacted components, the project

schedule components, activities, and total project duration all get updated, and the updated schedule is saved in the Revit database as the as-changed schedule. The as-changed schedule form that is saved in the CSV (“Comma Separated Values”) file exports to MS Project and the user can change the format from CSV to MS Project and then save the MS Project version of the as-changed schedule.

#### **4.2.5 Cost Impact**

The developed Cost Impact Revit add-in generates the report of project’s impacted components due to owner-led design changes along with the calculated costs needed to complete the impacted components and the total project cost. The Cost Impact add-in report also uses the color-code highlighting technique to ease the understanding of impacted components’ change type. The add-in is also calculates the change cost, which includes direct cost, indirect cost and impact cost (productivity and time-related cost). The two main factors in the estimation of the component’s cost are the component’s quantity ( $Q$ ) and the component’s unit cost ( $C$ ). The first main factor – quantity ( $Q$ ) – similar to Time Impact add-in, the data from the Check Change add-in is used to run the Cost Impact add-in, which means the list of impacted components are included, along with their change type and quantity ( $Q$ ). For deletion, the quantity is considered zero, for addition change type the new quantity is taken directly from the report developed in the Check-Change add-in, and for modification change type the quantity is calculated by finding the difference between the old ( $Q_{as-planned}$ ) and new ( $Q_{as-changed}$ ) quantity values, which means ( $\Delta Q$ ). For the second main factor – component’s unit cost ( $C$ ) – an external cost database is developed in the Excel spreadsheet format that provides the component’s unit cost ( $C$ ), using the RSMMeans assembly cost database (database samples are included

in Appendix C). RSMeans assembly codes' format follows the same logic as Autodesk Revit software uses to generate the unique ID of each component. Therefore, components in RSMeans and Autodesk Revit software carry the same assembly number and assembly description. The Cost Impact add-in links each impacted component to its unit cost (C) database by matching similar assembly IDs that exist between the impacted component list and developed cost database. After providing the cost for each impacted project components, the developed add-in uses the equation coded to estimate impacted component's unit cost by multiplying component quantity (Q) and the component unit cost (C).

The developed add-in exports the list of unimpacted components that stay the same in both the as-changed and as-planned project BIM models, along with the unit cost that exists in the as-planned model. Then, the unimpacted components are added to the impacted component report, and the output report is a list of the impacted and unimpacted components together with their estimated cost. The developed model then adds up the cost of the project's impacted and unimpacted components to get the project's modified direct cost. The total indirect cost can be input by the user, or the user can add the indirect cost to the add-in generated default indirect cost item form; the user is also able to add an additional indirect cost item to the default form.

The add-in then calculates the impact cost, which has two parts: productivity-related cost and time-related cost. In Equation 3-8 (Leonard et al., 1991), the user provides the planned contract hour from the project's as-planned contract, and the Time Impact developed add-in is used to get the project change hours since the Time Impact add-in provides the duration of the impacted components, and the Cost Impact add-in

adds up the impacted components duration to get the change hours and divides it by planned contract hours to get the change percentage (x). The estimates a, b, and x parameters are used in Equation 3-7 to determine the loss of productivity on percentage change (LP). Then, the estimated (LP) is multiplied by the cost of labor provided by the user to determine the productivity-related impact cost. The first factor needed to calculate the time-related cost impact is cost per day (cost per unit time), provided by the user from the project's signed contract documents.

To get the extension from the as-planned duration of the project day, the developed add-in uses the impacted component duration calculated by the Time Impact model and combines it with project's unimpacted components' duration to get project as-changed duration and then compares it with project's as-planned duration to get the extension from the as-planned duration of the project day. The developed add-in multiplies the calculated extension from the as-planned duration of the project day by cost per day, provided by the user to get project's time-related cost impact. Then, the developed add-in adds up the productivity and time-related impact costs to estimate the project's total impact cost. The add-in then estimates the project's change cost (as-changed) by adding the project's estimated direct cost, indirect cost and impact cost, then deduct the change cost from project's as-planned total cost as stated in project's as-planned contract to calculate the cost variance caused by owner requested design changes. The user can then use the result of analysis to see if the changes are beneficial to the project.

#### **4.2.6 Reporting and Highlighting Framework**

This section gives a summary of the add-ins' reporting and highlighting abilities. All the developed Revit add-ins in this study are designed in a way to present their output in the format of a two-sided report that includes the data related to both as-planned and as-changed BIM models components. The reporting aids the user to be able to compare the components' data of both models at the same time, which gives a clearer understanding of the changes involved in the project. The color-coded highlighting in all the add-ins is intended to visualize the project change types (addition, deletion, and modification). The changes are highlighted in both add-in's reports and BIM models based on their type with a specific color, which is coded the same for the all developed add-ins. There is connectivity between the BIM models and the reports, which gives users the ability to search for a component's data in a report by selecting the components in the BIM models or by selecting components in the report.

#### **4.2.7 Data Filtering Add-in**

The developed Revit Data Filtering add-in allows the user to generate several reports by choosing what data needs to get filtered. If the generated report contains a lot of components, it can be difficult to find information quickly. Data Filtering can be used to narrow down the data in the report, allowing the user to view only the information needed. The user is then able to define the filter method in a different field, and the Data Filtering displays only the rows that meet the criteria specified by the user and hides rows the user does not want to be displayed. The Data Filtering add-in has four principal steps: 1) generate a general report from the impacted and unimpacted components, 2) provide



filtering field, 3) provide filtering method, and 4) update the general project report based on the defined filter field and method.

First, the developed add-in combines the generated reports of Cost Impact and Time Impact add-ins in order to make a data filtering report. Therefore, the data filtering report consists of both as-planned and as-changed BIM model data, such as family type, assembly code, assembly description, as-planned cost, as-planned time, as-changed cost, as-changed time. Second, after generating the data filtering report the developed add-in asks the user to select the field of filtering, which means the user has to select one of the data items provided in the data filtering report (family type, assembly code, assembly description, as-planned cost, as-planned time, as-changed cost, as-changed time). The user can select one specific field at the time. Third, the next step is to select the filter method based on the type of field selected first. For example, if the type of selected field is family type in the filter method, the user has to define the type of family that needs to get filtered, such as a wall, door, window, column and so on. If it is assembly code and assembly description, the corresponding information needs to be provided in the filter method. If the type of selected field is as-planned time or as-changed time, the user has to define the number of days in the filter method. Finally, if the type of selected field is as-planned cost or as-changed cost, the user has to define the amount needed to filter in the filter method. Finally, after receiving the filter field type and filter method data, the developed add-in starts filtering the report based correspondingly on user input and generates the filtered report by hiding the rows containing the data that do not meet the defined filter field and filter method criteria, and the added filter in the report allows the user to analyze the data better.

### 4.3 Model Validation to a Case Study

#### 4.3.1 Change Ripple Effect Visualization Module

Using Autodesk Revit Architecture 2014, a three-story residential building with eight units in each level was generated for the case study section of this research, as shown in Figure 4-1. The as-changed model consists of three different types of design changes requested by the owner: addition, deletion, and modification of components of the architectural system. The user opens the as-planned and as-changed BIM models in Autodesk Revit as shown in Figure 4-2.

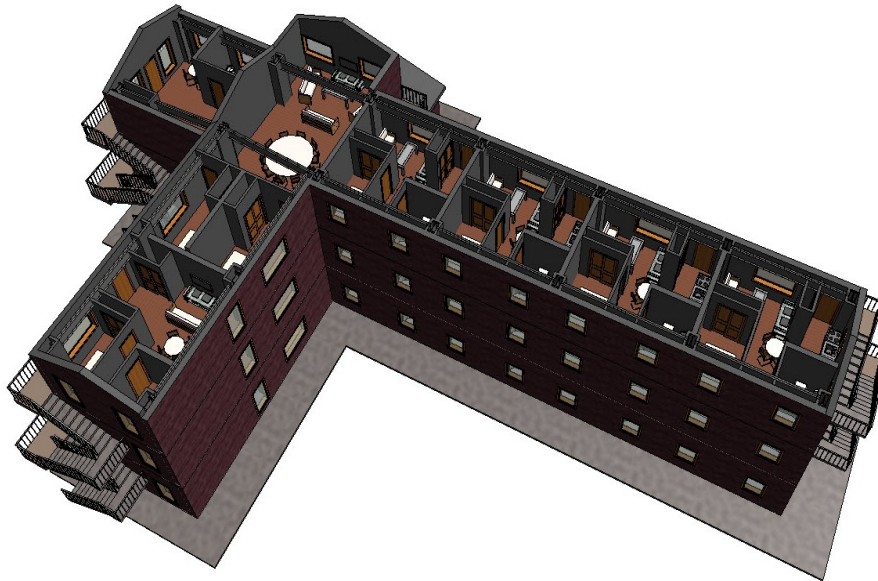


Figure 4–1: Case Study Model

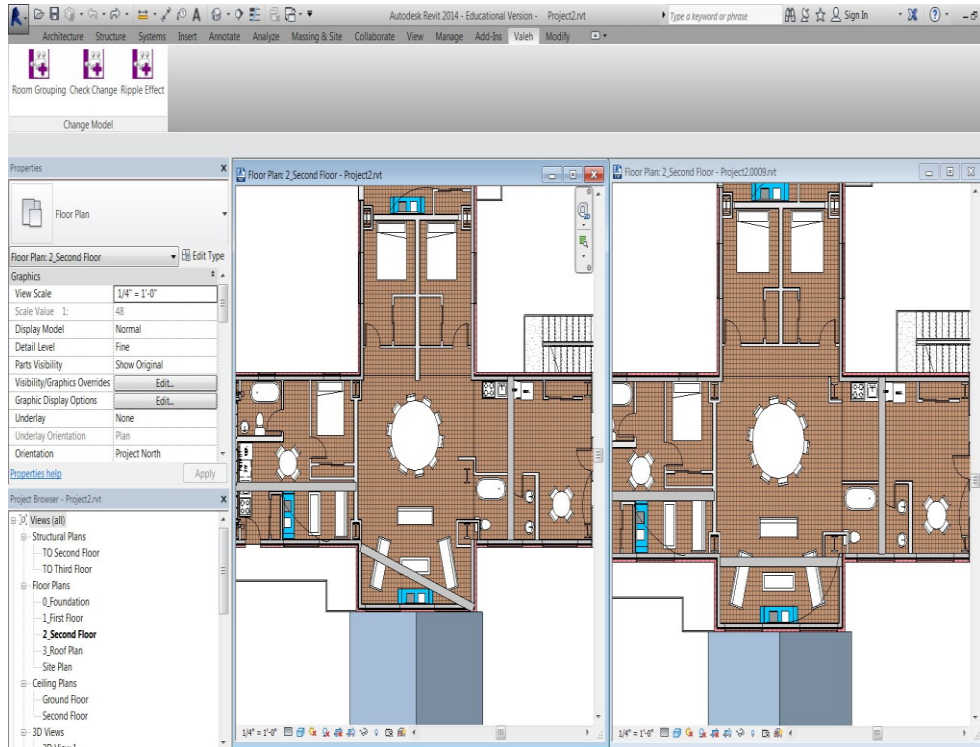


Figure 4-2: As-changed and As-planned BIM Models

After uploading the two BIM Models, the user selects the developed Room Grouping add-in, located on the top left-hand side of Revit interface, and selects all the components from every project system located in the room or area. After selecting all the components, the developed model saves the selected components under the same group category, as shown in Figure 4-3.

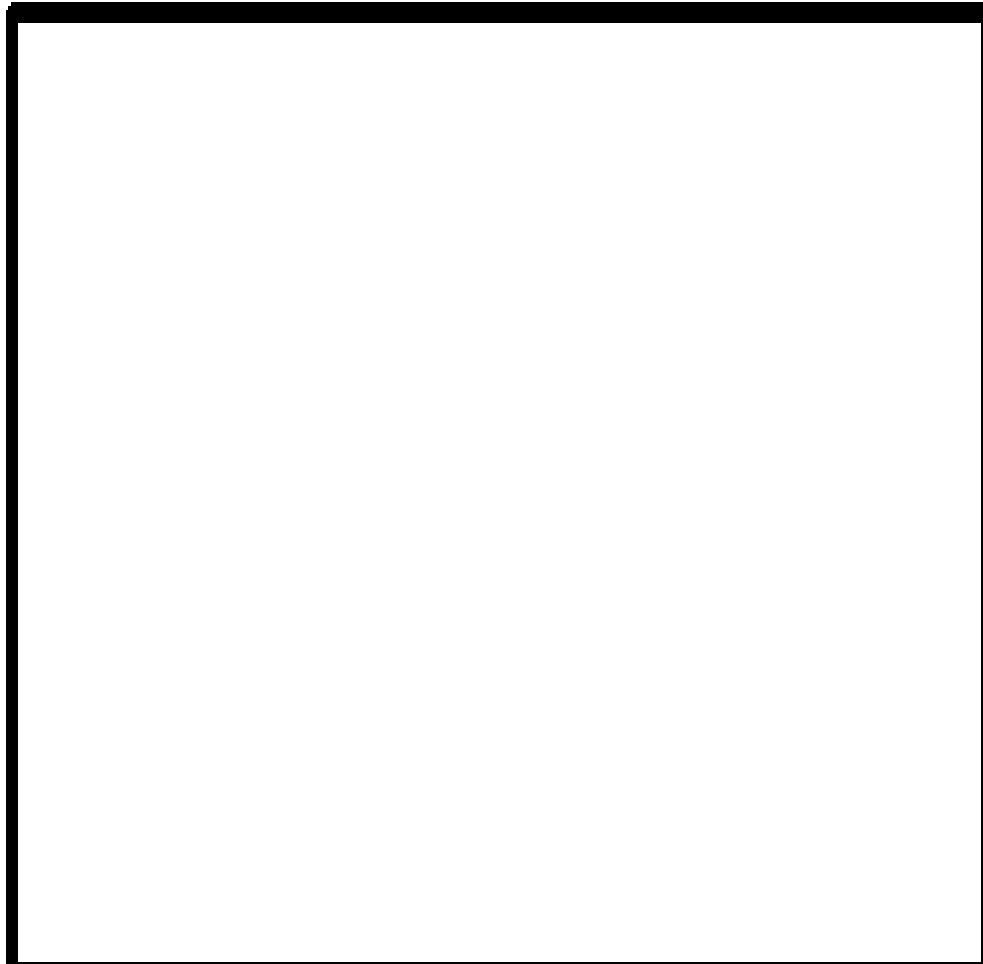


Figure 4–3: Room Grouping Add-in

After grouping the components of each area in the as-planned and as-changed BIM models, the developed model defines a room ID for each generated group. After creating a group, the user can select it at any time and add and/or remove selected components, as shown in Figure 4-4.

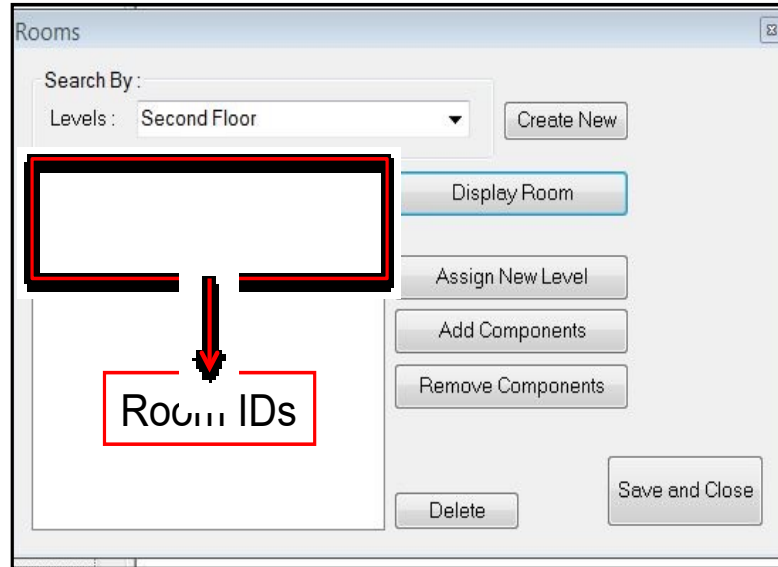


Figure 4-4: Rooms' Specifications Interface

The user can select the room ID, and the corresponding room gets highlighted in yellow in the as-changed BIM model, as shown in Figure 4-5.



Figure 4-5: Room Selection by Generated Group IDs

After grouping the components of the BIM models, the user runs the developed Check Change add-in located on the top left-hand side of the Revit interface, as shown in Figure 4-6.

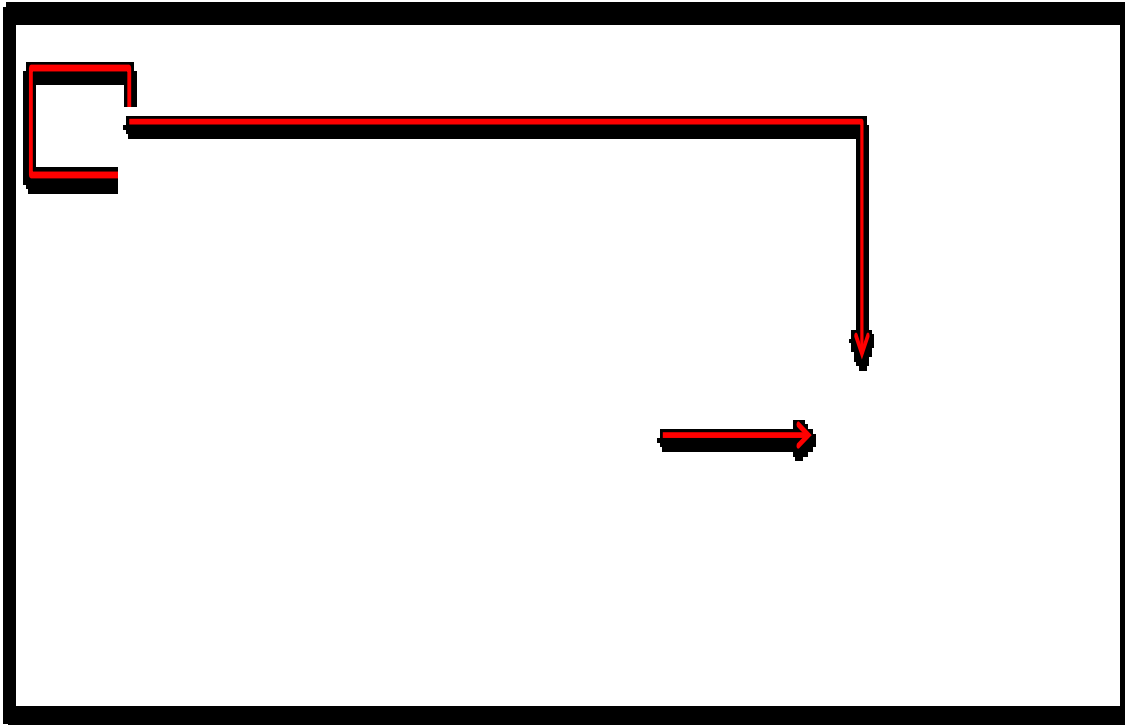


Figure 4-6: Check Change Add-in

The add-in commences the component-by-component comparison between the as-planned and as-changed BIM models in order to detect the differences and changes that exist between them. One of the outputs of the comparison model is a color-coded visualization, as shown in Figure 4-7. Each color denotes a different type of change: red for deletion, green for addition, and yellow for modification. The user can visualize the changes with the color code in every view of the Revit BIM model such as plan and 3D, as shown in Figure 4-8.



Figure 4-7: Plan View of Color Coded Changes



Figure 4-8: Section 3D View of the Color Code Highlight Visualization

The second output is the side-by-side color-coded report of the changed components, as shown in Figure 4-9. The left side of the report belongs to the as-planned BIM model, which shows the modified and deleted components. The right side of the model belongs to as-changed BIM model, which shows the modified and added components.

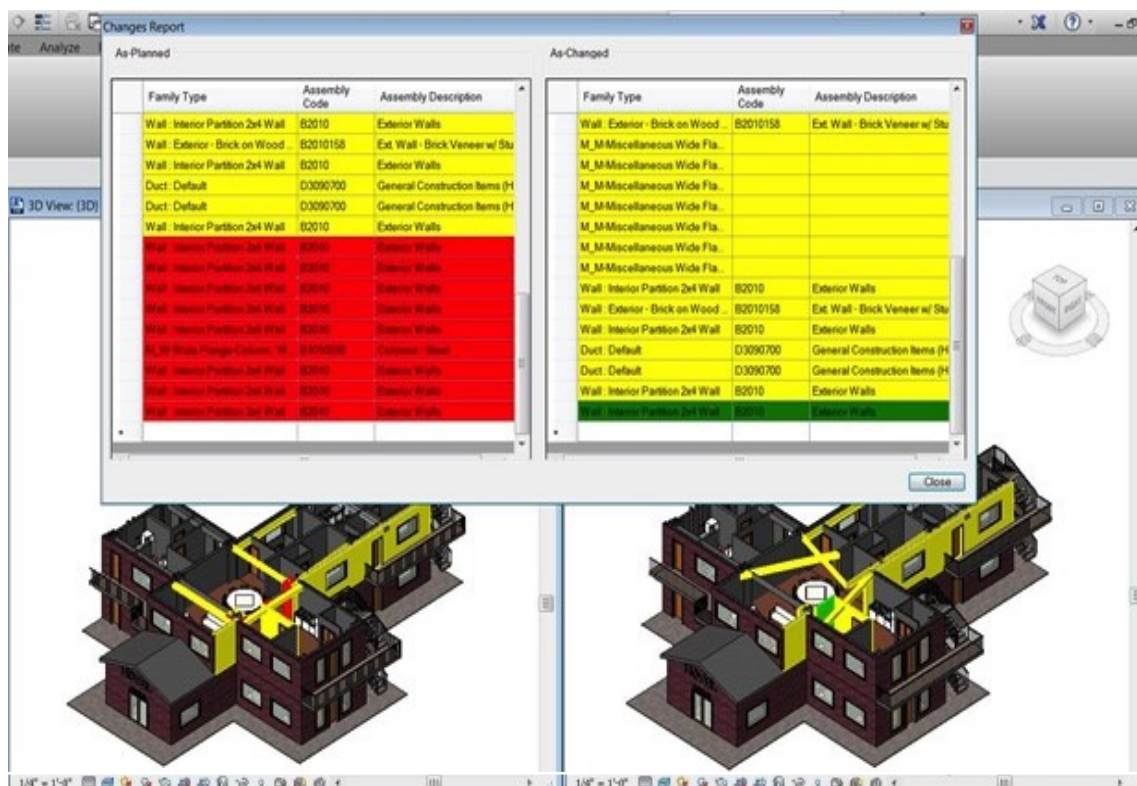


Figure 4-9: Color-coded Report

The Check Change add-in marks the impacted components without specifying the cause-and-effect relationship (ripple effect) between the changed components. To get the ripple effect of each owner-requested design change, the user selects the Ripple Effect add-in on the top left-hand side of the Revit interface and selects the individual direct changes in the model, as shown in Figure 4-10.





Figure 4–10: Selecting Individual Direct Changes and Ripple Effect Add-in

Upon selecting the direct change in the BIM model, the developed model highlights the components that are impacted due to the direct change in the BIM models. The developed add-in, at the same time, provides a report of the impacted components. The Ripple Effect add-in considers two levels of analysis for the impacted change on all building systems arising from the introduced direct change, as shown in Figure 4-11. This is performed in two stages. In the first stage, the ripple effect of the changed components is detected in the same room, as shown in Figure 4-12.

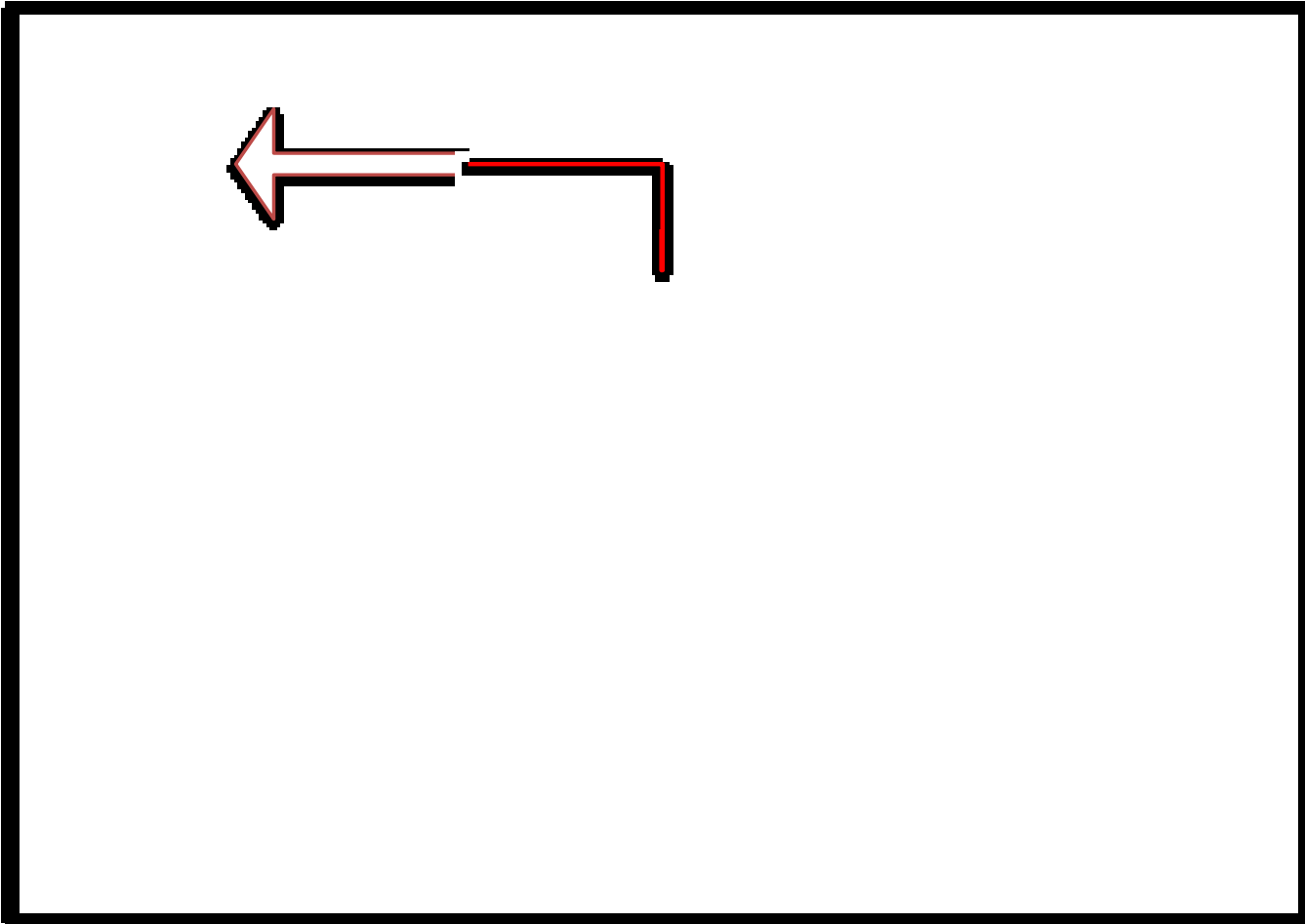


Figure 4–11: Change Ripple Effect Reports (Level 1- Level 2)

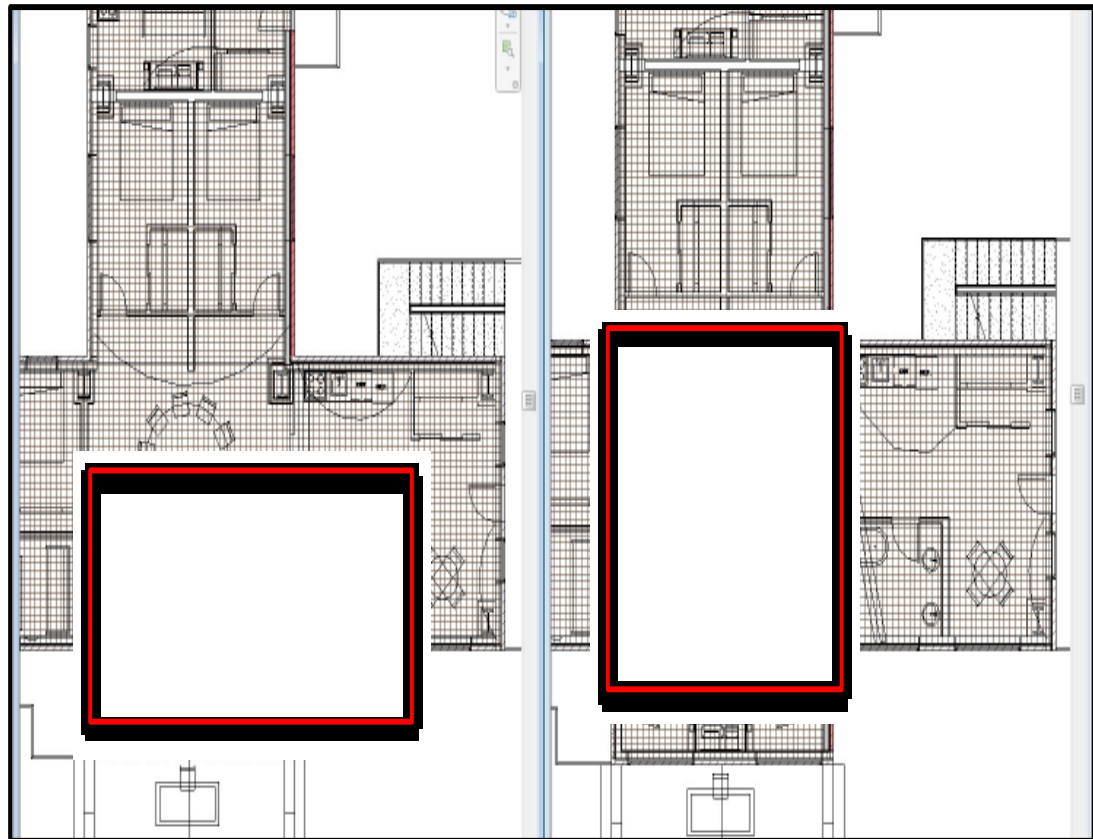
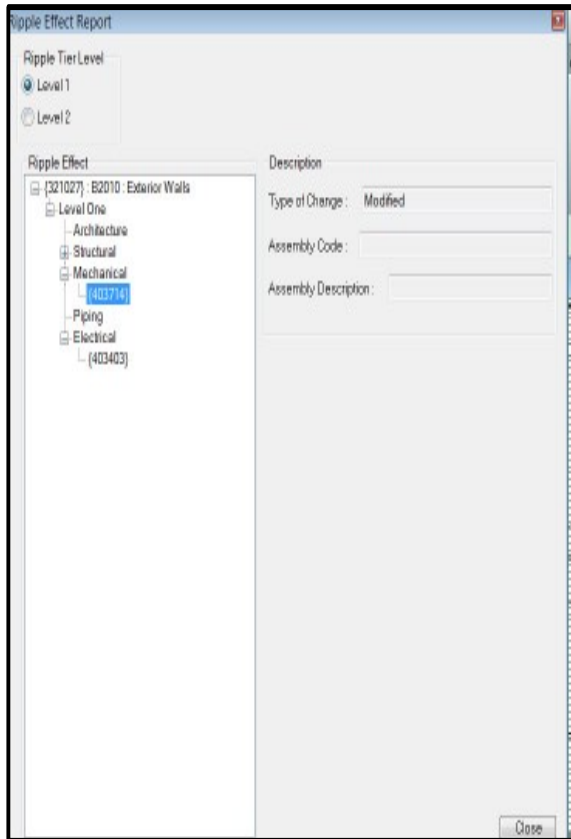


Figure 4-12: First Level Ripple Effect Model Highlights and Report

In the second stage, the ripple effect is detected in the surrounding rooms. The developed add-in considers the rooms that surround the introduced design change in vertical and horizontal directions. The same procedure applies to the rooms above and below the introduced change, as shown in Figure 4-13.

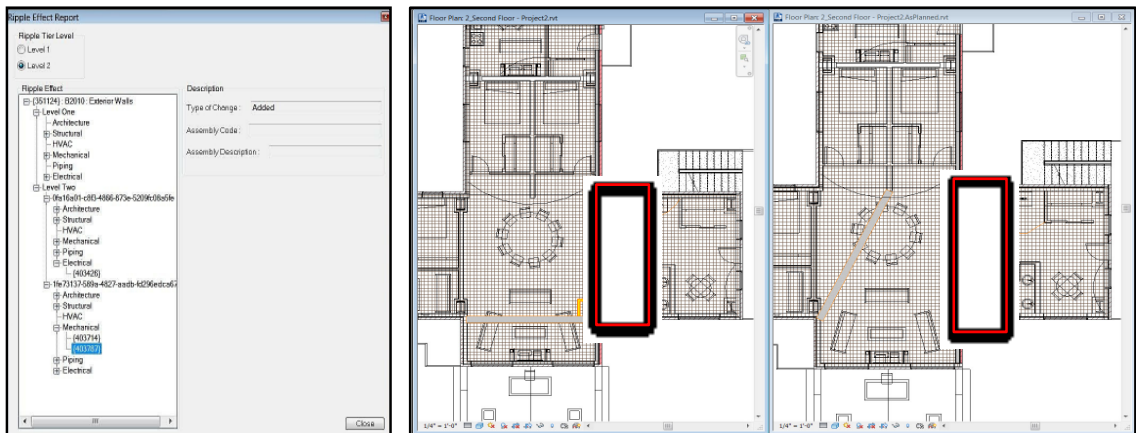


Figure 4–13: Second Level Ripple Effect Model Highlights and Report

The developed add-in is expected to facilitate the understanding of the scope of the introduced design changes and their ripple effect. The user can select a component in a model and the component's information gets highlighted in the report. This action can also work the other way around: the user can select a component in the generated report and the selected component gets highlighted in the BIM model, as shown in Figure 4-14.

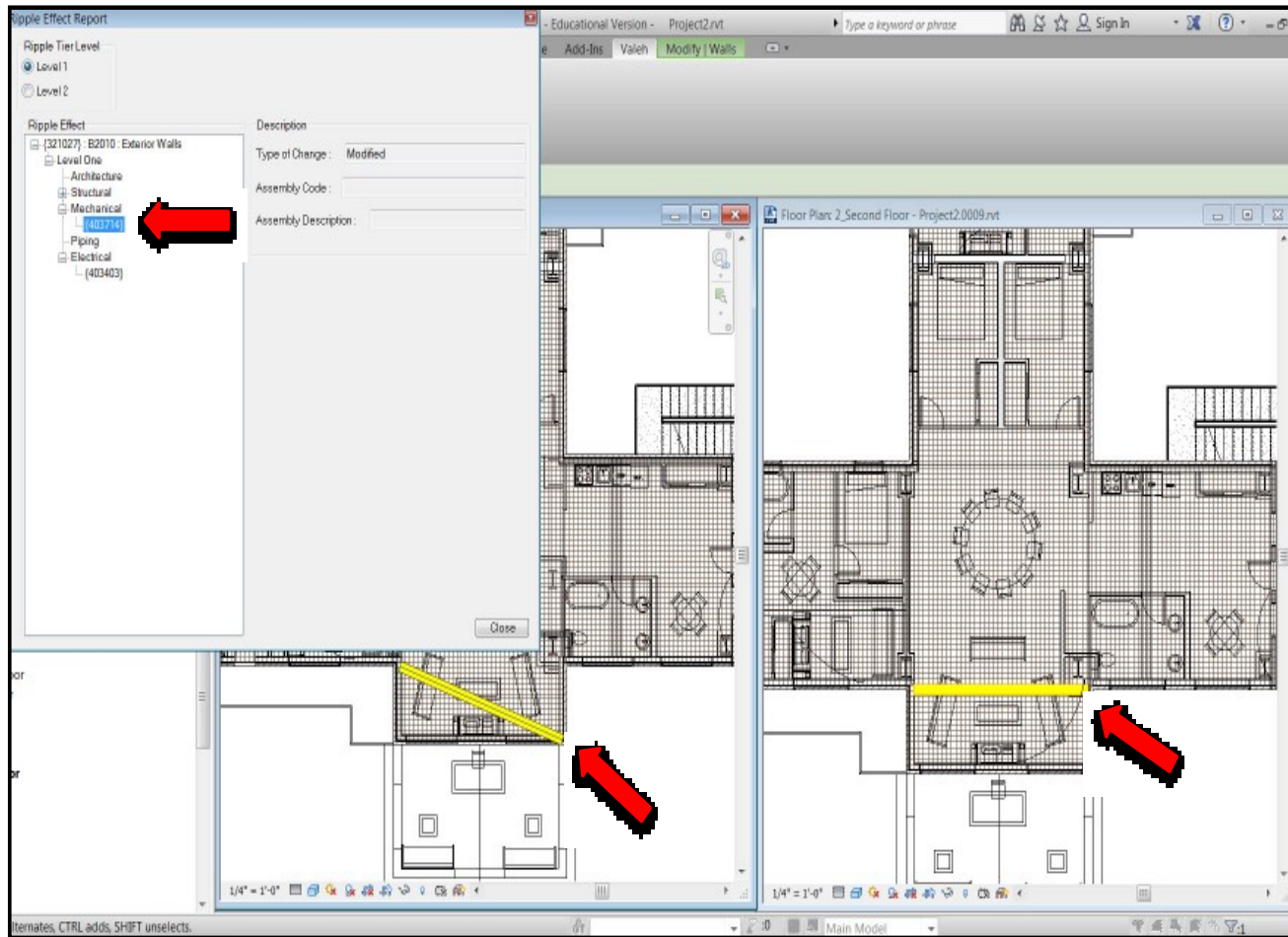


Figure 4-14: Connection between BIM Model and Ripple Effect Report

### 4.3.2 Change Time Impact Analysis Module

Autodesk Revit Architecture 2014 was selected to develop the case study of both the as-planned and as-changed BIM models. A residential building with one story and two units were generated for the case study section of this research, as shown in Figure 4-15. In the as-changed BIM model, the owner-requested design change types consist of components' additions to, deletions from, and modifications to project's architectural system, as shown in Table 4-1.

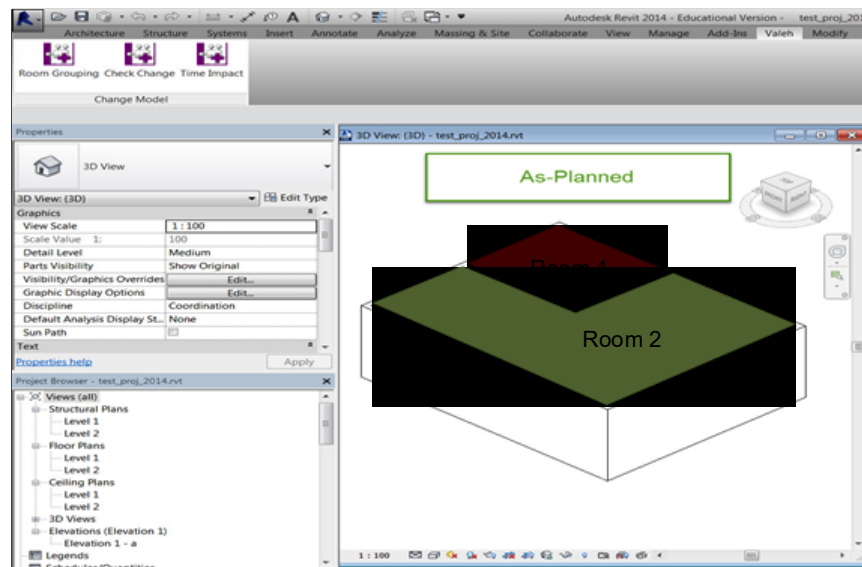


Figure 4–15: As-planned Model 3D View

For the as-changed BIM model, three scenarios were developed:

- Scenario 1: Applying change number one
- Scenario 2: Applying changes number one, two, three, and four
- Scenario 3: Applying all changes from number one to seven

For each scenario, an as-changed model was developed as well, shown in Figures 4-16, 4-17, and 4-18.

Table 4–1: Summary of Owner Requested Design Changes

<i>Number</i>	<i>System</i>	<i>Component</i>	<i>Location</i>	<i>Change Type</i>
1a	Architectural	Wall D	Room 1	Remove
b	Architectural	Door 1	Room 1	Remove
2a	Architectural	Wall C	Room 1	Modify
b	Architectural	Door 2	Room 1	Add
3a	Architectural	Door 3	Room 1	Add
4a	Architectural	Door 1	Room 2	Add
5a	Architectural	Wall A	Room 3	Add
6a	Architectural	Wall B	Room 3	Add
7a	Architectural	Wall C	Room 3	Add

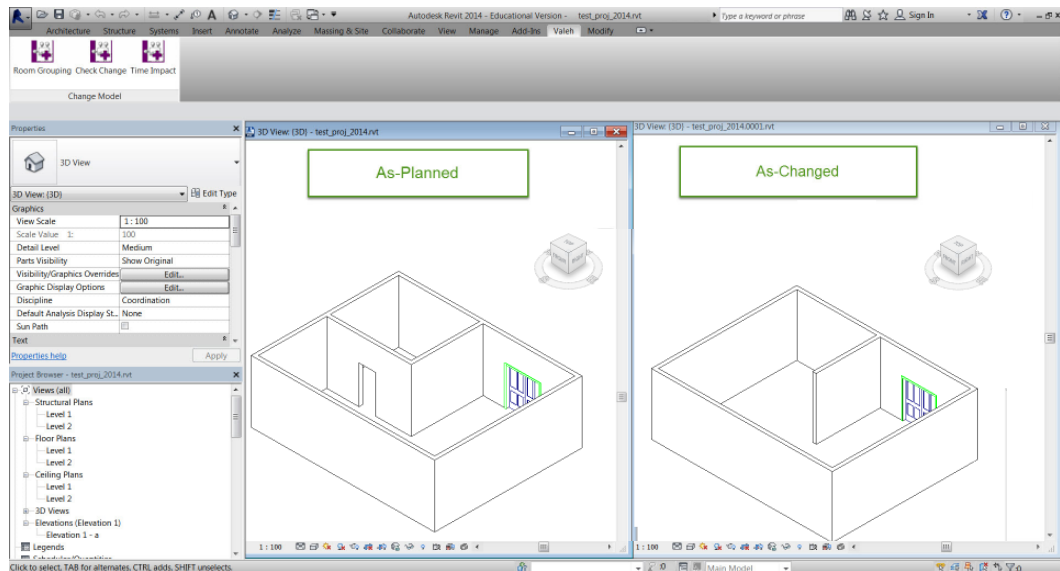


Figure 4–16: BIM Models 3D View for Scenario 1

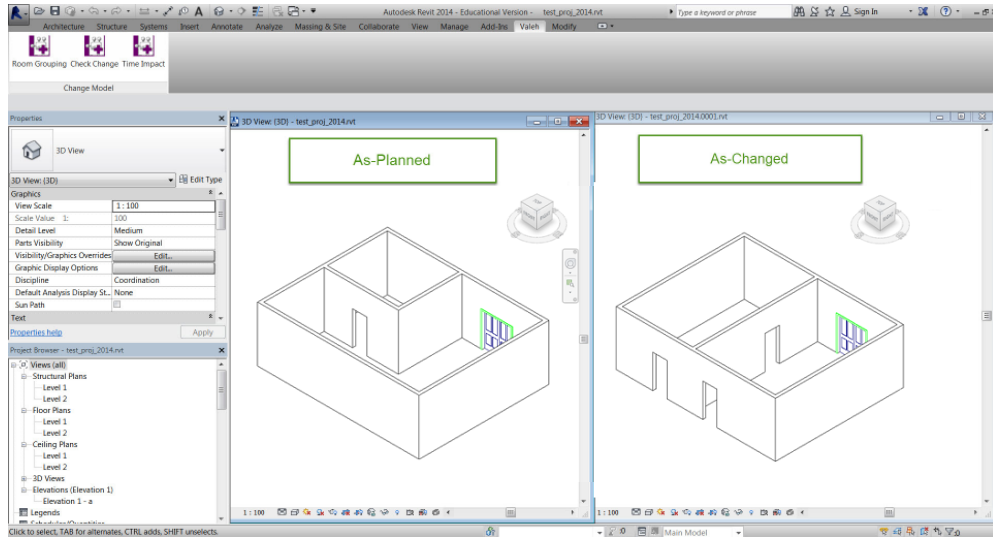


Figure 4-17: BIM Models 3D View for Scenario 2

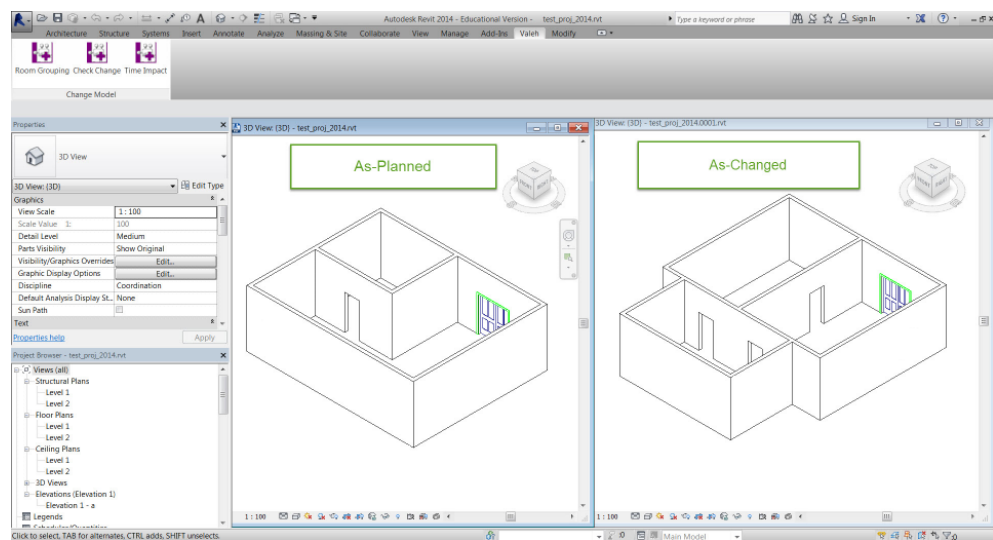


Figure 4-18: BIM Models 3D View for Scenario 3

After generating and uploading the two as-planned and as-changed BIM models, the next step is to identify all the impacted components using data from the Check Change add-in. The user selects the Check Change add-in, and it generates a two-sided report. The as-planned side of the report consists of modified, and deleted components and the as-changed side of the report consists of modified and added components, as



shown in Figures 4-19, 4-20 and 4-21. Here you can see the color codes used by the Check Change add-in: red for deletion, green for addition, and yellow for modification.

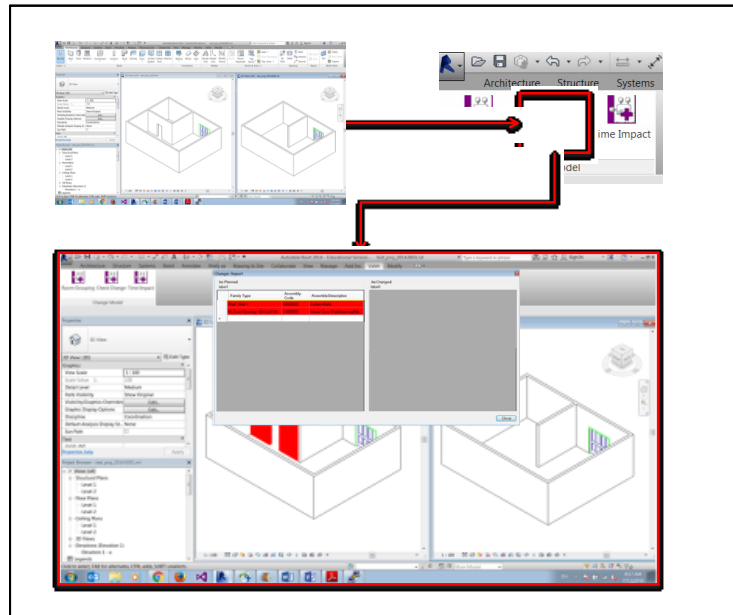


Figure 4-19: Check Change Add-in and Its Report Output for Scenario 1

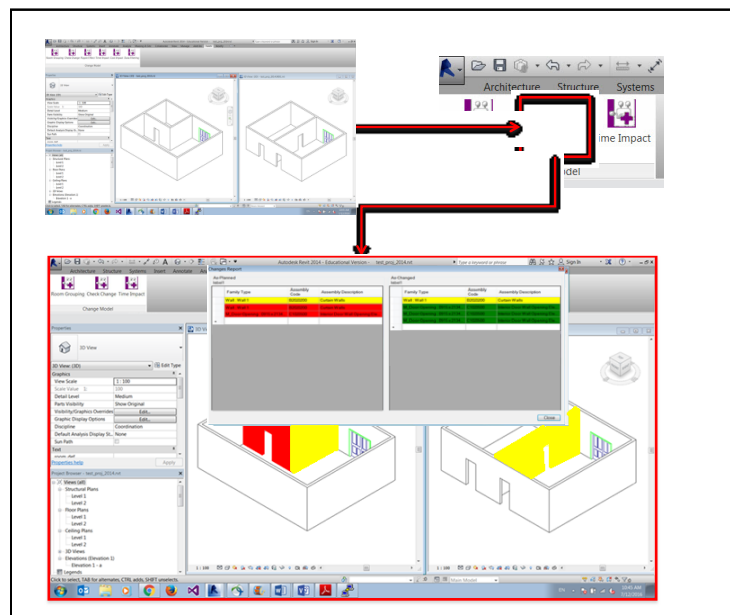


Figure 4-20: Check Change Add-in and Its Report Output for Scenario 2

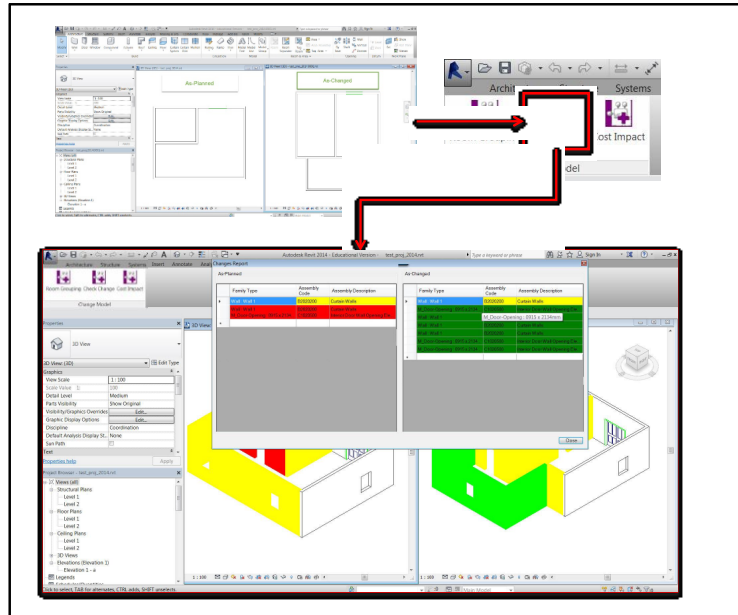


Figure 4–21: Check Change Add-in and Its Report Output for Scenario 3

The user then selects the developed Time Impact Add-in, located on the top left-hand side of the Revit interface. The Time Impact add-in generates a two-sided report: the right-hand side belongs to the as-planned model and left-hand side to the as-changed model. Both sides of the report consist of project’s unimpacted components and impacted components coming from the Check Change add-in generated report. The as-planned side of the report shows the impacted components due to deletion and modification change type. The as-changed side of the report shows the impacted components due to addition and modification change type, as shown in Figures 4-22, 4-23, and 4-24. As is shown in Figure 4-22, after selecting the Time Impact add-in, an interface appears that allows the user to choose the duration calculation method. The user has two options to select either “linear estimate proportional to quantities” or “modified to include productivity related factor.” In these three case study scenarios, linear estimation proportional to quantities is selected.

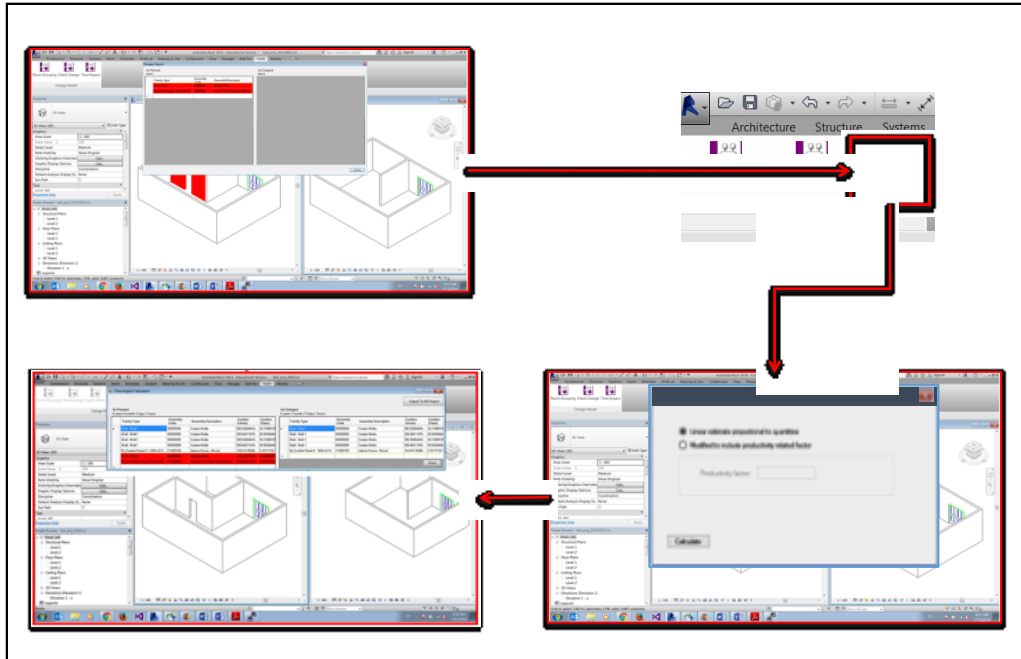


Figure 4–22: Time Impact Add-in and Its Report Output for Scenario 1

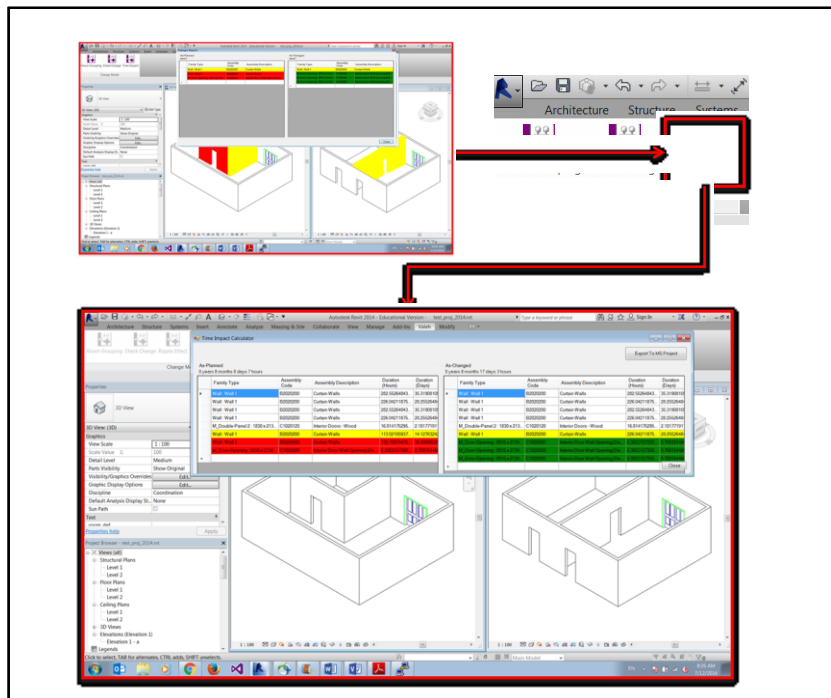


Figure 4–23: Time Impact Add-in and Its Report Output for Scenario 2

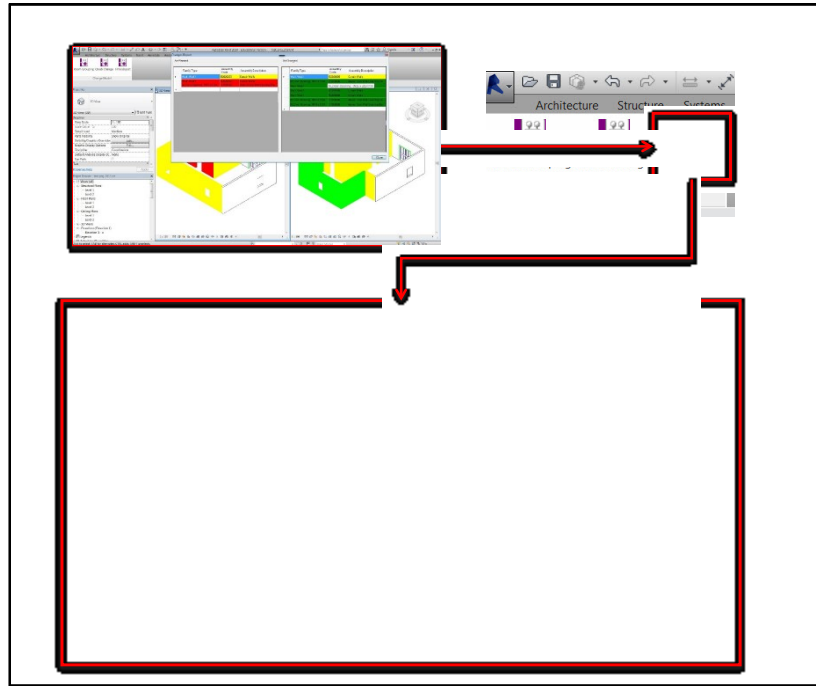


Figure 4–24: Time Impact Add-in and Its Report Output for Scenario 3

The time impact generated a report, in addition to family type, assembly code, and assembly description, consists of components' and the total project duration in hours and days, and color-coded change types, as shown in Figure 4-25. The developed Time Impact add-in is coded to calculate the duration for every impacted and unimpacted component by multiplying the components' quantity (Q) by their needed labor hours (LR). When it extracts the list of impacted components, the developed Time Impact add-in keeps the components' color-coded highlighting for the next step, which is the updating of the as-planned project schedule.

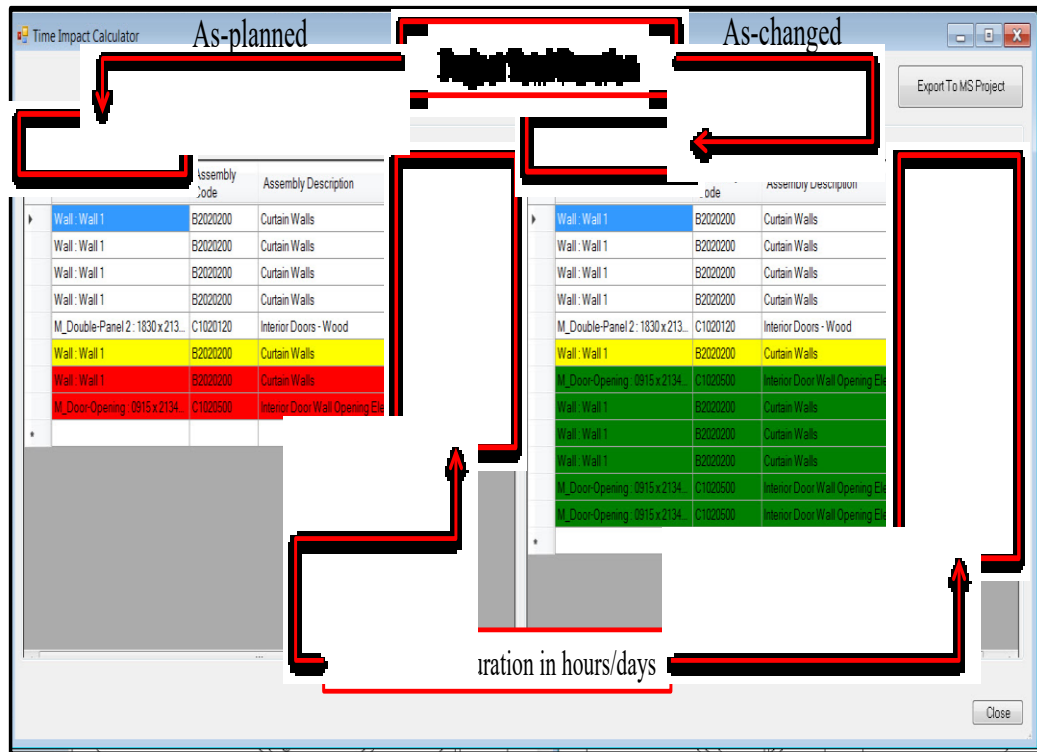


Figure 4–25: Time Impact Report Output

In this case study, the owner, after receiving the three scenarios' time impact reports, approved scenario number three, which is applying all changes from number one to seven. The next move, then, is to link the time-impact report to the project as-planned schedule and generate project as-changed schedule. The Room Grouping add-in is used to link the impacted components' duration to the project's as-planned schedule to create the as-planned schedule. To do this, the user selects the developed room grouping add-in located on the top left-hand side of the Revit interface and selects all the components of the project's architectural system located in the same room or area; the selected components are saved under the same group category, and a room ID is generated for each group. In other words, the components belonging to the same space carry the same room ID, as shown in Figure 4-26. All the components that are shared between two separate areas or more are grouped in that area.

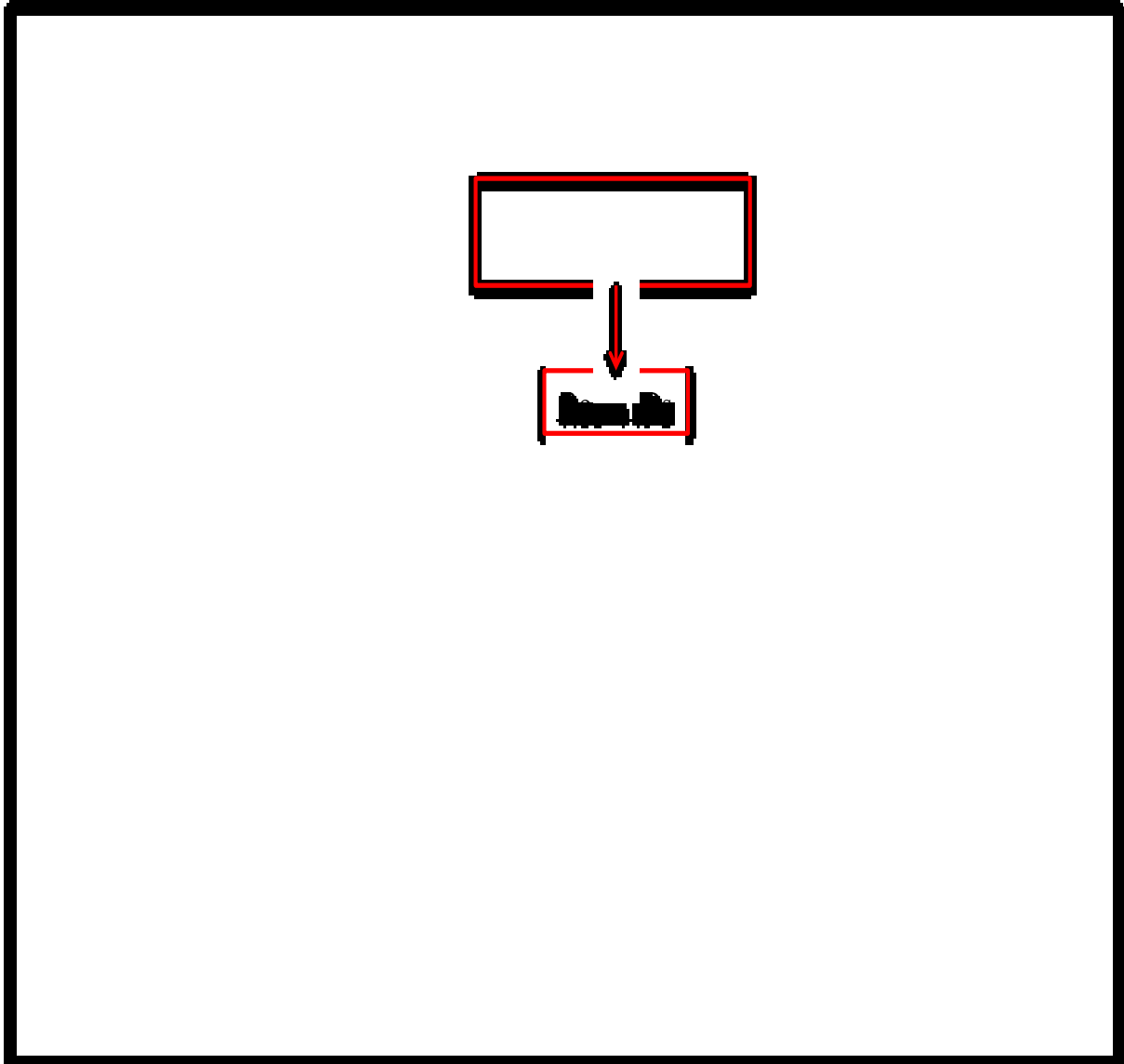


Figure 4–26: Room Grouping Add-in and Generated Group IDs

The as-planned project schedule is generated with the same logic as the grouping add-in, meaning the schedule should have three levels: floor, room, and components. The floor is the project activity, and the components are project sub-activities. The as-planned schedule of the project is developed with the same logic in MS Project software, as shown in Figure 4-27.

The project has one level (floor) and two rooms, which means two groups and two activities are developed. Each activity consists of sub-activities, or the components related to each activity (room). For shared components, the duration is calculated only once. For example, when a wall is in the middle of two rooms, the component is part of two room groups, but in the schedule, the duration for that component is considered zero for one of the groups.

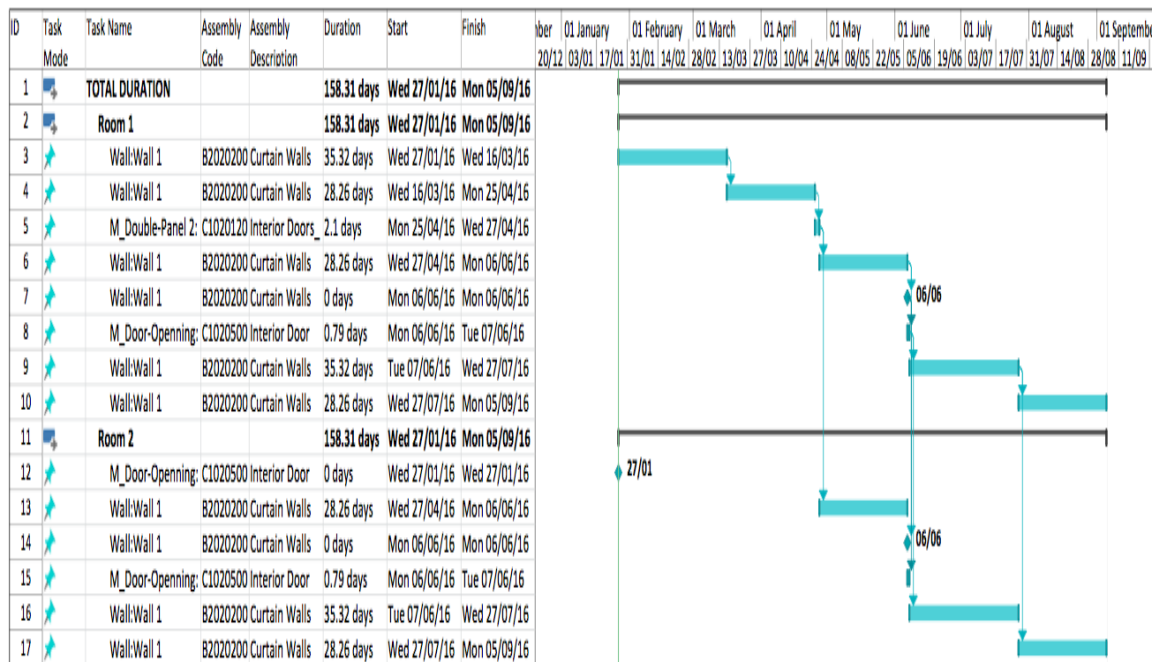


Figure 4–27: Project’s Developed As-planned Schedule in MS Project

To link the impacted components to the as-planned schedule, the user first opens the as-planned schedule (MPP) file developed in MS Project program in Revit, as shown in Figure 4-28.

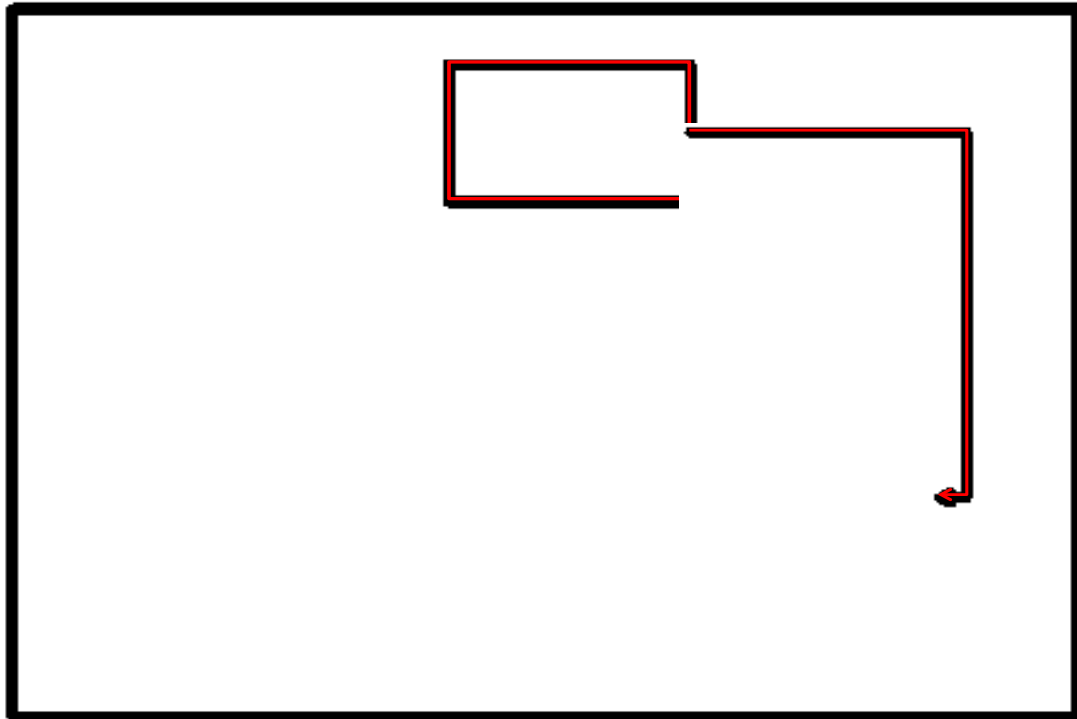


Figure 4–28: Browsing for As-planned Schedule in MPP File Format

Then, the developed model links changes' duration to the schedule by matching the as-planned components unique IDs with the unique IDs of the developed time impact add-in report. The developed model is coded in order to find activities that belong to the impacted components by matching the as-planned group's IDs with the time impact report's component group IDs. By mapping and updating the impacted components' duration into the project as-planned schedule the project activity and total duration are automatically updated in the updated schedule and generate the as-changed schedule in CSV ("Comma Separated Values") file format in Revit. Now, the user selects the "export to MS project" add-in on the top right-hand side of the time impact main interface to export the as-changed CSV file to MS Project, as shown in Figure 4-29.



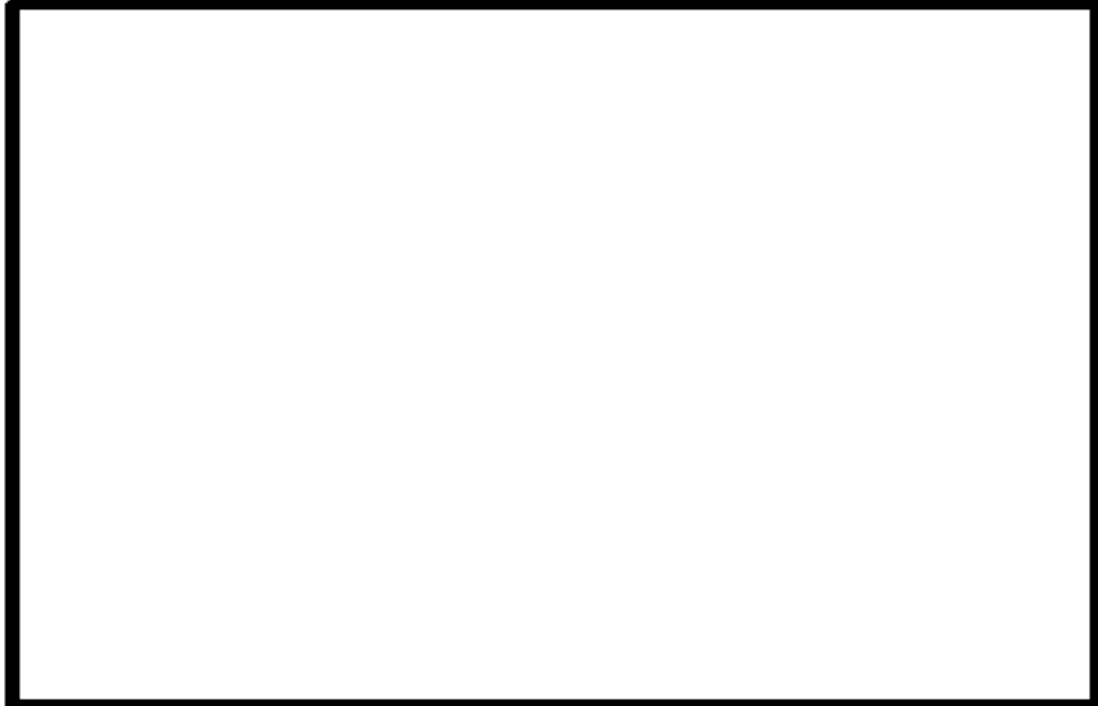


Figure 4–29: Export Generated As-changed Schedule in CSV Format to MS Project

After the user selects the button “Export to MS project,” the next window that pops up is “Browse for Folder,” and the user now has to look for the as-changed report schedule in CSV file format and open it in MS project, as shown in Figure 4-30. Then, the as-changed CSV file is opened in MS Project, and before generating the as-change schedule in MPP file format, the user has to do the mapping to verify and edit how to map the data, as shown in Figures 4-31 and 4-32.

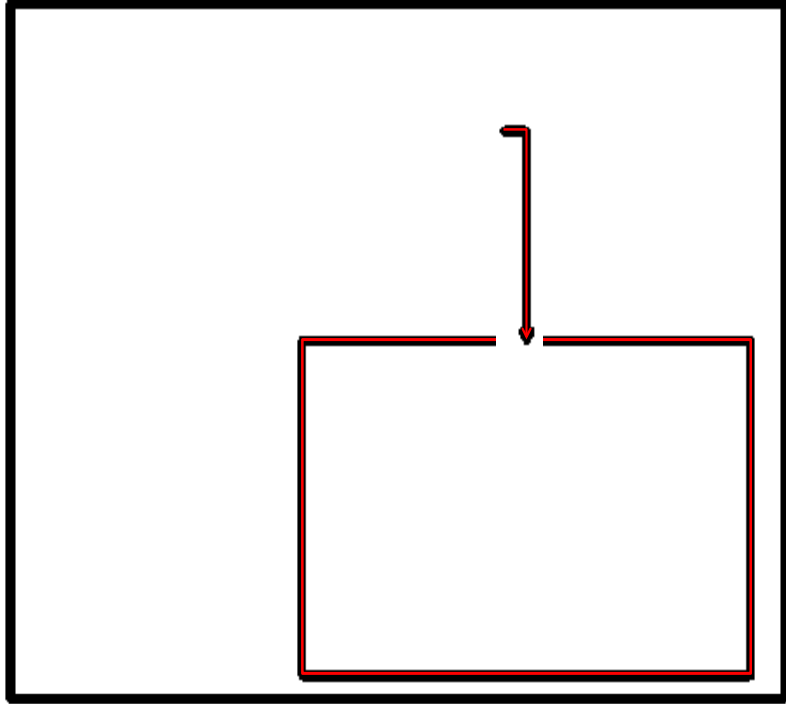


Figure 4–30: Select As-changed Schedule CSV File

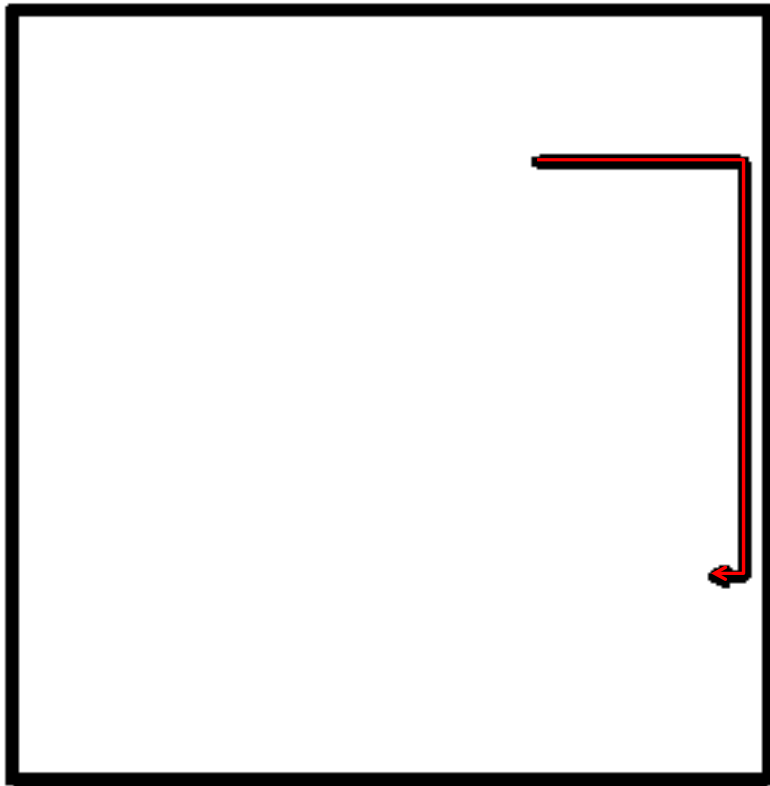


Figure 4–31: Map and Import the As-changed Schedule CSV File to MPP File



Figure 4–32: Task Mapping

The user, after mapping the CSV file, now clicks the next button, then clicks “save as MPP file,” finally clicks on the finish button. The user opens the saved MPP file, and the project’s updated “as-changed” schedule should open, as shown in Figure 4-33.

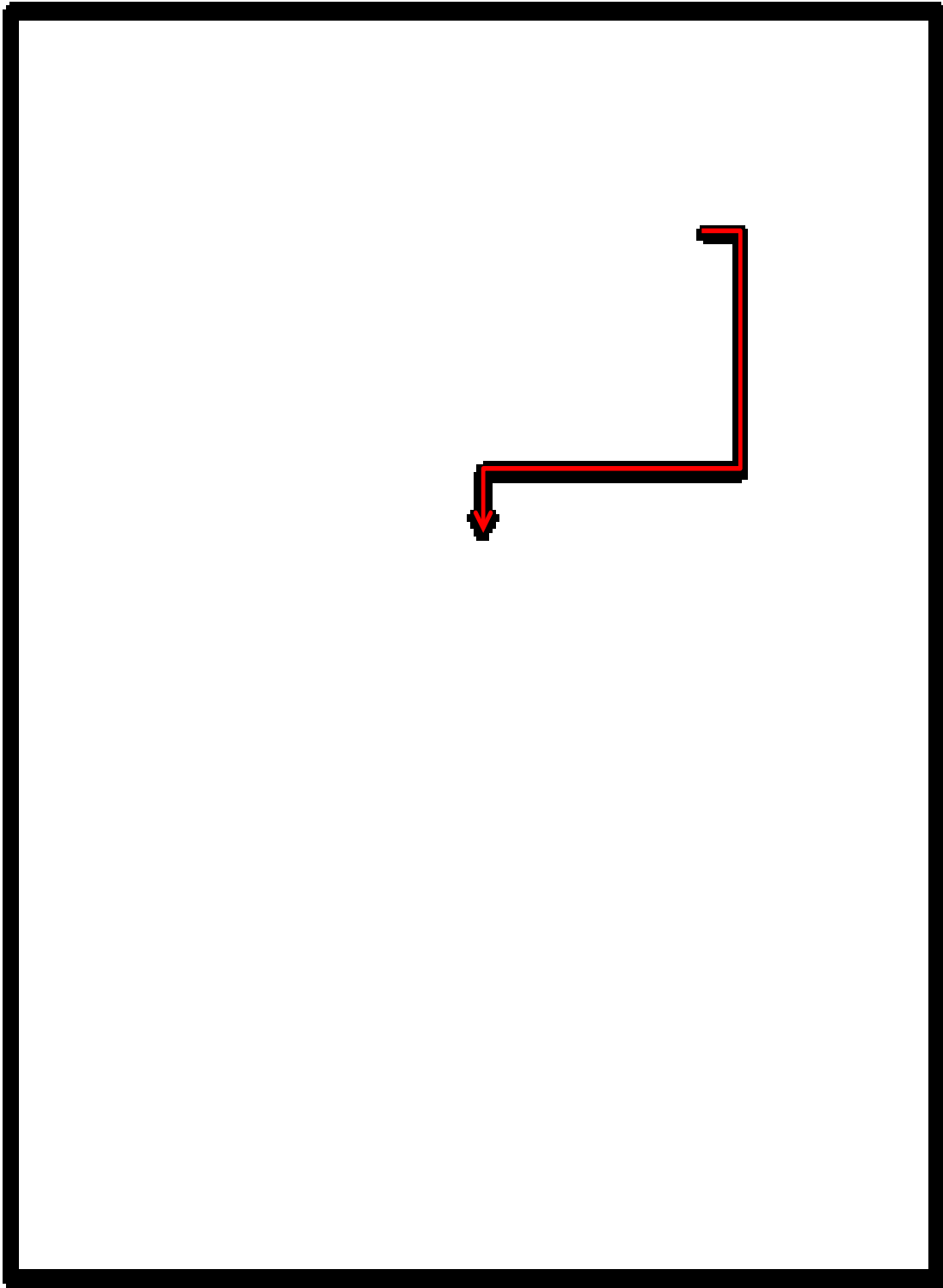


Figure 4–33: Generating the As-changed Schedule in MPP File Format

### 4.3.3 Change Cost Impact Analysis Module

The automation of cost ripple effect of owner-requested design changes served as the case study. In this section, the same case study as Time Impact add-in is used for the as-planned model, which was a residential building with one story and two units, and for the as-changes model scenario 3 BIM model is used, as shown in Figure 4-34. Autodesk Revit Architecture software 2014 is used to generate the as-planned and as-changed case study BIM models.

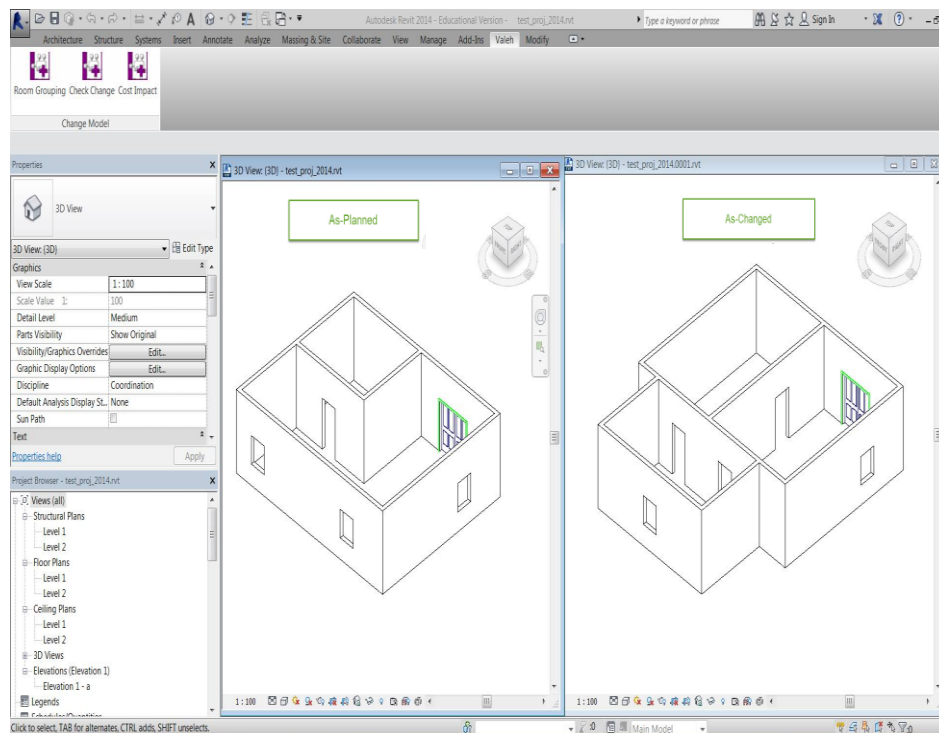


Figure 4–34: Case Study Model

After generating the project's as-planned and as-changed BIM models, the next step is to find out the differences that exist between the BIM models' components; the differences between the project's BIM models determine the project's impacted components. After the user opens the project as-planned and as-changed BIM models in Autodesk Revit interface, the Check Change add-in located on the top left-hand side of

the Revit interface runs and generates a side-by-side comparison report, as is shown in Figure 4-35.

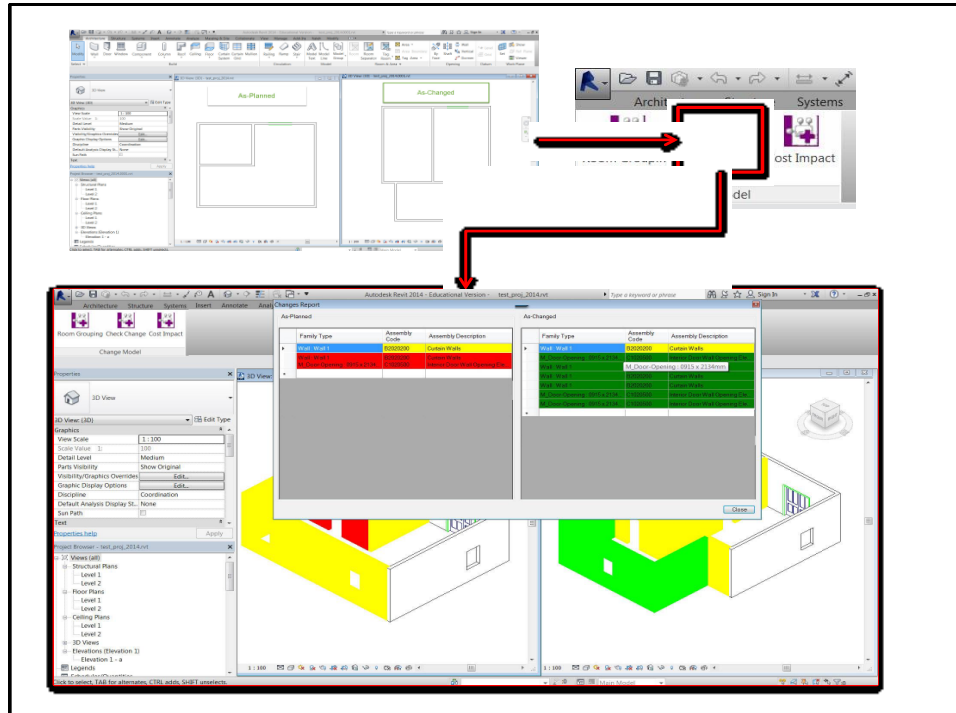


Figure 4–35: Check Change Add-in and Its Report Output

The report's as-planned side has unimpacted, modified, and deleted components, and the report's as-changed side has as-changed unimpacted, modified, and added components. The report presents the change types with different color codes: red for deletion, green for addition and yellow for modification, as shown in Figure 4-36.

The screenshot shows a 'Changes Report' window with two main sections: 'As-Planned' and 'As-Changed'. Each section contains a table with three columns: 'Family Type', 'Assembly Code', and 'Assembly Description'. The 'As-Planned' table has three rows: a blue row for 'Wall - Wall 1' (B2020200, Curtain Walls), a red row for 'Wall - Wall 1' (B2020200, Curtain Walls), and a red row for 'M\_Door-Opening : 0915 x 2134' (C1020500, Interior Door Wall Opening Ele.). The 'As-Changed' table has six rows: a blue row for 'Wall - Wall 1' (B2020200, Curtain Walls), a green row for 'M\_Door-Opening : 0915 x 2134' (C1020500, Interior Door Wall Opening Ele.), a green row for 'Wall - Wall 1' (B2020200, Curtain Walls), a green row for 'Wall - Wall 1' (B2020200, Curtain Walls), a green row for 'M\_Door-Opening : 0915 x 2134' (C1020500, Interior Door Wall Opening Ele.), and a green row for 'M\_Door-Opening : 0915 x 2134' (C1020500, Interior Door Wall Opening Ele.). A 'Close' button is located at the bottom right of the window.

As-Planned				As-Changed			
	Family Type	Assembly Code	Assembly Description		Family Type	Assembly Code	Assembly Description
▶	Wall - Wall 1	B2020200	Curtain Walls	▶	Wall - Wall 1	B2020200	Curtain Walls
	Wall - Wall 1	B2020200	Curtain Walls		M_Door-Opening : 0915 x 2134	C1020500	Interior Door Wall Opening Ele.
*	M_Door-Opening : 0915 x 2134	C1020500	Interior Door Wall Opening Ele.		Wall - Wall 1	B2020200	M_Door-Opening : 0915 x 2134mm
					Wall - Wall 1	B2020200	Curtain Walls
					Wall - Wall 1	B2020200	Curtain Walls
					M_Door-Opening : 0915 x 2134	C1020500	Interior Door Wall Opening Ele.
					M_Door-Opening : 0915 x 2134	C1020500	Interior Door Wall Opening Ele.
				*			

Figure 4-36: Check Change Add-in Color-coded Report

The user then runs the developed “Cost Impact” add-in also located on the top left-hand side of the Revit interface in order to get an estimate of the project’s change cost and the ripple effect of owner-requested design changes on the project’s total cost (as-changed cost), as shown in Figure 4-37. The developed cost impact add-in provided includes the project’s modified direct cost, indirect impact cost, total change cost (as-changed), and cost variance caused by change. To better describe each part of the cost impact, the report is separated into different sections, as shown in Figure 4-38. Each section of the developed cost impact report add-in is explained below.

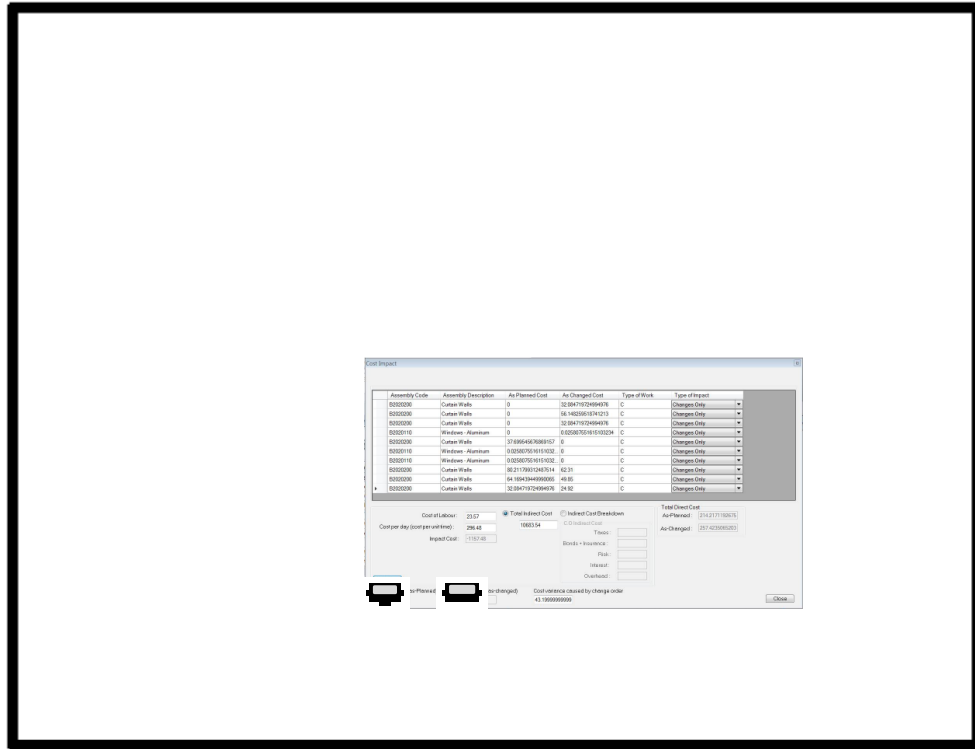


Figure 4-37: Cost Impact Add-in and Its Report Output

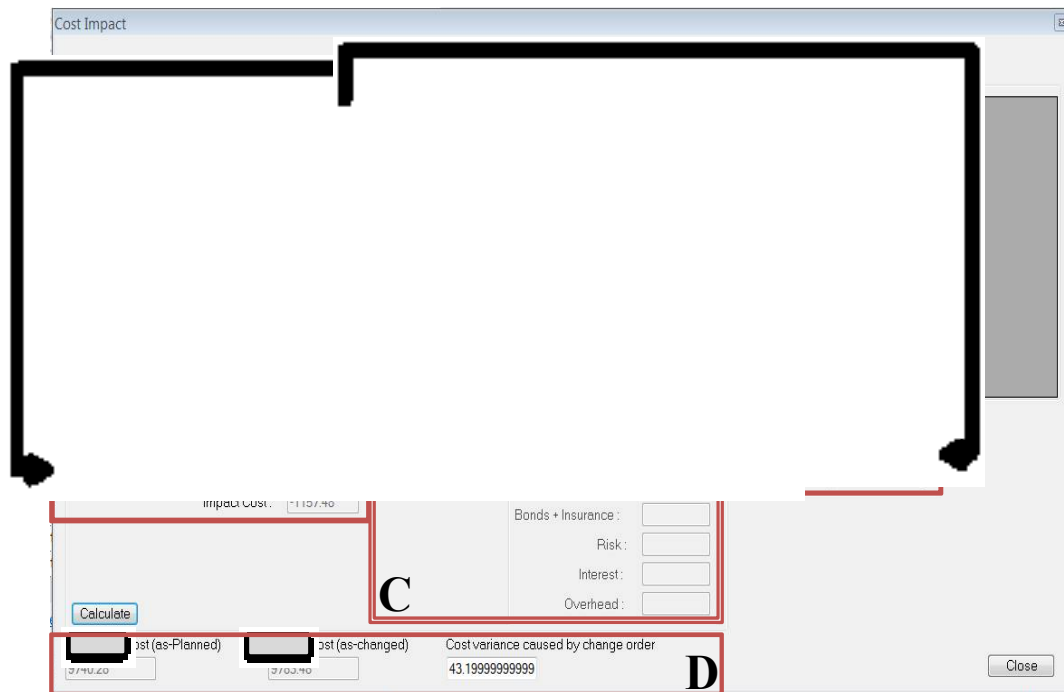


Figure 4-38: Cost Impact Add-in Generated Report



Section A: The report provided by the cost impact add-in in section A includes the as-planned BIM model's deleted components, the as-changed BIM model's added components, and both BIM models' modified components along so as to add up the impacted component cost of the assigned as-changed and as-planned BIM models with the project's available unimpacted cost to calculate the project's as-planned and as-changed total direct cost.

Section B: Section B of the report is related to the process of estimating the project's impact cost, which is a combination of productivity related and time-related costs. In order to estimate the productivity related cost, this study coded the (Leonard et al., 1991) model mentioned in the implementation section. Here, the user has to choose the type of work and type of impact. For this case study, C was selected for the type of work, which denotes architectural work, and change only was selected for the type of impact. The user also has to input cost per day (cost per unit time) to estimate time related cost. Time-related cost is calculated by multiplying the extension from the original project duration in days by the user cost per day input. For estimating a project's extension in days the Time Impact add-in output is used to run the coded equation of time-related impact, as shown in Figure 4-39.

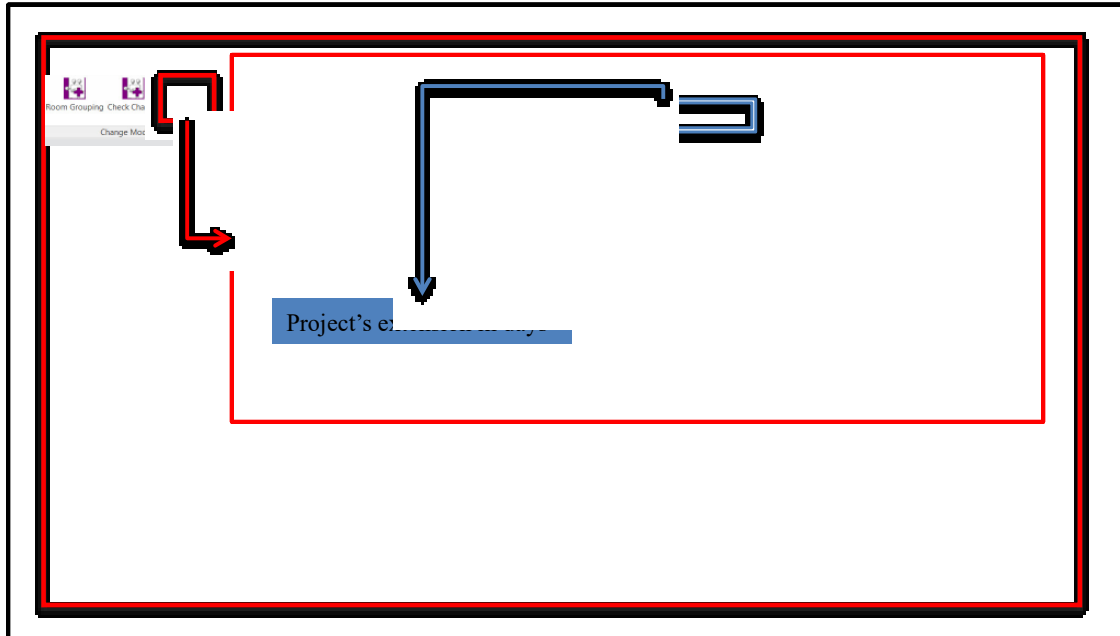


Figure 4–39: Report of Cost Impact Division

Section C: To calculate a project’s indirect cost, two options are available in section C. A user can either directly input the total cost amount related to project contract indirect cost or separately input the cost of each item belonging to the indirect cost category into the indirect cost breakdown section provided by the developed Cost Impact add-in. The user is also able to add other indirect cost related factors to the indirect cost breakdown.

Section D: In this section, the developed add-in calculates the project’s change cost (as-changed) and cost variance caused by change. By adding the direct cost from section A, impact cost (productivity related and time-related) from section B, and indirect impact cost from section C, the developed Cost Impact add-in provides the project’s change cost (as-changed). Then, the developed model estimates the project’s cost variance caused by the change by deducing the project’s as-planned total cost from the project’s change cost (as-changed). The user uses the cost data provided in section D to

see if the requested design change is beneficial based on the project's total cost (as-planned) increases or decrease.

#### **4.3.4 Data Filtering**

Automation of data filtering served as the case study. The developed add-in generates a filtered report by applying the filter criteria and constraints defined by the user. In this section, the main database is provided from the case study used for the change time impact analysis module and change cost impact analysis module. It means the as-planned and as-changed BIM model is developed, and the Check Change, Time Impact, and Cost Impact add-ins are applied to the model. Therefore, the first thing the user needs to do is select the Data Filtering add-in located on the left-hand side of the Revit interface. After the selection has been made, the add-in generates data filtering automatically, as shown in Figure 4-40. The generated data filtering report has six individual columns, which consists of both the as-planned and as-changed impacted components with cost and time data, plus the components' family type, assembly code, and assembly description, as shown in Figure 4-41. In order to run a filter in the generated report, the user has to perform three steps, as shown in Figure 4-42: a) filter field selection, b) filter method selection, and c) select the filter bottom to start the process of filtering and to generate a filtered report.

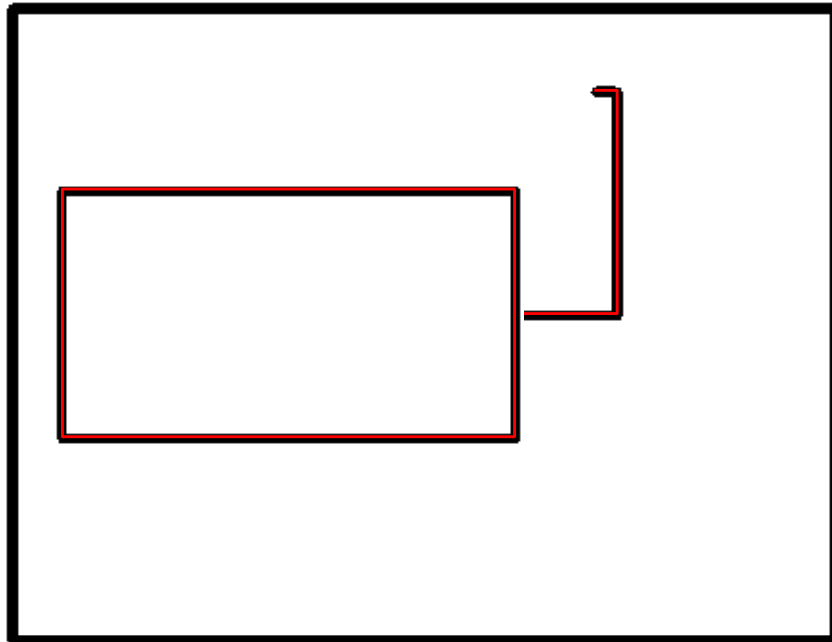


Figure 4–40: Data Filtering Add-in and Its Report Output

Data Filtering

Field:

Filter Method: =

Wall : Wall 1	B2020200	Curtain Walls	0	113.02105937545198	0	32.084719724994976
Wall : Wall 1	B2020200	Curtain Walls	0	197.78685390704095	0	56.148259518741213
Wall : Wall 1	B2020200	Curtain Walls	0	113.02105937545198	0	32.084719724994976
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	0	6.3053157356314706	0	0
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	0	6.3053157356314706	0	0
M_Window-Square...	B2020110	Windows - Aluminum	0	1.0462520925041849	0	0.025807551615103...
Wall : Wall 1	B2020200	Curtain Walls	132.79974476615632	0	37.699545676869157	0
M_Window-Square...	B2020110	Windows - Aluminum	1.0462520925041849	0	0.025807551615103...	0
M_Window-Square...	B2020110	Windows - Aluminum	1.0462520925041849	0	0.025807551615103...	0
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	6.3053157356314706	0	0	0
Wall : Wall 1	B2020200	Curtain Walls	282.55264843862994	282.55264843862994	80.211799312487443	73.8
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090388	226.04211875090388	64.169439449889937	33.29
Wall : Wall 1	B2020200	Curtain Walls	282.55264843863023	282.55264843863023	80.211799312487514	41.61

Figure 4–41: Data Filtering Add-in Report Output

Family Type	Assembly Code	Assembly Description	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	0	6.3053157356314706	0	0
Wall : Wall 1	B2020200	Curtain Walls	0	113.02105937545198	0	32.084719724994976
Wall : Wall 1	B2020200	Curtain Walls	0	197.78685390704095	0	56.148259518741213
Wall : Wall 1	B2020200	Curtain Walls	0	113.02105937545198	0	32.084719724994976
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	0	6.3053157356314706	0	0
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	0	6.3053157356314706	0	0
M_Window-Square ...	B2020110	Windows - Aluminum	0	1.0462520925041849	0	0.025807551615103...
Wall : Wall 1	B2020200	Curtain Walls	132.79974476615632	0	37.699545676869157	0
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0	0.025807551615103...	0
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0	0.025807551615103...	0
M_Door-Opening : 0...	C1020500	Interior Door Wall O...	6.3053157356314706	0	0	0
Wall : Wall 1	B2020200	Curtain Walls	282.55264843862994	282.55264843862994	80.211799312487443	73.8
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090388	226.04211875090388	64.169439449989937	33.29
Wall : Wall 1	B2020200	Curtain Walls	282.55264843863023	282.55264843863023	80.211799312487514	41.61

Figure 4–42: Data Filtering Add-in Report Output

In step 1, the filter field is as shown in Figure 4-43, and the user has the option to select one of the following options: family type, assembly code, assembly description, as-planned time, as-changed time, as-planned cost, or as-changed cost. In step 2, the user has to define the filter method for the selected filter type, as shown in Figure 4-44. In step 3, the user then selects the bottom filter, and the filtered report is generated automatically. Figures 4-45 to 4-51 provide the different scenarios between the filters filed and the filter method.

Assembly Description	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
Interior Door Wall O...	0	6.3053157356314706	0	0
Curtain Walls	0	113.02105937545198	0	32.084719724994976
Wall : Wall 1	B2020200	197.78685390704095	0	56.148259518741213
Wall : Wall 1	B2020200	113.02105937545198	0	32.084719724994976
M_Door-Opening : O...	C1020500	Interior Door Wall O...	0	0
M_Door-Opening : O...	C1020500	Interior Door Wall O...	0	0
M_Window-Square ...	B2020110	Windows - Aluminum	0	0.025807551615103...
Wall : Wall 1	B2020200	Curtain Walls	132.79974476615632	37.699545676869157
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0.025807551615103...
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0.025807551615103...
M_Door-Opening : O...	C1020500	Interior Door Wall O...	6.3053157356314706	0
Wall : Wall 1	B2020200	Curtain Walls	282.55264843862994	80.211799312487443
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090388	64.169439449889937
Wall : Wall 1	B2020200	Curtain Walls	282.55264843863023	80.211799312487514

Figure 4-43: Data Filtering Add-in Report Field Options

Assembly Description	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
Interior Door Wall O...	0	6.3053157356314706	0	0
Curtain Walls	0	113.02105937545198	0	32.084719724994976
Wall : Wall 1	B2020200	197.78685390704095	0	56.148259518741213
Wall : Wall 1	B2020200	113.02105937545198	0	32.084719724994976
M_Door-Opening : O...	C1020500	Interior Door Wall O...	0	0
M_Door-Opening : O...	C1020500	Interior Door Wall O...	0	0
M_Window-Square ...	B2020110	Windows - Aluminum	0	0.025807551615103...
Wall : Wall 1	B2020200	Curtain Walls	132.79974476615632	37.699545676869157
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0.025807551615103...
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	0.025807551615103...
M_Door-Opening : O...	C1020500	Interior Door Wall O...	6.3053157356314706	0
Wall : Wall 1	B2020200	Curtain Walls	282.55264843862994	80.211799312487443
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090388	64.169439449889937
Wall : Wall 1	B2020200	Curtain Walls	282.55264843863023	80.211799312487514

Figure 4-44: Data Filtering Add-in Report Filter Method Options

Data Filtering

Filter

Code	Assembly Description	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
	Curtain Walls	0	113.02105937545198	0	32.084719724994976
	Curtain Walls	0	197.78685390704095	0	56.148259518741213
	Curtain Walls	0	113.02105937545198	0	32.084719724994976
	Curtain Walls	132.79974476615632	0	37.699545676869157	0
	Curtain Walls	282.55264843862994	282.55264843862994	80.211799312487443	73.8
2020200	Curtain Walls	226.04211875090388	226.04211875090388	64.169439449989937	33.29
2020200	Curtain Walls	282.55264843863023	282.55264843863023	80.211799312487514	41.61
2020200	Curtain Walls	226.04211875090434	226.04211875090434	64.169439449990065	33.29
2020200	Curtain Walls	113.02105937545198	226.04211875090397	32.084719724994976	16.64

Close

Figure 4-45: Filter Report Based on Family Type

Data Filtering

Filter

Family Type	Assembly Description	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
M_Window-Squ	findows - Aluminum	0	1.0462520925041849	0	0.0258075516151032...
M_Window-Squ	findows - Aluminum	1.0462520925041849	0	0.0258075516151032...	0
M_Window-Square	findows - Aluminum	1.0462520925041849	0	0.0258075516151032...	0
M_Window-Square	findows - Aluminum	1.0462520925041849	1.0462520925041849	0.0258075516151032...	0.01

Close

Figure 4-46: Filter Report Based on Assembly Code

Data Filtering

Filter

Family Type	Assen	As-Planned Time	As-Changed Time	As-Planned Cost	As-Changed Cost
Wall : Wall 1	B20202		113.02105937545198	0	32.084719724994976
Wall : Wall 1	B20202		197.78685390704095	0	56.148259518741213
Wall : Wall 1	B20202		113.02105937545198	0	32.084719724994976
Wall : Wall 1	B20202	32.79974476615632	0	37.699545676869157	0
Wall : Wall 1	B20202...	32.55264843862994	282.55264843862994	80.211799312487443	73.8
Wall : Wall 1	B2020200	26.04211875090388	226.04211875090388	64.169439449989937	33.29
Wall : Wall 1	B2020200	32.55264843863023	282.55264843863023	80.211799312487514	41.61
Wall : Wall 1	B2020200	26.04211875090434	226.04211875090434	64.169439449990065	33.29
Wall : Wall 1	B2020200	13.02105937545198	226.04211875090397	32.084719724994976	16.64

Close

Figure 4-47: Filter Report Based on Assembly Description

Data Filtering

Filter

Family Type	Assen	As-Changed Time	As-Planned Cost	As-Changed Cost
M_Door-Opening : 0...	C1020F	3053157356314706	0	0
Wall : Wall 1	B20202	13.02105937545198	0	32.084719724994976
Wall : Wall 1	B20202	97.78685390704095	0	56.148259518741213
Wall : Wall 1	B20202	13.02105937545198	0	32.084719724994976
M_Door-Opening : 0...	C1020F	3053157356314706	0	0
M_Door-Opening : 0...	C1020F	3053157356314706	0	0
M_Window-Square...	B20201	0462520925041849	0	0.0258075516151032...
Wall : Wall 1	B2020200		37.699545676869157	0
M_Window-Square...	B2020110		0.0258075516151032...	0
M_Window-Square...	B2020110		0.0258075516151032...	0
M_Door-Opening : 0...	C1020500		0	0
M_Double-Panel 2 : ...	C1020120	6.814175295017257	2.3143871584826505	1.2
Wall : Wall 1	B2020200	26.04211875090397	32.084719724994976	16.64
M_Window-Square...	B2020110	0462520925041849	0.0258075516151032...	0.01

Close

Figure 4-48: Filter Report Based on As-planned Time



Data Filtering

Filter

Family Type	Assembly Code	Asst De	As-Planned Cost	As-Changed Cost
M_Door-Opening : 0...	C1020500	Interi		0
Wall : Wall 1	B2020200	Curt		32.084719724994976
Wall : Wall 1	B2020200	Curt		56.148259518741213
Wall : Wall 1	B2020200	Curt		32.084719724994976
M_Door-Opening : 0...	C1020500	Interi		0
M_Door-Opening : 0...	C1020500	Interior Door Wall Op...	0	0
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090388	4.169439449989937
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090434	4.169439449990065
M_Double-Panel 2 : ...	C1020120	Interior Doors - Wood	16.814175295017257	1.3143871584826505
Wall : Wall 1	B2020200	Curtain Walls	113.02105937545198	2.084719724994976

Close

Figure 4-49: Filter Report Based on As-Changed Time

Data Filtering

Filter

Family Type	Assen	As-Planned Cost	As-Changed Cost	
Wall : Wall 1	B2020200		0	
M_Window-Square ...	B2020110		0	
M_Window-Square ...	B2020110		0	
Wall : Wall 1	B2020200		73.8	
Wall : Wall 1	B2020200		33.29	
Wall : Wall 1	B2020200	Curtain Walls	282.55264843863023	41.61
Wall : Wall 1	B2020200	Curtain Walls	226.04211875090434	33.29
M_Double-Panel 2 : ...	C1020120	Interior Doors - Wood	16.814175295017257	1.2
Wall : Wall 1	B2020200	Curtain Walls	113.02105937545198	16.64
M_Window-Square ...	B2020110	Windows - Aluminum	1.0462520925041849	1.01

Close

Figure 4-50: Filter Report Based on As-planned Cost

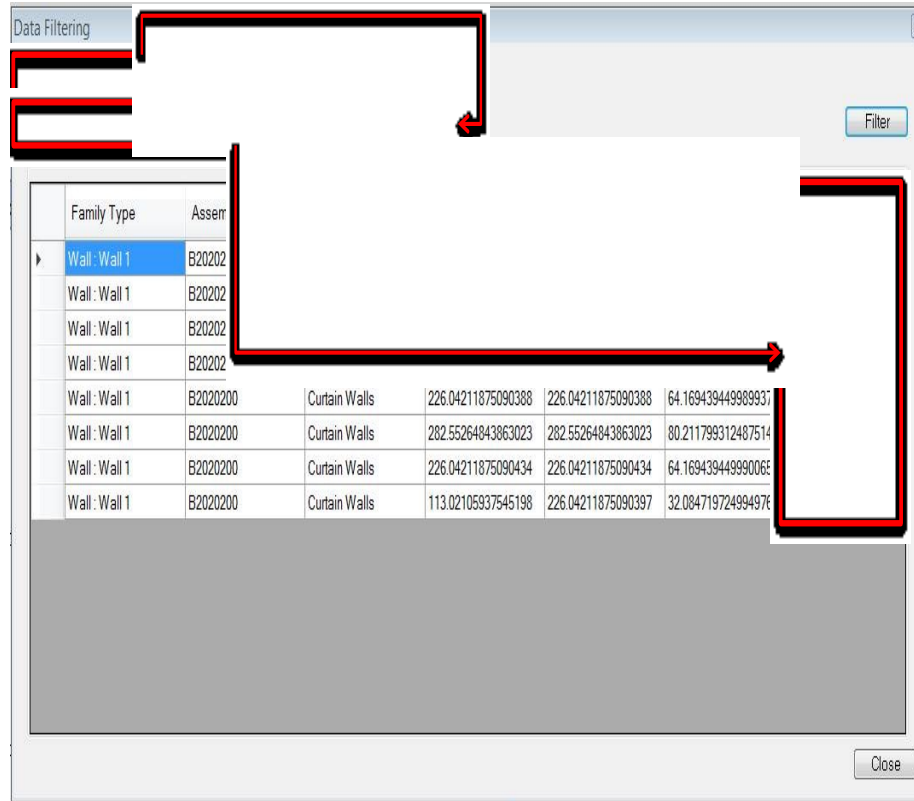


Figure 4–51: Filter Report Based on As-changed Cost

#### 4.4 Summary, Analysis and Discussion of Results

This chapter presents the computer implementation of the developed model, BIM-Change. It also highlights the developed system’s framework modules, and describes the user interfaces designed to enable users to see the ripple effect of requested design changes, as well as the quantification of the changes in terms of project cost and time. The developed software BIM-Change was coded using the “Visual C# .Net” programming language. It consists of six computational add-ins: Check Change, Ripple Effect, Room Grouping, Time Impact, and Cost Impact, Data Filtering, as shown in Figure 4-52.

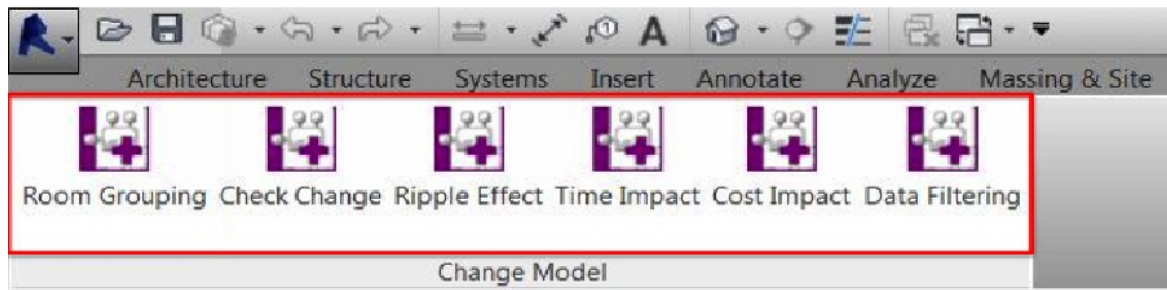


Figure 4–52: Developed Model Add-ins

The Check Change add-in can be used as an advanced tool for data acquisition, data analysis, and data reporting and highlighting. The Ripple Effect add-in can be used to determine the impact of a direct design change on other project components. The Room Grouping add-in can be used to generate a micro-level WBS for the entire project, as well as a unique ID for each group. The Time Impact add-in can be used to quantify and analyze the ripple effect of changes on a project’s total duration by estimating the total duration in days needed for each impacted component of the generated as-changed BIM model. The Cost Impact add-in can be used to quantify and analyze the ripple effect of changes on a project’s total cost through estimating the unit cost of each impacted component of the generated as-changed BIM model. The Data Filtering add-in can be used for narrowing down the data in the report generated based on the data extracted from the Time Impact and Cost Impact add-ins, allowing the user to view only the information related to the selected filter field and method. Sample source code and sequence diagrams of the Check Change, Room Grouping, Ripple Effect, Time Impact, Cost Impact and Data Filtering add-ins are included in Appendix D.

BIM-Change outperformed the capabilities provided by commercially available software systems. As shown in Table 4-2, the limitations and abilities of the

commercially available models such as Vico, Innovaya, Autodesk Navisworks, Synchro and Assemble (as described in section 2.9) are compared with the developed BIM-Change model. All of these models have some common limitations: they do not have the ability to track the consequences of design changes throughout the project, from one element to the next, nor are they able to ascertain the ripple effect of changes on a project's time and cost. In terms of visualization, these models are able to visualize and color-code the changed component based on change type. In terms of the impact of changes on cost, these models are unable to perform a cost analysis, but Innovaya, BIMestiMate, and Assemble are capable of quickly generating an automated cost estimate, which includes only direct costs—not indirect costs, impact costs or change costs. In addition, the only system that has an estimating platform to calculate the component unit cost is Innovaya. In terms of determining the impact of changes on time, Innovaya, Navisworks, and Synchro are capable of providing a visual 4D simulation by linking the model to the available schedule. However, they cannot estimate the durations of the impacted components and update the schedule based on these new durations. Also, none of them consider productivity.

Table 4–2: Comparison Table (BIM-Change Model vs. Assemble, BIMestiMate, Innovaya, Navisworks, Synchro and Viso)

Software Name	Features													
	Visualization			C	Time Impact				Cost Impact				L	M
	A		B		D	E	F	G	H	I	J	K		
	2D	3D												
Assemble	No	Yes	No	Yes	No	No	No	No/No	Yes	No	No	No	No	No
BIMestiMate	No	Yes	No	Yes	No	No	No	No/ No	Yes	No	No	No	No	No
Innovaya	No	Yes	No	Yes	Yes	No	No	Yes/No	Yes	No	No	Yes	No	No
Navisworks	No	Yes	No	Yes	Yes	No	No	Yes/No	Yes	No	No	No	No	Yes
Synchro	No	No	No	No	Yes	No	No	Yes/No	No	No	No	No	No	No
Vico	Yes	Yes	No	No	No	No	No	No/No	No	No	No	No	No	No
BIM-Change	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes/Yes	Yes	Yes	Yes	Yes	Yes	Yes

A: Change Types

F: Considering Productivity Factor

K: Estimating Platform

B: Ripple Effect

G: Schedule Linking/ Updating

L: Modification in the Components' Geometry

C: Review the Quantity Variances

H: Direct Cost

M: Model Integration

D: Visual 4D Simulation

I: Impact Cost

E: Estimate Component's Duration

J: Change Cost

According to Google, Assemble is the most commonly used and most reviewed software in the industry. Also, it is the most compatible with BIM-Change based on Assemble's capabilities and features. Therefore, a case study similar to the one shown in section 4.3.3 is used here to run Assemble in order to demonstrate its capabilities and output. As shown in Figure 4-53, the user selects the two Revit versions of a project model for comparison, and then selects OK in the provided Assemble interface. In Figure 4-54, the interface of Assemble's result is separated into different sections, each of which is explained below:

Section A: This section shows the two version of a project model that has been compared. It is easy to understand which version of the model is selected as a base for the comparison.

Section B: This section shows the changes the user has to click on to get the results of models' comparison.

Section C: This section shows the type of changes that exist between the two versions, along with the number of changes in each type: added, removed, type changed only, quantity changed only, type and quantity changed, and unchanged. Each change type has its color code, which is used to visualize the change type in the 3D model of the project in section D.

Section D: This section shows Assemble's visualization capability by overlaying the two versions of the model on top of each other in order to determine the changes that exist between them. Then, the changes are color-coded based on their type, as explained in section C.

Section E: This section shows each version of the models' components quantity and the component variances between the two versions. Also, this section provides each version's components' unit cost and the cost variances between the two versions. For the newly added components, the user has to insert the unit cost manually since there is no estimation platform available in Assemble.

Therefore, Assemble is able to visualize the change type, review the quantity variances and estimate the change components' direct cost. However, BIM-Change is further able to visualize the ripple effect of the changes in terms of cost impact, estimating the impact cost and change cost in addition to the direct cost. Moreover, BIM-Change analyzes the impact of changes on project time by estimating the changed components' duration and updating the project schedule by linking the new estimated durations. Assemble is a cloud-based system, so the user is only able to modify descriptive data about the model. However, since BIM-Change is not cloud-based this allows the user to modify the components' geometry of the BIM models anytime during the analysis.

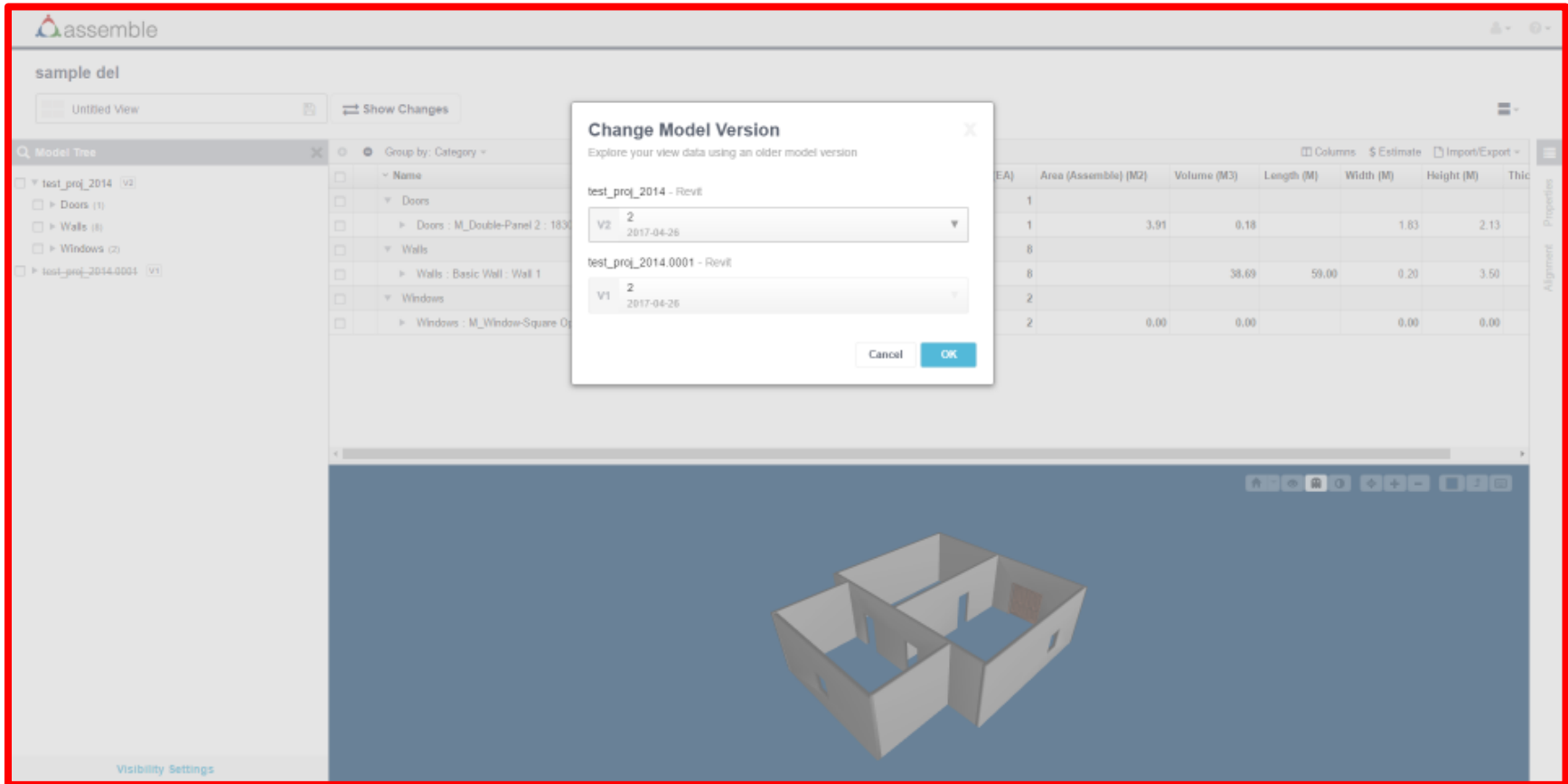


Figure 4–53: Assemble System Cloud-based Platform



The screenshot displays the Assemble software interface for change analysis. The main window is titled "sample del" and shows a comparison between two versions of a model: "test\_proj\_2014" version v2 (dated 04/26/2017) and version v1 (dated 04/26/2017). The interface is divided into several sections:

- Comparing Models (A):** A sidebar on the left where the two versions are selected for comparison.
- Showing Changes (B):** A central table displaying the differences between the two versions, grouped by category.
- Show Variances For (C):** A section at the bottom left with checkboxes for filtering variances: Added (4), Removed (3), Type Changed Only (0), Quantity Changed Only (2), Type And Quantity Changed (0), and Unchanged.
- 3D Model View (D):** A 3D visualization of the model at the bottom right, with different components highlighted in various colors (green, purple, blue) to represent the changes.
- Table (F):** A detailed table of changes, including columns for Name, Model Name, Quantity (A, B, Variance), Unit, and Total Cost (A, B, Variance).

Name	Model Name	Quantity				Total Cost			
		A	B	Variance	Unit	A	B	Variance	
Walls	test_proj_2014	107.16	60.64	46.52	M2	257.39	214.16	43.23	
Walls : Basic Wall : Wall 1	test_proj_2014	107.16	60.64	46.52	M2	257.39	214.16	43.23	
Windows	test_proj_2014		1	2	(1.00)	EA	0.03	0.06	0.03
Windows : M_Window-Square Opening : 0900 x 1200mm	test_proj_2014		1	2	(1.00)	EA	0.03	0.06	0.03

Figure 4–54: Assemble Software Change Analysis Output

## **Chapter 5: Conclusions and Future Work**

### **5.1 Summary and Conclusions**

Owner-generated design changes are very common in building projects, so understanding the ripple effect of them is critical for making rational design decisions. Often project owners request design changes after approving the final project design without considering the impact such changes will have on the design of other interrelated building components. Analyzing and calculating the ripple effect of owner-requested design changes on a project's schedule and cost is very time-consuming and requires expert knowledge. They may also increase the probability of conflicts among project participants. Most conflicts between project owners and contractors can be attributed to the owners' lack of knowledge that a simple change in one part of the project may cause a series of changes in other parts of the project. Therefore, owner-requested design changes need to be managed in an effective manner: first, by identifying the ripple effect of the design change on other project components, and second, by quantifying the impact of the design change's ripple effect on project cost and time. The associated direct and indirect impacts of a project change have motivated scientists to figure out a way to minimize the chances of project failure.

A complete literature review of the existing research highlights the limitations of previously developed BIM and non-BIM models in various aspects, such as the lack of computer implementation, the lack of ripple effect visualization, the lack of integration and so on. Although the impacts of change have been studied extensively in the literature, most studies focus merely on numerical labor productivity instead of developing a

computed model for estimating the impact of change on project cost and time. This lack of an integrated change management model led to the development of the current model for the efficient management of project design changes. This study proposes a novel BIM-based model for design-change management in building project named BIM-Change. The main model was developed in several separate add-ins, and the Revit Application Programming Interface (API) was used to develop these add-in(s) coded in C#. To identify the ripple effect of owner-requested design change on other project components, a BIM-based add-in named Check-change was developed. This add-in compares the “as-planned” building information model with “as-changed” building information model to identify and visualize the sequence of impacted design changes, considering such introduced changes on the quantities and specifications of impacted building components and their respective dependencies. Moreover, the Ripple Effect add-in was developed to generate a detailed report for each contemplated design change and visualize the ripple effects. The impacted components are then classified into three categories of change type (added, deleted and modified). After a database of impacted project components is developed and the type of impacted components is identified, its related quantities are extracted from the project BIM model to estimate the time and cost impacts of a design change. To quantify the ripple effect of owner-requested design change on project time, a BIM-based quantification add-in named Time Impact calculates the impact of design changes and their ripple effect on a project’s total duration. After analyzing the ripple effect over time, the model updates the project schedule accordingly.

The developed model links the newly estimated components’ durations to the project’s as-planned schedule, and updates project activities and total duration based on

the impacted components' durations. The Room Grouping add-in was developed to ease the process of schedule linking. Next, to quantify the ripple effect of owner-requested design change on project cost, a BIM-based quantification add-in named Cost Impact was developed. This add-in calculates the costs needed for each impacted component, and provides the project's updated direct cost. Moreover, it calculates the change impact cost (in terms of productivity and time), considering the project's total indirect costs. The developed model is also capable of calculating the cost variance caused by a change, which informs the owner of the costs added or deducted from the overall project cost. Finally, the Data Filtering add-in was developed to help the user browse through data faster by filtering unnecessary and unwanted data. This model was then applied to a case study to demonstrate its usefulness and illustrate its essential features.

The key benefits of the developed model are: Accelerating the time-consuming process of change impact analysis on project cost and time, aiding owners and their agents in determining the ripple effect of a design change before making a decision; providing owners with the information needed to make enlightened decisions in order to identify beneficial design changes for the project and avoiding detrimental changes; allowing users to try several what-if scenarios for owner-requested design changes and see how they may impact project cost and schedule; controlling and prioritizing design changes at project design based on the owner's preferences before making any final decisions; enhancing the level of communication among project participants, the owner, designers and other participants; and preventing conflicts and disputes from arising, thus decreasing the chance of project failure.

## 5.2 Research Contributions and Limitations

The contributions of this research are intended to address the limitations associated with current practices and existing change management models. Specifically, the main contributions of this research are:

- An extensive review and study of previous BIM and non-BIM models for change management; identifying their related advantages and limitations.
- The development of an innovative and integrated method and its related algorithms to design change management using:
  - BIM Technology
  - Autodesk Revit Software
  - C# Visual Studio
- The development of an integrated, automated BIM-based model and its associated algorithms for tracking and visualizing the ripple effect of design changes in building projects. This model constitutes other contributions:
  - Developing a micro-level work breakdown structure (WBS) algorithm for grouping the project's BIM model areas by adding the project's components as a new project level;
  - Developing a component-by-component comparison technique to track and highlight the project's direct and indirect changes;
  - Developing a comparison report between the components of the project's as-planned and as-changed BIM models;
  - Developing a color code visualization technique to ease the understating of the change types in the project BIM model and generated comparison

report;

- Developing the ripple effect report to highlight the change path by selecting the individual direct design change and then demonstrating the cause and effect relationship between the direct and indirect changes; and
  - Integrating and linking the ripple effect report data and BIM model to ease the understanding of the cause and effect relationship between the contemplated change and its ripple effect on the other project components.
- The development of a BIM-based model and its respective algorithms to advance the precision of estimating a design change's ripple effect on a project's total cost.

This model constitutes other contributions:

- Automated calculation of a project's impacted component direct cost;
  - Automated calculation of the change cost by using Moselhi's (1998) change cost estimate framework;
  - An automation of Leonard's (1991) model to calculate productivity-related impact costs;
  - Automated the estimation of time-related change costs; and
  - Automated calculation of as-planned costs, as-changed costs and cost variance due to project changes.
- The development of a BIM-based model and its respective algorithms to advance the precision of estimating a design change's ripple effect on a project's schedule.

This model constitutes other contributions:

- Automated calculation of a project's impacted components and project's total duration; and

- Automated updating of project schedule (as-changed) by linking the calculated duration of the impacted components into the as-planned project schedule.
- The utilization of different building project case studies to demonstrate the developments made in the course of this research—namely Room Grouping, Ripple Effect, Check Change, Time Impact, Cost Impact, and Data Filtering.

The following limitations were taken into account during the creation, validation, and implementation of the model and add-ins developed in this research:

- This study only automated the identification of change and analysis of its impact; other steps in the change management process are not considered, such as logging, registering and monitoring the approved design changes.
- The expert knowledge is not imbedded in the system. So, the developed model cannot automatically generate the modified BIM model, which includes all building systems (e.g., MEP, HVAC) after applying the changes to the original BIM model. Therefore, the user has to provide both original and modified BIM models.
- Some of the add-ins of the developed model are not fully automated and require user interaction with the system (for example, the selection of the components in Room Grouping add-in, and the selection of individual direct design changes in Ripple Effect add-in).
- This study used only Leonard's (1991) regression model and Moselhi's (1998) developed framework to automate project's productivity related cost and change cost, respectively.

### **5.3 Future work and Recommendations**

This study aims to develop an integrated quantitative BIM model for design change management; however, the existing study can be improved through some enhancements and extensions. Some recommendations for future work are:

- Investigate the potential application of the proposed method on other project types, such as industrial, highway, heavy construction, and so on.
- Study and incorporate other models for estimating the impact of change.
- Provide flexibility to use other software for example, link the data generated by Time Impact add-in to Primavera instead of MS Project.
- Experiment with system dynamic using the developed algorithm of this study.
- The possibility of integrating the developed model with a Knowledge-based system can be explored in order to determine the ripple effect of any design change in other project systems, such as architectural, mechanical, electrical, and HVAC. One of the potential solution is to integrate dependency structure matrix (DSM) design approach with BIM.



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# Appendix A: Labor Hour Database Sample

The screenshot shows an Excel spreadsheet titled "Labour Hour .xlsx". The ribbon includes Home, Layout, Tables, Charts, SmartArt, Formulas, Data, and Review. The spreadsheet data is as follows:

	A	B	C	D	E	F	G	H	I	J	K
9	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
10	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
11	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
12	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
13	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
14	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
15	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
16	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
17	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
18	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
19	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
20	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
21	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
22	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
23	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
24	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
25	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
26	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
27	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
28	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
29	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
30	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
31	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
32	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
33	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
34	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
35	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
36	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
37	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
38	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
39	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
40	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
41	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
42	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
43	M_Concrete-Round-Column: 450mm	B1010240	Columns - CIP	0.229							
44	Concrete-Rectangular-Column: 600 x 300 mm	B1010240	Columns - CIP	0.073							
45	Concrete-Rectangular-Column: 600 x 300 mm	B1010240	Columns - CIP	0.073							
46	M_Concrete-Round-Column: 600mm	B1010240	Columns - CIP	0.237							
47	Concrete-Rectangular-Column: 700 x 400 mm	B1010240	Columns - CIP	0.16							
48	Concrete-Rectangular-Column: 400 x 300 mm	B1010240	Columns - CIP	0.136							
49	Concrete-Rectangular-Column: 400 x 300 mm	B1010240	Columns - CIP	0.136							

A green callout box on the right side of the spreadsheet contains the following text:

- Column A: Assembly Description
- Column B: Assembly ID
- Column C: Component Type
- Column D: Labor Hour (LH)



## Appendix B: Mapping RSMMeans Components' Assembly Type into Unit Type (Al-Mashta, 2010)

UniFormat II			MasterFormat 95														MasterFormat 2004																																
Level One	Level Two	Level Three	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16																	
			Sitework	Concrete	Masonry	Metals	Wood / Plastic	Thermal and Moisture	Doors and Windows	Finishes	Specialties	Equipment	Furnishings	Special Construction	Conveying Systems	Mechanical	Electrical	Existing Conditions	Concrete	Masonry	Metals	Wood, Plastics, and Composites	Thermal and Moisture	Openings	Finishes	Specialties	Equipment	Furnishings	Special Construction	Conveying Equipment	Fire Suppression	Plumbing	Heating Ventilating and Air Conditioning	Integrated Automation	Electrical	Communications	Electronic Safety and Security	Earthwork	Exterior Improvements	Utilities									
A Substructure	A10 Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	A20 Basement Construction	A2010 Basement Excavation A2020 Basement Walls	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
B Shell	B10 Super Structure	B1010 Floor Construction B1020 Roof Construction	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
	B20 Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
	B30 Roofing	B3010 Roof Coverings B3020 Roof Openings	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
C Interiors	C10 Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	C20 Stairs	C2010 Stair Construction C2020 Stair Finishes	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	C30 Interior Finishes	C3010 Wall finishes C3020 Floor Finishes C3030 Ceiling Finishes	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
D Services	D10 Conveying	D1010 Elevator and Lifts D1020 Escalators and Moving Walks D1090 Other Conveying Systems	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
	D20 Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rain Water Drainage D2090 Other Plumbing Systems	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	D30 HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	D40 Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■



## Appendix C: RSMMeans Assembly Cost Database Sample

### Commercial New Construction

- A Substructure
  - A10 Foundations
    - A1010 Standard Foundation
      - A1010110 Strip Footings
    - A1020 Special Foundation
      - A1020110 C.I.P. Concrete Piles
    - A1030 Slab On Grade
      - A1030120 Plain & Reinforced
  - A20 Basement Construction
    - A2010 Basement Excavation
      - A2010110 Building Excavation & Backfill
    - A2020 Basement Walls
      - A2020110 Walls, Cast in Place
- B Shell
  - B10 Superstructure
    - B1010 Floor Construction
      - B1010201 C.I.P. Column- Round Tied
    - B1020 Roof Construction
      - B10201102 Wood/ Flat or Pitched
  - B20 Exterior Enclosure
    - B2010 Exterior Walls
      - B2010101 Cast on Place Concrete
    - B2020 Exterior Windows
      - B2020102 Wood Windows
    - B2030 Exterior Doors
      - B2030110 Glazed Doors, Steel or Aluminum
  - B30 Roofing
    - B3010 Roof Coverings
      - B3010105 Built-Up
    - B3020 Roof Openings
      - B3020110 Skylights
- C Interiors
  - C10 Interior Construction
    - C1010 Partitions
      - C1010102 Concrete Block Partitions- Regular Weight
    - C1020 Interior Doors
      - C1020102 special Doors

- C1030 Fittings
        - C1030110 Toilet Partitions
    - C20 Stairs
      - Stair Construction
        - C2010110 Stairs
    - C30 Interior Finishes
      - C3010 Wall Finishes
        - C3010230 Paint & Covering
      - C3020 Floor Finishes
        - C3020410 Tile & Covering
      - C3030 Ceiling Finishes
        - C3030105 Plaster Ceilings
  - D Services
    - D10 Conveying
      - D1010 Elevators and Lifts
        - D1010110 Hydraulic
      - D1020 Escalators and Moving Walks
        - D1020110 Moving Stairs
      - D1090 Other Conveying Systems
        - D1090410 Miscellaneous Types
    - D20 Plumbing
      - D2010 Plumbing Fixtures
        - D2010110 Water Closet Systems
      - D2020 Domestic Water Distribution
        - D2020210 Electric Water Heaters- Residential Systems
      - D2040 Rain Water Drainage
        - D2040210 Roof Drain Systems
      - D2090 Other Plumbing Systems
        - D2090810 Piping- Installed- Unit Costs
    - D30 HVAC
      - D3010 Energy Supply
        - D3010510 Apartment Building Heating- Fin Tube Radiation
      - D3020 Heat Generating Systems
        - D3020102 Small Heating Systems, Hydronic, Electric Boilers
      - D3030 Cooling Generating Systems
        - D3030110 Chilled Water, Air Condenser Systems
      - D3040 Distribution Systems
        - D3040106 Field Fabricated Air Handling Unit
      - D3050 Terminal & Package Units
        - D3050120 Unit Heaters, Gas

- D3090 Other HVAC Systems/ Equip
        - D3090310 Fume Hood Exhaust Systems
    - D40 Fire Protection
      - D4010 Sprinklers
        - D4010310 Dry Pipe Sprinkler Systems
      - D4020 Standpipes
        - D4020310 Wet Standpipe Risers
      - D4090 Other Fire Protection Systems
        - D4090910 Fire Suppression Unit Components
    - D50 Electrical
      - D5010 Electrical Service/ Distribution
        - D5010110 High Voltage Shielded Conductors
      - D5020 Lighting and Branch Wiring
        - D5020110 Receptacle (by Wattage)
      - D5030 Communications and Security
        - D5030310 Telephone Systems
      - D5090 Other Electrical Systems
        - D5090210 Generators (by KW)
  - E Equipment & Furnishing
    - E10 Equipment
      - E1010 Commercial Equipment
        - E1010110 Security/ Vault, EACH
      - E1020 Industrial Equipment
        - E1020110 Ecclesiastical Equipment, EACH
      - E1030 Vehicular Equipment
        - E1030110 Vehicular Service Equipment, EACH
      - E1090 Other Equipment
        - E1090110 Maintenance Equipment, EACH
    - E20 Furnishings
      - E2010 Fixed Furnishings
        - E2010310 Window Treatment, EACH
      - E2020 Movable Furnishings
        - E2020210 Furnishing/ EACH
  - F Special Construction
    - F10 Special Construction
      - F1010 Special Structures
        - F1010120 Air-Supported, S.F.
      - F1020 Integrated Construction
        - F1020110 Integrated Construction, EACH
      - F1030 Special Construction Systems
        - F1030120 Sound, Vibration, and Seismic Construction, S.F.

- F1040 Special Facilities
        - F1040210 Ice Rinks, EACH
  - G Building Site work
    - G10 Site Preparation
      - G1010 Site Clearing
        - G1010120 Clear & Grub Site
      - G1020 Site Demolitions and Relocations
        - G1020205 Remove Underground Water Pipe Including Earthwork
      - G1030 Site Earthwork
        - G1030105 Cut & Fill Gravel
    - G20 Site Improvements
      - G2010 Roadways
        - G2010230 Bituminous Roadway Gravel Base
      - G2020 Parking Lots
        - G2020210 Parking Lots Gravel Base
      - G2030 Pedestrian Paving
        - G2030110 Bituminous Sidewalks
      - G2040 Site Development
        - G2040105 Fence & Guardrails
      - G2050 Landscaping
        - G2050410 Lawns & Ground Cover
    - G30 Site Mechanical Utilities
      - G3010 Water Supply
        - G3010110 Water Distribution Piping
      - G3020 Sanitary Sewer
        - G3020110 Drainage & Sewage Piping
      - G3030 Storm Sewer
        - G3030210 Manholes & Catch Basins
      - G3060 Fuel Distribution
        - G3060110 Gas Service Piping
    - G40 Site Electrical Utilities
      - G4010 Electrical Distribution
        - G4010312 Underground Power Feed
      - G4020 Site Lighting
        - G4020110 Site Lighting
    - G90 Other Site Construction
      - G9020 Site Repair & Maintenance
        - G9020100 Clean and Wrap Marine Piles

## **Electrical**

- D Service

- D20 Plumbing
  - D2020 Domestic Water Distribution
- D30 HVAC
  - D3020 Heat Generating Systems
- D40 Fire Protection
  - D4090 Other Fire Protection
- D50 Electrical
  - D5010 Electrical Service/ Distribution
    - D5010110 High Voltage Shielded Conductors
  - D5020 Lighting and Branch Wiring
    - D5020110 Receptacle (by Wattage)
  - D5030 Communications and Security
    - D5030310 Telephone Systems
  - D5090 Other Electrical Systems
    - D5090210 Generators (by KW)
  - G Building Sitework
    - G10 Site Preparation
      - G1030 Site Earthwork
        - G1030805 Trenching Common Earth
    - G40 Site Electrical Utilities
      - G4010 Electrical Distribution
        - G4010312 Underground Power Feed
      - G4020 Site Lighting
        - G4020110 Site Lighting

### **Mechanical**

- A Substructure
  - A20 Basement Construction
    - A2020 Basement Walls
      - A2020220 Sub drainage Piping
- D Services
  - D20 Plumbing
    - D2020 Domestic Water Distribution
  - D30 HVAC
    - D3010 Energy Supply
      - D3010510 Apartment Building Heating- Fin Tube Radiation
    - D3020 Heat Generating Systems
      - D3020102 Small Heating Systems, Hydronic, Electric Boilers
    - D3030 Cooling Generating Systems
      - D3030110 Chilled Water, Air Condenser Systems
    - D3040 Distribution Systems
      - D3040106 Field Fabricated Air Handling Unit
- G Building Site work

- G10 Site Preparation
  - G1030 Site Earthwork
    - G1030805 Trenching Common Earth
- G30 Site Mechanical Utilities
  - G3010 Water Supply
    - G3010110 Water Distribution Piping
  - G3020 Sanitary Sewer
    - G3020110 Drainage & Sewage Piping
  - G3030 Storm Sewer
    - G3030210 Manholes & Catch Basins
  - G3060 Fuel Distribution
    - G3060110 Gas Service Piping

### **Plumbing**

- D Services
  - D20 Plumbing
    - D2010 Plumbing Fixtures
      - D2010110 Water Closet Systems
      - D2010936 Five Fixture Bathroom, One Wall Plumbing
    - D2020 Domestic Water Distribution
      - D2020210 Electric Water Heaters- Residential Systems
    - D2040 Rain Water Drainage
      - D2040210 Roof Drain Systems
  - D30 HVAC
    - D3010 Energy Supply
      - D3010510 Apartment Building Heating- Fin Tube Radiation
    - D3020 Heat Generating Systems
      - D3020102 Small Heating Systems, Hydronic, Electric Boiler
    - D3090 Other HVAC Systems/Equip
      - D3090320 Garage Exhaust Systems
  - D40 Fire Protection
    - D4010 Sprinklers
      - D4010310 Dry Pipe Sprinkler Systems
    - D4020 Standpipes
      - D4020310 Wet Standpipe Risers
    - D4090 Other Fire Protection Systems
      - D4090910 Fire Suppression Unit Components
- G Building Site work
  - G10 Site Preparation
    - G1030 Site Earthwork



- G1030805 Trenching Common Earth
- G20 Site Improvements
  - G2040 Site Development
    - G2040920 Swimming Pools
  - G2050 Landscaping
    - G2050710 Site Irrigation
- G30 Site Mechanical Utilities
  - G3010 Water Supply
    - G3010121 Water Service, Lead Free
  - G3020 Sanitary Sewer
    - G3020302 Septic Systems
  - G3030 Storm Sewer
    - G3030210 Manholes & Catch Basins

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Quantity	Assembly Number	Source	SubC	Description	Unit	Material O&P	Installation O&P	Total O&P	Ext. Material O&P	Ext. Installation O&P	Ext. Total O&P	Labor Type	Data Release	CCI Location	Notes
1	A10103101450			Foundation underdrain, outside only, perforated HDPE, 8" diameter	L.F.	\$ 8.55	\$ 2.29	\$ 10.84	\$ 8.55	\$ 2.29	\$ 10.84	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103101500			Foundation underdrain, outside only, perforated HDPE, 12" diameter	L.F.	\$ 16.37	\$ 5.17	\$ 21.54	\$ 16.37	\$ 5.17	\$ 21.54	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103101600			Foundation underdrain, outside only, corrugated metal, 16 ga, asphalt coated, 6" diameter	L.F.	\$ 13.89	\$ 4.05	\$ 17.94	\$ 13.89	\$ 4.05	\$ 17.94	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103101650			Foundation underdrain, outside only, corrugated metal, 8" diameter	L.F.	\$ 17.91	\$ 4.34	\$ 22.25	\$ 17.91	\$ 4.34	\$ 22.25	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103101700			Foundation underdrain, outside only, corrugated metal, 10" diameter	L.F.	\$ 22.15	\$ 5.79	\$ 27.94	\$ 22.15	\$ 5.79	\$ 27.94	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103000			Foundation underdrain, outside and inside, PVC, 4" diameter	L.F.	\$ 10.01	\$ 7.72	\$ 17.73	\$ 10.01	\$ 7.72	\$ 17.73	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103100			Foundation underdrain, outside and inside, PVC, 8" diameter	L.F.	\$ 17.40	\$ 8.61	\$ 26.01	\$ 17.40	\$ 8.61	\$ 26.01	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103400			Foundation underdrain, outside and inside, perforated HDPE, 6" diameter	L.F.	\$ 11.40	\$ 3.65	\$ 15.05	\$ 11.40	\$ 3.65	\$ 15.05	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103450			Foundation underdrain, outside and inside, perforated HDPE, 8" diameter	L.F.	\$ 17.03	\$ 4.57	\$ 21.60	\$ 17.03	\$ 4.57	\$ 21.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103500			Foundation underdrain, outside and inside, perforated HDPE, 12" diameter	L.F.	\$ 32.90	\$ 10.35	\$ 43.25	\$ 32.90	\$ 10.35	\$ 43.25	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103600			Foundation underdrain, outside and inside, corrugated metal, 16 ga, asphalt coated, 8" diameter	L.F.	\$ 27.78	\$ 8.08	\$ 35.86	\$ 27.78	\$ 8.08	\$ 35.86	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103650			Foundation underdrain, outside and inside, corrugated metal, 8" diameter	L.F.	\$ 35.82	\$ 8.67	\$ 44.49	\$ 35.82	\$ 8.67	\$ 44.49	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103103700			Foundation underdrain, outside and inside, corrugated metal, 10" diameter	L.F.	\$ 44.59	\$ 11.56	\$ 56.15	\$ 44.59	\$ 11.56	\$ 56.15	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103200000			Foundation dampproofing		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103200800			Foundation dampproofing		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103201000			Foundation dampproofing, bituminous, 1 coat, 4" high	L.F.	\$ 1.46	\$ 3.83	\$ 5.29	\$ 1.46	\$ 3.83	\$ 5.29	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103201400			Foundation dampproofing, bituminous, 1 coat, 8" high	L.F.	\$ 2.92	\$ 7.65	\$ 10.57	\$ 2.92	\$ 7.65	\$ 10.57	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103201800			Foundation dampproofing, bituminous, 1 coat, 12" high	L.F.	\$ 4.39	\$ 11.88	\$ 16.27	\$ 4.39	\$ 11.88	\$ 16.27	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103202000			Foundation dampproofing, bituminous, 2 coats, 4" high	L.F.	\$ 2.87	\$ 4.68	\$ 7.55	\$ 2.87	\$ 4.68	\$ 7.55	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	A10103202400			Foundation dampproofing, bituminous, 2 coats, 8" high	L.F.	\$ 5.73	\$ 9.35	\$ 15.08	\$ 5.73	\$ 9.35	\$ 15.08	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
				Foundation dampproofing									Year		

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6	Data Release :Year 2015														Assembly Cost Estimate				
7																			
8	Quantity	Assembly Number	Source	SubC	Description	Unit	Material O&P	Installation O&P	Total O&P	Ext. Material O&P	Ext. Installation O&P	Ext. Total O&P	Labor Type	Data Release	CCI Location	Notes			
9	1	B20101010000			Cast in place concrete		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
10	1	B20101010001			Walls		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
11	1	B20101012050			Cast in place concrete		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
12	1	B20101012100			Concrete wall, reinforced, 8' high, 6" thick, plain finish, 3000 PSI	S.F.	\$ 6.34	\$ 12.00	\$ 18.34	\$ 6.34	\$ 12.00	\$ 18.34	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
13	1	B20101012200			Concrete wall, reinforced, 8' high, 6" thick, plain finish, 4000 PSI	S.F.	\$ 6.47	\$ 12.00	\$ 18.47	\$ 6.47	\$ 12.00	\$ 18.47	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
14	1	B20101012300			Concrete wall, reinforced, 8' high, 6" thick, plain finish, 5000 PSI	S.F.	\$ 6.62	\$ 12.00	\$ 18.62	\$ 6.62	\$ 12.00	\$ 18.62	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
15	1	B20101012400			Concrete wall, reinforced, 8' high, 6" thick, rubbed 1 side, 3000 PSI	S.F.	\$ 6.34	\$ 14.38	\$ 20.72	\$ 6.34	\$ 14.38	\$ 20.72	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
16	1	B20101012500			Concrete wall, reinforced, 8' high, 6" thick, rubbed 1 side, 4000 PSI	S.F.	\$ 6.47	\$ 14.38	\$ 20.85	\$ 6.47	\$ 14.38	\$ 20.85	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
17	1	B20101012600			Concrete wall, reinforced, 8' high, 6" thick, rubbed 1 side, 5000 PSI	S.F.	\$ 6.62	\$ 14.38	\$ 21.00	\$ 6.62	\$ 14.38	\$ 21.00	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
18	1	B20101012700			Concrete wall, reinforced, 8' high, 6" thick, aged wood liner, 3000 PSI	S.F.	\$ 7.88	\$ 13.74	\$ 21.62	\$ 7.88	\$ 13.74	\$ 21.62	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
19	1	B20101012800			Concrete wall, reinforced, 8' high, 6" thick, aged wood liner, 4000 PSI	S.F.	\$ 8.01	\$ 13.74	\$ 21.75	\$ 8.01	\$ 13.74	\$ 21.75	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
20	1	B20101012900			Concrete wall, reinforced, 8' high, 6" thick, aged wood liner, 5000 PSI	S.F.	\$ 8.21	\$ 13.74	\$ 21.95	\$ 8.21	\$ 13.74	\$ 21.95	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
21	1	B20101013000			Concrete wall, reinforced, 8' high, 6" thick, light sand blast 1 side, 3000 PSI	S.F.	\$ 7.02	\$ 13.79	\$ 20.81	\$ 7.02	\$ 13.79	\$ 20.81	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
22	1	B20101013100			Concrete wall, reinforced, 8' high, 6" thick, light sand blast 1 side, 4000 PSI	S.F.	\$ 7.15	\$ 13.79	\$ 20.94	\$ 7.15	\$ 13.79	\$ 20.94	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
23	1	B20101013300			Concrete wall, reinforced, 8' high, 6" thick, light sand blast 1 side, 5000 PSI	S.F.	\$ 7.35	\$ 13.79	\$ 21.14	\$ 7.35	\$ 13.79	\$ 21.14	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
24	1	B20101013400			Concrete wall, reinforced, 8' high, 6" thick, heavy sand blast 1 side, 3000 PSI	S.F.	\$ 7.68	\$ 17.26	\$ 24.94	\$ 7.68	\$ 17.26	\$ 24.94	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
25	1	B20101013500			Concrete wall, reinforced, 8' high, 6" thick, heavy sand blast 1 side, 4000 PSI	S.F.	\$ 7.81	\$ 17.26	\$ 25.07	\$ 7.81	\$ 17.26	\$ 25.07	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
26	1	B20101013600			Concrete wall, reinforced, 8' high, 6" thick, heavy sand blast 1 side, 5000 PSI	S.F.	\$ 8.01	\$ 17.26	\$ 25.27	\$ 8.01	\$ 17.26	\$ 25.27	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
27	1	B20101013700			Concrete wall, reinforced, 8' high, 6" thick, 3/4" bevel rustic strip, 3000 PSI	S.F.	\$ 6.50	\$ 12.78	\$ 19.28	\$ 6.50	\$ 12.78	\$ 19.28	OPN	Year 2015	QUEBEC / MONTREAL (C11)				
28	1	B20101013800			Concrete wall, reinforced, 8' high, 6" thick, 3/4" bevel rustic strip, 4000 PSI	S.F.	\$ 6.62	\$ 12.78	\$ 19.40	\$ 6.62	\$ 12.78	\$ 19.40	OPN	Year 2015	QUEBEC / MONTREAL (C11)				

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6	Data Release :Year 2015															
7	Assembly Cost Estimate															
8	Quantity	Assembly Number	Source	SubC	Description	Unit	Material O&P	Installation O&P	Total O&P	Ext. Material O&P	Ext. Installation O&P	Ext. Total O&P	Labor Type	Data Release	CCI Location	Notes
9	1	C10101020000			Concrete block partitions		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
10	1	C10101020001			Block partitions		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
11	1	C10101020800			Concrete block partitions - regular weight		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
12	1	C10101020801					\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
13	1	C10101021000			Concrete block (CMU) partition, regular weight, hollow, 4" thick, no finish	S.F.	\$ 2.22	\$ 5.17	\$ 7.39	\$ 2.22	\$ 5.17	\$ 7.39	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
14	1	C10101021010			Concrete block (CMU) partition, regular weight, hollow, 4" thick, gyp plaster 2 coat, 1 side	S.F.	\$ 2.62	\$ 7.55	\$ 10.17	\$ 2.62	\$ 7.55	\$ 10.17	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
15	1	C10101021020			Concrete block (CMU) partition, regular weight, hollow, 4" thick, gyp plaster, 2 coat, 2 sides	S.F.	\$ 3.02	\$ 9.97	\$ 12.99	\$ 3.02	\$ 9.97	\$ 12.99	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
16	1	C10101021100			Concrete block (CMU) partition, regular weight, hollow, 4" thick, lime plaster - 2 coat, 1 side	S.F.	\$ 2.47	\$ 7.55	\$ 10.02	\$ 2.47	\$ 7.55	\$ 10.02	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
17	1	C10101021150			Concrete block (CMU) partition, regular weight, hollow, 4" thk, lime portland - 2 coat, 1 side	S.F.	\$ 2.48	\$ 7.55	\$ 10.03	\$ 2.48	\$ 7.55	\$ 10.03	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
18	1	C10101021200			Concrete block (CMU) partition, regular weight, hollow, 4" thick, portland - 3 coat, 1 side	S.F.	\$ 2.50	\$ 7.91	\$ 10.41	\$ 2.50	\$ 7.91	\$ 10.41	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
19	1	C10101021400			Concrete block (CMU) partition, regular weight, hollow, 4" thick, 5/8" gyp board, 1 side	S.F.	\$ 2.85	\$ 6.80	\$ 9.65	\$ 2.85	\$ 6.80	\$ 9.65	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
20	1	C10101021410			Concrete block (CMU) partition, regular weight, hollow, 4" thick, 5/8" gyp board, 2 sides	S.F.	\$ 3.49	\$ 8.48	\$ 11.97	\$ 3.49	\$ 8.48	\$ 11.97	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
21	1	C10101021500			Concrete block (CMU) partition, regular weight, hollow, 6" thick, no finish	S.F.	\$ 2.80	\$ 5.56	\$ 8.36	\$ 2.80	\$ 5.56	\$ 8.36	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
22	1	C10101021510			Concrete block (CMU) partition, regular weight, hollow, 6" thick, gyp plaster 2 coat, 1 side	S.F.	\$ 3.21	\$ 7.93	\$ 11.14	\$ 3.21	\$ 7.93	\$ 11.14	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
23	1	C10101021520			Concrete block (CMU) partition, regular weight, hollow, 6" thick, gyp plaster 2 coat, 2 sides	S.F.	\$ 3.60	\$ 10.35	\$ 13.95	\$ 3.60	\$ 10.35	\$ 13.95	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
24	1	C10101021600			Concrete block (CMU) partition, regular weight, hollow, 6" thick, lime plaster - 2 coat, 1 side	S.F.	\$ 3.05	\$ 7.93	\$ 10.98	\$ 3.05	\$ 7.93	\$ 10.98	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
					Concrete block (CMU) partition,											

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Quantity	Assembly Number	Source	SubC	Description	Unit	Material O&P	Installation O&P	Total O&P	Ext. Material O&P	Ext. Installation O&P	Ext. Total O&P	Labor Type	Data Release	CCI Location	Notes
1	D1000000000					\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101100000			Hydraulic		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101100001			Elevators		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101100			Hydraulic		\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101300			Hydraulic, passenger elevator, 1500 lb, 2 floors, 100 FPM	Ea.	\$ 61,485.90	\$ 13,305.60	\$ 74,791.50	\$ 61,485.90	\$ 13,305.60	\$ 74,791.50	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101400			Hydraulic, passenger elevator, 1500 lb, 5 floors, 100 FPM	Ea.	\$ 108,157.50	\$ 35,337.60	\$ 143,495.10	\$ 108,157.50	\$ 35,337.60	\$ 143,495.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101600			Hydraulic, passenger elevator, 2000 lb, 2 floors, 100 FPM	Ea.	\$ 62,665.80	\$ 13,305.60	\$ 75,971.40	\$ 62,665.80	\$ 13,305.60	\$ 75,971.40	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101700			Hydraulic, passenger elevator, 2000 lb, 5 floors, 100 FPM	Ea.	\$ 109,468.50	\$ 35,337.60	\$ 144,806.10	\$ 109,468.50	\$ 35,337.60	\$ 144,806.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101101900			Hydraulic, passenger elevator, 2500 lb, 2 floors, 100 FPM	Ea.	\$ 65,550.00	\$ 13,305.60	\$ 78,855.60	\$ 65,550.00	\$ 13,305.60	\$ 78,855.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102000			Hydraulic, passenger elevator, 2500 lb, 5 floors, 100 FPM	Ea.	\$ 112,090.50	\$ 35,337.60	\$ 147,428.10	\$ 112,090.50	\$ 35,337.60	\$ 147,428.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102200			Hydraulic, passenger elevator, 3000 lb, 2 floors, 100 FPM	Ea.	\$ 67,516.50	\$ 13,305.60	\$ 80,822.10	\$ 67,516.50	\$ 13,305.60	\$ 80,822.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102300			Hydraulic, passenger elevator, 3000 lb, 5 floors, 100 FPM	Ea.	\$ 114,057.00	\$ 35,337.60	\$ 149,394.60	\$ 114,057.00	\$ 35,337.60	\$ 149,394.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102500			Hydraulic, passenger elevator, 3500 lb, 2 floors, 100 FPM	Ea.	\$ 71,449.50	\$ 13,305.60	\$ 84,755.10	\$ 71,449.50	\$ 13,305.60	\$ 84,755.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102600			Hydraulic, passenger elevator, 3500 lb, 5 floors, 100 FPM	Ea.	\$ 117,990.00	\$ 35,337.60	\$ 153,327.60	\$ 117,990.00	\$ 35,337.60	\$ 153,327.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102800			Hydraulic, passenger elevator, 4000 lb, 2 floors, 100 FPM	Ea.	\$ 73,416.00	\$ 13,305.60	\$ 86,721.60	\$ 73,416.00	\$ 13,305.60	\$ 86,721.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101102900			Hydraulic, passenger elevator, 4000 lb, 5 floors, 100 FPM	Ea.	\$ 119,956.50	\$ 35,337.60	\$ 155,294.10	\$ 119,956.50	\$ 35,337.60	\$ 155,294.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101103100			Hydraulic, passenger elevator, 4500 lb, 2 floors, 100 FPM	Ea.	\$ 77,349.00	\$ 13,305.60	\$ 90,654.60	\$ 77,349.00	\$ 13,305.60	\$ 90,654.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101103200			Hydraulic, passenger elevator, 4500 lb, 5 floors, 100 FPM	Ea.	\$ 123,889.50	\$ 35,337.60	\$ 159,227.10	\$ 123,889.50	\$ 35,337.60	\$ 159,227.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101104000			Hydraulic, hospital elevators, 3500 lb, 2 floors, 100 FPM	Ea.	\$ 103,569.00	\$ 13,305.60	\$ 116,874.60	\$ 103,569.00	\$ 13,305.60	\$ 116,874.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101104100			Hydraulic, hospital elevators, 3500 lb, 5 floors, 100 FPM	Ea.	\$ 167,152.50	\$ 35,337.60	\$ 202,490.10	\$ 167,152.50	\$ 35,337.60	\$ 202,490.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101104300			Hydraulic, hospital elevators, 4000 lb, 2 floors, 100 FPM	Ea.	\$ 103,569.00	\$ 13,305.60	\$ 116,874.60	\$ 103,569.00	\$ 13,305.60	\$ 116,874.60	OPN	Year 2015	QUEBEC / MONTREAL (C11)	
1	D10101104400			Hydraulic, hospital elevators, 4000 lb, 5 floors, 100 FPM	Ea.	\$ 167,152.50	\$ 35,337.60	\$ 202,490.10	\$ 167,152.50	\$ 35,337.60	\$ 202,490.10	OPN	Year 2015	QUEBEC / MONTREAL (C11)	

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## **Appendix D: Developed Model Algorithms and Sample Codes**

### **Model Algorithms**

#### **Room Grouping**

Open Form

if 'Create Room' clicked

then Allow user to select components in room

if 'Add Components' clicked and room is selected

then hide all components already in room and allow user to select components.

if 'Remove Components' clicked and room is selected

then hide all components except components belonging to the selected room.

if 'Display Room' clicked and room is selected

then highlight all components in room

Close Form

#### **Check Change**

Look for as\_changed project.

Compare all GUIDs of elements.

If element exist in as\_planned but not in as\_changed

then Highlight element in Red in as\_planned document

If element exist in as\_changed but not in the as\_planned

then Highlight element in Green in as\_changed document

If element exist in as\_changed and as\_planned but have different properties

then Highlight element in both documents in Yellow

## **Ripple Effect**

Look for as\_changed project.

User selects source of change.

Find Room the source belongs to.

Find all adjacent Rooms.

Find components in Room that intersects with source.

Check if components have been modified.

Find modified components that intersect with components found above including those in the adjacent rooms

Highlight all found modified components and source.

Open form, create tree view to display the levels of change and group them by discipline.

## **Time Impact**

Look for as\_changed project.

Look for RSMMeans Document with time impact per component.

Prompt user to select as\_planned MS Project.

Compare components in MS Project to as\_planned Revit project by Assembly Code, Assembly Description, calculated duration.

If element exist in as\_planned but not in as\_changed

then Highlight element in Red in as\_planned table

If element exist in as\_changed but not in the as\_planned

then Highlight element in Green in as\_changed table

If element exist in as\_changed and as\_planned but have different properties

then Highlight element in both tables in Yellow

Calculate duration for both tables

If Export clicked

then prompt user to select folder to create as\_changed MS Project.

create .csv file with as\_changed table components.

### **Cost Impact**

Look for as\_changed project.

Look for RSMMeans Document with component cost.

Open Form

calculate all components' cost based on record found in RSMMeans

Display all changes in a table.

Prompt user to input variables

if 'Calculate' clicked

then Calculate as\_planned and as\_changed total duration.

### **Data Filtering**

Prompt user for field to filter on.

Prompt user for values.

Run query.

Display results.

### **Model Sample Codes**

#### **Room Grouping**

To add component to room

```
public void AddElem(Element _elem)
```



```

{
    SharedParams sp = SharedParams.GetRef(m_doc);

    List<Category> cats = utils.GetValidCategories(m_doc);

    Parameter p_room = sp.GetSharedParameter(_elem, PARAM_DEF_ROOM,
BuiltInParameterGroup.PG_TEXT, cats);

    if (p_room == null) { return; } //throw new Exception("No parameter created"); }

    string room_str = p_room.AsString();

    if (room_str == null) { room_str = ""; }

    if(!csvtool.exists_in_csv(room_str, m_guid))
    {
        room_str = csvtool.add_csv(room_str, m_guid);

        p_room.Set(room_str);

        m_elems.Add(_elem);
    }
}

```

To Highlight\_Elements

```

public static void Highlight_Elements(View _v, IEnumerable<Element> _list, Color
_color, bool _do_trans = true)
{
    if ((_list.ToList<Element>()).Count == 0) { return; }

    List<ElementId> ids = (from x in _list select x.Id).ToList<ElementId>();

    Document doc = _v.Document;

    Transaction trans = new Transaction(doc);

    if(_do_trans) trans.Start("change_elem_color");
}

```

```

List<Element> fill_elems = GetElementsByType(doc, typeof(FillPatternElement));
Element solid_fill_elem = fill_elems.Find(x => x.Name.Equals("Solid fill"));
OverrideGraphicSettings settings = new OverrideGraphicSettings();
settings.SetCutFillColor(_color);
settings.SetCutLineColor(_color);
settings.SetProjectionFillColor(_color);
settings.SetProjectionLineColor(_color);
settings.SetCutFillPatternVisible(true);
settings.SetProjectionFillPatternVisible(true);
if (solid_fill_elem != null) {
settings.SetProjectionFillPatternId(solid_fill_elem.Id); }
ids.ForEach(x => _v.SetElementOverrides(x, settings));
if(_do_trans) trans.Commit();
}

```

### **Check Change**

Find all elements not in as\_planned but in as\_changed

```
void calc_added()
```

```

{
    m_added = (from x in m_change_all_elems where (m_orig_all_elems.Find(c =>
c.ID.Equals(x.ID)) == null) select x).ToList<IComponent>();
}

```

Find all elements not in as\_changed but in as\_planned

```
void calc_removed()
```

```

    {
        m_removed = (from x in m_orig_all_elems where (m_change_all_elems.Find(c
=> c.ID.Equals(x.ID)) == null) select x).ToList<IComponent>();
    }

```

Find all elements in both but has been modified

```
void calc_modified()
```

```

    {
        foreach (IComponent orig_c in m_orig_all_elems)
        {
            IComponent copy_c = m_change_all_elems.Find(c => c.ID.Equals(orig_c.ID));
            if (copy_c == null) { continue; }
            if (!utils.areElementsEqual(orig_c.Elem, copy_c.Elem))
            {
                m_copy_modified.Add(copy_c);
                m_orig_modified.Add(orig_c);
            }
        }
    }

```

### **Ripple Effect**

```

void GetRippleEffect(ChangeComponent _main, List<ChangeComponent>
_components, List<ChangeComponent> _ripple)
    {
        CAD.Element main_elem = _main.Component.Elem;
        if (!_ripple.Contains(_main)) { _ripple.Add(_main); }
        if (_components.Contains(_main)) { _components.Remove(_main); }
    }

```

```

        List<CAD.Element> elems = (from x in _components select
x.Component.Elem).ToList<CAD.Element>());

        List<CAD.Element> intersecting_elems =
utils.GetIntersectingElements(main_elem);

        foreach(CAD.Element int_elem in intersecting_elems)
        {
            ChangeComponent cc_elem = _components.Find(x =>
x.ID.Equals(int_elem.UniqueId));

            if(cc_elem != null && !cc_elem.ID.Equals(_main.ID))
            {
                if (!_main.ChangeType.Equals(ChangeComponent.ELEM_REMOVED)
&&
                !cc_elem.ChangeType.Equals(ChangeComponent.ELEM_REMOVED)))
                {
                    _ripple.Add(cc_elem);
                }
                _components.Remove(cc_elem);
            }
        }

```

### **Time Impact**

```

private void btnExport_Click(object sender, EventArgs e)
{
    FolderBrowserDialog fbd = new FolderBrowserDialog();
    fbd.SelectedPath = Path.GetDirectoryName(m_orig_doc.PathName);
}

```

```

if(fbd.ShowDialog(this) == System.Windows.Forms.DialogResult.OK)
{
    MPP_Manager as_changed_MPP = new MPP_Manager(m_copy_doc,
MPP_Manager.FILE_TYPE.AS_CHANGED);
    as_changed_MPP.WriteToFile(fbd.SelectedPath);
}

```

### **Cost Impact**

```

private void btnCalc_Click(object sender, EventArgs e)
{
    double indirect_cost = calc_CO_indirect_cost();
    double impact_cost = calc_impact_cost();
    double as_planned_direct_cost = calc_CO_direct_cost(true);
    double as_changed_direct_cost = calc_CO_direct_cost(false);
    double as_planned_coc = Math.Round(as_planned_direct_cost + indirect_cost +
impact_cost, 2);
    double as_changed_coc = Math.Round(as_changed_direct_cost + indirect_cost +
impact_cost, 2);
    double costVariance = as_changed_coc - as_planned_coc;
    txtCOC_as_planned.Text = as_planned_coc.ToString();
    txtCOC_as_changed.Text = as_changed_coc.ToString();
    txtcostVariance.Text = costVariance.ToString();
    txtImpactCost.Text = impact_cost.ToString();
    txtAsChangedTotDirect.Text = as_changed_direct_cost.ToString();
}

```

```
txtAsPlannedTotDirect.Text = as_planned_direct_cost.ToString();
```

### **Data Filtering**

```
private void btnFilter_Click(object sender, EventArgs e)
{
    string sel_col = cbField.SelectedItem.ToString();
    string sel_op = cbFilter.SelectedItem.ToString();
    if(string.IsNullOrEmpty(txtOne.Text))
    {
        ((dgReport.DataSource as BindingSource).DataSource as
        DataTable).DefaultView.RowFilter = null;
        return;
    }
    string filter = string.Empty;
    bool isNumericField = !(sel_col.Equals(COL_FAMTYPE) ||
        sel_col.Equals(COL_ASMCODE) ||
        sel_col.Equals(COL_ASMDESC));
    bool isBetweenOp = sel_op.Equals(OP_BETWEEN);
    bool isContainsOp = sel_op.Equals(OP_CONTAINS);
    if(!isBetweenOp && !isContainsOp)
    {
        if (isNumericField) { filter = string.Format("[{0}] {1} {2}", sel_col, sel_op,
        double.Parse(txtOne.Text)); }
        else { filter = string.Format("[{0}] {1} '{2}'", sel_col, sel_op, txtOne.Text); }
```

```

    }
else
{
    if(isBetweenOp)
    {
        filter = string.Format("[{0}] >= {1} AND [{0}] <= {2}", sel_col,
double.Parse(txtOne.Text), double.Parse(txtTwo.Text));
    }
    if(isContainsOp)
    {
        filter = string.Format("[{0}] LIKE '%{1}%", sel_col, txtOne.Text);
    }
}
if(!string.IsNullOrEmpty(filter))
    ((dgReport.DataSource as BindingSource).DataSource as
DataTable).DefaultView.RowFilter = filter;

```