THESIS

COST OF USING BUILDING INFORMATION MODELING (BIM) IN RETROFIT PROJECTS

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Gaurav Singh Odhyan

Department of Construction Management

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Advisor: Svetlana Olbina

Mary Nobe
Hilla Skiba

ABSTRACT

COST OF USING BUILDING INFORMATION MODELING (BIM) IN RETROFIT PROJECTS

Building information modeling (BIM) is a process that involves the creation and use of an *n*-dimensional model that can be used in the design, construction, and operation of a building. BIM is changing the process by which buildings are designed, constructed, and used by future generations. However, many owners require seeing quantitative measurements when discussing the benefits of BIM, and these benefits are difficult to quantify into a cost. Previous research has shown the benefits of BIM in new construction, but there is no sufficient research on the benefits of BIM in retrofit projects. BIM can assist in understanding existing buildings and executing the retrofit work. The research goal is to show owners and contractors the cost of using BIM in retrofit projects by comparing the cost benefits of implementing BIM with the fees required.

This research provides a methodology to calculate and quantify the cost of using BIM on retrofit projects and evaluate whether BIM is a worthwhile investment for owners. There are three objectives of this research:

1. Identify the factors used in calculating the cost benefits of using BIM in retrofit projects.
2. Develop a systematic approach to cost analysis to quantify the cost benefits of using BIM in retrofit projects.
3. Perform a cost analysis to investigate whether there are economic benefits of using BIM compared to not using BIM for retrofit projects.

A comprehensive literature review is conducted to understand the benefits of implementing BIM in construction projects. After determining the factors that could be used to quantify the benefits of using BIM in retrofit projects, a methodology is developed for the quantification of these benefits into a cost. The developed methodology is applied to a real-life retrofit project. The potential cost benefits of implementing BIM in this project are calculated based on measurable cost benefits associated with reduced change orders and reduced schedule overruns. A cost analysis has been performed using the cost benefits and the fees required for implementing BIM in a retrofit project.

The research shows that the use of BIM has prevented five change orders in the real-life project. The change orders would have resulted in rework costs as well as schedule overruns. The cost of rework and penalties due to schedule overruns caused by the change orders are calculated. The cost analysis shows that in some scenarios the fee required to implement BIM is higher than the cost benefits of using BIM, and in some scenarios the fee required to implement BIM is lower than the cost benefits. In one of the scenarios, BIM has resulted in a loss of 59% of the fees required to implement BIM in the retrofit project, and in another scenario, BIM has resulted in a gain of 17%. This research attempts to analyze the cost related to the use of BIM in a retrofit project. The research results provide the owners and the general contractors with an estimate of the cost related to BIM use in the project.

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Chapter 1: INTRODUCTION

This chapter provides a background on how the use of building information modeling (BIM) and virtual design and construction (VDC) has radically transformed the process by which buildings are constructed and retrofitted. It also focuses on the cost of using BIM in retrofit projects. In addition, this chapter introduces the problem statement, the purpose of the research, and the research objectives, and concludes by stating the scope and limitations of the study.

1.1 Background

As humanity progresses, the energy required to sustain human life is increasing constantly. Energy resources are depleting quickly, and the environment is also affected significantly by the greenhouse gases (GHG) emitted during the production of energy. According to the U.S. Energy Information Administration (US EIA), the building sector consumes 47.6% of the energy and 74.9% of the electricity produced in the United States (McGraw Hill Construction, 2009) and is thus one of the major consumers of energy in this country. The US EIA also states that the building sector is the largest contributor to climate change and is responsible for 44.6% of GHG emissions (McGraw Hill Construction, 2009) in the country while the global building sector accounts for 40% of total global CO_2, one of the primary greenhouse gases emissions (Wong & Zhou, 2015).

Existing buildings consume more energy than new buildings due to their lack of the advanced technology used in new construction, such as better heating, ventilation, and air conditioning (HVAC) systems and lighting systems. The current rate of new construction in developed countries such as the United States, the United Kingdom, Japan, and South Korea, is low. The replacement rate of existing buildings with new buildings is only approximately 1.0–3.0% per annum, and therefore, the main activities of the construction sector increasingly shift to modifications, retrofits, and deconstruction of existing buildings (Ma, Cooper, Daly, & Ledo, 2012; Volk, Stengel, & Schultmann, 2014).

Retrofitting existing buildings provides benefits such as improved energy efficiency, reduced maintenance costs, increased staff productivity, and better thermal comfort. In addition to these benefits, retrofitting may also help improve a nation's energy security and corporate social responsibility, create job opportunities, and make buildings more livable (Ernst & Young, 2010; Sweatman & Managan, 2010).

As time has progressed, so has the technology used in the construction industry. The advent of BIM has transformed the design and construction processes of construction industry, and previous research has shown the benefits of using BIM in construction. These benefits include a reduction in change orders, a reduction in project completion delays, and the accelerated discovery of construction conflicts. Building information modeling efficiently integrates environmental analysis into the design and delivery of energy efficient buildings (Krygiel & Nies, 2008). The use of BIM in building retrofits can prove very beneficial to economic and environmental sustainability. These benefits could be sufficient reasons to invest in the software, manpower, training, and time required for the implementation of BIM (Giel & Issa, 2013).

However, there remain issues hampering the implementation of BIM in the architecture, engineering, and construction (AEC) industry. The high initial cost of BIM, a lack of understanding of BIM, and the fear of change that exists within the industry have resulted in the relatively slow adoption of BIM by contractors (Giel & Issa, 2013). The AEC industry is money driven, and the use of BIM can be justified only if the economic benefits of BIM are greater than the investment into it. In order to prove to the stakeholders the economic benefits of BIM, the potential cost savings data of implementing BIM must be collected and analyzed (Giel & Issa, 2013).

1.2 Problem Statement

Besides providing construction benefits, the use of BIM can prove very helpful in the search for the most energy efficient retrofit solution for the project (Ma et al., 2012). The more efficient the retrofit solution, the more energy it can save, thus reducing the operation costs of the building. The use of BIM has been regarded as one of the most important innovations that address problems related to performance in the construction industry (Eastman, Teicholz, Sacks, & Liston, 2011). Despite the great potential that BIM has to offer, in many countries, the advancement of BIM is in its relative infancy, with a high percentage of construction projects not using BIM (Aibinu & Venkatesh, 2014; Jensen & Jóhannesson, 2013). According to McGraw Hill Construction (2014), among the developed countries, 31% of construction companies use BIM in 15–30% of their projects, and 17% of the companies use BIM in more than 60% of their projects. According to Giel and Issa (2013), despite the benefits BIM has to offer, many construction professionals and contractors do not use BIM due to the high initial cost of BIM implementation. The economic benefits of BIM for new construction projects have been researched in the past; however, there is no sufficient research showing the economic benefits of using BIM in retrofit projects. According to Woo and Menassa (2014), it is difficult to estimate if whether a retrofit solution will prove to be economical in the future.

1.3 Research Aim

This research aims to provide insight on the cost of using BIM in retrofit projects. A real-life retrofit project using BIM was analyzed, and the cost of using BIM was calculated. A cost study of using BIM during the preconstruction and construction phases of the project was performed, and conclusions were made about the potential cost to an owner of using BIM.

1.4 Research Objectives

This research has three objectives:

- To identify the factors to be used in calculating the cost benefits of using BIM in retrofit projects.
- To develop a systematic approach to cost analysis to quantify the cost benefits of using BIM in retrofit projects.
- To perform a cost analysis to investigate whether there are economic benefits to using BIM.

1.5 Scope and Limitations

This study used both quantitative and qualitative building project data, such as requests for information (RFIs) and change order logs, total project costs, and charges for schedule overruns. For this research, it was assumed that these factors were in direct correlation with BIM's execution, but it is likely other variables also contributed to the real-life retrofit project's success. In terms of location, productivity, clients, architects, and contractors, every construction project is unique, and it is very difficult to identify and quantify which benefits are directly related to the implementation of BIM and which are related to better work ethic, better coordination among the project stakeholders, and other variables.

The research also made several assumptions in estimating the cost of using BIM, and these assumptions may lead to differences between the calculations of the actual cost of using BIM in the implementation of the project and the cost estimated in this research. For cost estimation, RSMeans 2013 was used for the price data, and the cost numbers were adjusted according to the location of the retrofit project; in the actual project, the costs could have been different.

Lastly, the cost benefits estimated in this research and produced by BIM could have been achieved by multiple parties, including the owner or the contractors. This research assumed all costs were directly related to the owners.

Chapter 2: LITERATURE REVIEW

1.1 Introduction

According to the definition provided by the National Association for Industrial and Office Parks (NAIOP), a retrofit involves substantial functional changes intended to modernize building systems and processes such as heating, ventilation, and air conditioning (HVAC), security, fire alarms, and energy management (Cresa, 2012). The goal of retrofitting a building is the adaptive reuse of that building for a new purpose that allows the building to retain its integrity while meeting the needs of modern occupants (Cresa, 2012). As the world is progressing towards a better future, the ideas of environmental, economic, and social sustainability are gaining popularity. The need for a sustainable retrofit by modern occupants originates from these ideas.

A retrofit improves energy efficiency, reduces maintenance costs, and increases staff productivity and thermal comfort. Retrofitting also helps improve a nation's energy security and corporate social responsibility, create job opportunities, and make buildings more livable (Ernst & Young, 2010; Sweatman & Managan, 2010). According to Ernst and Young (2010), in South Wales, Australia, a total of approximately $25 million to $99 million, including the construction and operation benefits of energy efficient products and the indirect benefits of the businesses associated with these products, could be realized by the year 2020 within the market of energy efficiency in buildings.

2.1.1 The Need for Retrofitting

According to the U.S. Energy Information Administration, the building sector consumes 48% of the energy and 75% of the electricity produced in the United States (McGraw Hill Construction, 2009). In Europe, the building sector's energy consumption accounts for more than 40% of total energy consumption (Pérez-Lombard, Ortiz, & Pout, 2008). This makes the construction industry a major energy consumer across the globe. Energy demand is constantly rising, and nonrenewable resources are being quickly depleted. These issues are raising alarms all over the world. To tackle these issues, all energy consuming industries must follow processes to make their use of energy more efficient. As a major consumer of energy, the construction industry has great potential to reduce global energy consumption. The construction industry is also a major emitter of greenhouse gases (GHG). The U.S. Energy Information Administration states that the U.S. building sector is the largest contributor to climate change and is responsible for 45% of all greenhouse gas (GHG) emissions (McGraw Hill Construction, 2009) in the United States. Globally, the building sector accounts for 40% of total CO_2 emissions (Wong & Zhou, 2015).

Most of these issues of energy consumption and GHG emission are related to the operation of buildings, including their heating and cooling systems, lighting, electrical appliances, and other building service systems. The energy consumed during the operation phase of the building life cycle accounts for 30–40% of total global GHG emissions (United Nations Environment Programme, 2007). Due to the rise in energy costs and the current objectives to decrease GHG emissions, demand is increasing for the addition of energy efficient processes to existing buildings. To cater to this demand for energy efficiency, countries and individuals have set goals for green and sustainable construction. For instance, the EU Energy Targets have set an energy goal for 2020, according to which the EU needs to decrease its CO_2 emissions by 20% and increase its energy efficiency by 20%, with respect to the levels in 1990 (Lagüela, Díaz-Vilariño, Martínez, & Armesto, 2013). Most countries have also adopted rating systems for sustainable design and construction (Wong & Zhou, 2015). Such systems include Leadership in Energy and Environmental Design (LEED) (US), Building Research Establishment Environmental Assessment Methodology (BREEAM) (UK), Green Star (Australia), the Comprehensive

Assessment System for Built Environmental Efficiency (CASBEE) (Japan), and the Building Environmental Assessment Method (BEAM) Plus (Hong Kong). These goals and ratings need to be achieved in both new and existing buildings.

The rate of new construction in developed countries is low, and existing buildings are being replaced by new buildings at a rate of only 1.0–3.0% per annum, and therefore, the construction sector increasingly shifts to the modifying, retrofitting, and deconstruction of existing buildings (Ma et al., 2012; Volk et al., 2014). In the United States, an analysis of existing buildings showed that 80% of the reported 71.6 billion square feet of existing buildings needed retrofitting (Hammond, Nawari, & Walters, 2014). The building retrofitting sector has a great potential to reduce energy usage, and therefore, contribute to reaching sustainable energy targets. The main objective of retrofitting is not only to improve environmental and economic sustainability by reducing energy usage and GHG emissions, but also to improve social sustainability by providing a better and healthier living environment to the people.

2.1.2 Issues Related to Retrofitting

One of the most important deciding factors for beginning any project or process is the potential outcome, and the most basic way to measure this outcome in a retrofit project is its potential economic and environmental success. Social sustainability is also an important factor, but the quantification of social sustainability is a challenge. Owners want to be sure that a retrofit project will have economic benefits in addition to the environmental benefits before taking up a retrofit project. However, according to Woo and Menassa (2014), the economic outcome of a retrofit solution is difficult to estimate.

Although the latest technologies, such as BIM, laser scanning, and energy modeling, are being used to estimate the potential outcomes of retrofit projects, there are still many challenges to doing this properly. One of the most important issues is the challenge of data collection for the analysis of building performance. Building data are analyzed mainly using building information models, and the more accurate the data, the more accurate the analysis of the results. However, due to the absence of accurate data obtained from actual buildings in operation, designers rely on estimated values of data on energy loads, air flows, or heat transfers, in order to carry out energy simulations, and the estimated data do not bring the full potential of BIM (Crosbie, Dawood, & Dawood, 2011). Also, it is quite difficult to accurately map the building; hidden deterioration in the walls (façades) is difficult to identify and can affect estimated U-values. The energy habits of building occupants also pose a significant challenge (Ochoa & Capeluto, 2015).

Another challenge encountered in estimating the project's economic and environmental outcomes is that there are many uncertainties, such as climate change, service changes, human behavioral changes, and government policy changes, all of which directly affect the selection of retrofit technologies, and hence, the success of a retrofit project (Ma et al., 2012). Buildings are quite distinct in their characteristics, and these unique characteristics make a generalized solution for retrofitting pointless (Ma et al., 2012). In addition, the selection of energy conservation methods for a building is difficult and depends on the building's thermodynamic performance and the physical interactions among different energy conservation measures (Ma et al., 2012). These issues make it very difficult for contractors and designers to identify retrofit solutions for an existing building that will prove to be beneficial in both economic and environmental terms.

2.2 Existing Retrofit Technologies

The energy consumed in buildings is distributed among the following major areas: HVAC, lighting, water heating, and plug load. More than half (55%) of the energy consumption in small and medium size buildings is due to the use of HVAC equipment. Lighting, HVAC, and plug loads account for almost 90% of the total consumption of energy (Katipamula et al., 2012). Alajmi (2012) estimated that 6.5% of a building's annual energy consumption can be reduced by low or no cost capital investments, whereas almost half (49.3%) of the annual energy consumption can be reduced through extensive investment in retrofitting of the potential areas of energy consumption.

The latest technologies have provided the retrofit sector with techniques that utilize energy conservation measures in areas of potential energy consumption such as HVAC, electric lighting, the building envelope, equipment (e.g., plug loads), and serviced hot water (Hong et al., 2015). Li, Hong, and Yan (2014) pointed out that the three most commonly used energy efficient strategies in high performance buildings are daylighting, high efficiency HVAC systems, and improved building envelopes. Of the buildings they analyzed, they found that 76.5% used daylighting, 64.7% used high efficiency HVAC systems, and 62.7% used an improved building envelope. However, a building's characteristics, such as location, size, envelope, and systems (e.g., electrical, heating, cooling, and ventilation) play a significant role in the effectiveness of these technologies for energy savings (Li et al., 2014).

Ma et al. (2012) categorized retrofit technologies into three groups:

- Supply-side management: These technologies include retrofits of building electrical systems and renewable energy systems such as solar hot water, solar photovoltaics, wind energy, and geothermal energy that provide alternative energy supplies for buildings. Due to the increased awareness of environmental issues, there has been increased interest in the use of renewable energy technologies as building retrofit solutions.
- Demand-side management: These technologies include strategies that reduce a building's heating and cooling demand, and the use of energy efficient equipment and low

energy technologies. The retrofitting of building fabric and the use of other technologies, such as air tightness and window shading, can reduce the heating and cooling demands of a building. Low energy technologies such as advanced control schemes, natural ventilation, heat recovery, and thermal storage systems, are also used to reduce the heating and cooling demands of a building.

- Change of energy consumption patterns: These include human factors such as comfort requirements, occupancy regimes, management and maintenance, occupant activities, and access to control. Human factors have the potential to increase or decrease the energy efficiency of a building.

There are many retrofit solutions available on the market, but it is challenging to determine a general retrofit solution for buildings because characteristics of buildings are unique. According to Ma et al. (2012), a major issue in building retrofitting is the uniqueness of different buildings that renders a generalized solution for retrofitting useless. The retrofit measures used in one building may not be suitable for use in another building.

HVAC retrofits are common in buildings. Some examples of existing HVAC solutions used for retrofitting are variable refrigerant flow, water source heat pumps, variable air volume, chilled beams, and dedicated outside air. These options are selected for retrofitting based on HVAC standards such as energy efficiency, the cost of installation, user comfort, and degree of maintenance (Woo & Menassa, 2014).

Among lighting solutions, compact fluorescent lights (CFLs) and light emitting diode lights (LEDs) are the most prominent substitution for incandescent light bulbs. Compact fluorescent lights pollute the environment more than LEDs. They also have a lower efficiency rating and shorter lifespans than LEDs but are economically more cost effective. However, LEDs have a higher cost of installation (Vahl, Campos, & Casarotto Filho, 2013). According to Salata et al. (2014), as long as reliability and service life are relevant, LED represents a more convenient choice economically.

The role of the building envelope in building energy performance is as mediator between the indoor and outdoor environment. The building envelope is a determining factor in thermal comfort and energy efficiency (Patterson, Vaglio, & Noble, 2014). Among major energy efficient façades are double skin façades and hybrid glass façades. Rendering mortar in the façades also affects the energy efficiency of a building. According to Brás and Gomes (2015), cement based and hydraulic lime mortar contribute more to global warming, while the introduction of cork granules into normal mortar compositions reduces global warming especially when cork is added at a proportion of 70%.

The most cost effective retrofit solutions are passive heating and cooling techniques such as well-designed sun shades, the efficient use of daylighting, passive cooling via thermal exchange with the ground, and night ventilation. Although such passive cooling technologies are available and cost effective, the common choice among building owners is mechanical cooling (Pagliano et al., 2009).

2.3 Selecting Optimal Retrofit Solutions

2.3.1 Overview of Decision Making Methodology for the Optimal Retrofit Solution

The economic and environmental benefits of retrofitting buildings have been acknowledged in previous research; however, there are no specific guidelines for selecting an optimal retrofit solution (Ma et al., 2012). Due to the uniqueness of buildings, a generalized retrofit solution is not useful (Ma et al., 2012). A decision making methodology for an optimal retrofit solution is required that would make retrofitting not only environmentally sustainable but also economically and socially sustainable.

Currently, there are many retrofit solutions for buildings readily available on the market. The selection of a retrofit solution for a particular project is a multi-objective optimization problem, and this selection is subject to many constraints and limitations, such as specific building characteristics, total available budget, project target, building service types and efficiency, and building fabric (Ma et al., 2012).

While the economic benefits form an important criterion in the selection of retrofit technologies, other criteria should also be considered. For a successful and efficient retrofit project, the optimal solution is a trade-off among a range of factors, such as energy efficiency, technical aspects, regulations, and environmental, economic, and social sustainability (Ma et al., 2012).

A building's performance during a building’s operation phase is a function of its sub-systems working together in a complex fashion. The actual performance of a building or its sub-systems is not accurately known until long after a design decision is made (Thompson & Bank, 2010). This makes building retrofit projects more complex.

Ma et al. (2012) proposed a systematic approach to the identification, determination, and implementation of the best solution for retrofitting any type of building requiring minor modifications. According to them, the overall process involved in the retrofit of a building is divided into the following five major phases:

1. Project setup and pre-retrofit survey: In this phase, the scope and targets of the project are determined. Resource availability is then determined to frame the budget and program of work. A pre-retrofit survey is sometimes required to understand the building’s operational problems and the main concerns of its occupants.

2. Energy audit and performance assessment: In this phase, the building's energy data are analyzed, building energy usage is measured, areas of energy waste are identified, and no cost and low cost energy conservation measures are proposed. Building energy benchmarking is performed using selected performance indicators or green building rating systems. Diagnostics can be used to identify inefficient equipment, improper control schemes, and any malfunctions in the building's operation.
3. Identification of retrofit options: In this phase, the performance of different retrofit alternatives can be assessed quantitatively using energy and economic analysis and risk assessment methods. The relevant energy related and non-energy related factors allows the prioritization of retrofit alternatives.
4. Site implementation and commissioning: In this phase, the retrofit solution is implemented. Testing and commissioning of the retrofit solution are then performed to ensure the building and its service systems operate in an optimal manner.
5. Validation and verification of energy savings: In this phase, standard measurement and verification methods are used to verify energy savings. A post occupancy survey can be performed to analyze the satisfaction of the building owner and occupants (AEPCA, 2004; EVO, 2007; Ma et al., 2012).

Ma et al. (2012) divided this strategy into two parts: a) model and tool selection and strategic planning, and b) major retrofit activities, as shown in Figure 1.

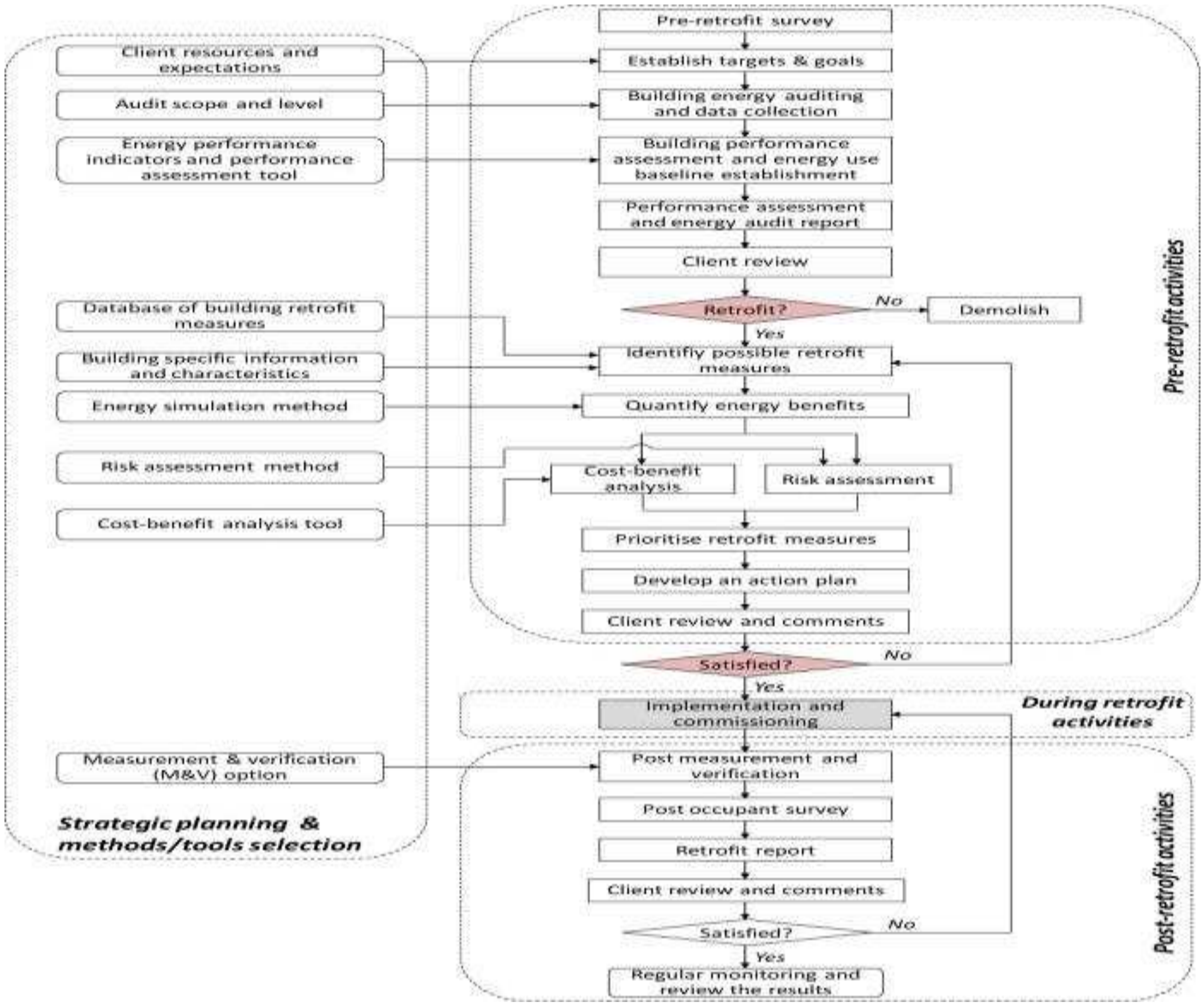

Figure 1. Strategy for identification, determination, and implementation of optimal building retrofit solutions. From Ma et al., 2012, p. 893.

2.3.2 Decision Support Tools for Retrofits

Decision support tools are useful for quickly identifying and determining optimal retrofit measures. Woo and Menassa (2014) proposed the virtual retrofit model, an integrated computational platform that supports the informed decision making of cost effective, technology led, and transformative retrofits of aging commercial buildings. For the selection of potential retrofit solutions, they performed a market analysis and held discussions with stakeholders. They used a virtual retrofit model to identify the best solution among the selected retrofit solutions based on various factors. They also performed an occupancy survey (among various building stakeholders) to identify the influence of economic, environmental, social, and technical factors on the stakeholder requirements in relation to potential retrofit solutions. They analyzed these data, along with energy data and economic data, using the analytical hierarchy process to identify the most efficient retrofit solution.

Guo, Belcher, and Roddis (1993) developed a software tool to solve commercial building lighting retrofit problems by integrating knowledge based and database approaches. Simple tests showed that the tool can meet two main validation criteria: consistency of performance and ability to be modified to reflect other practices. Flourentzou, Genre, and Roulet (2002) proposed interactive decision tool software (TOBUS) for office building retrofits. The tool consists of seven modules: building description and dimensions, building diagnostics, indoor environmental quality, energy use, retrofit scenarios, cost analysis, and result reporting. The tool can support the user in establishing information on the building's state and help identify the actions required to upgrade the building's performance.

Juan, Gao, and Wang (2010) developed an integrated decision support system to recommend a set of sustainable renovation process for existing office buildings. Figure 2 shows the architecture of this decision support system, which was developed based on the consideration of tradeoffs between renovation cost, improved building performance, and environmental impact.

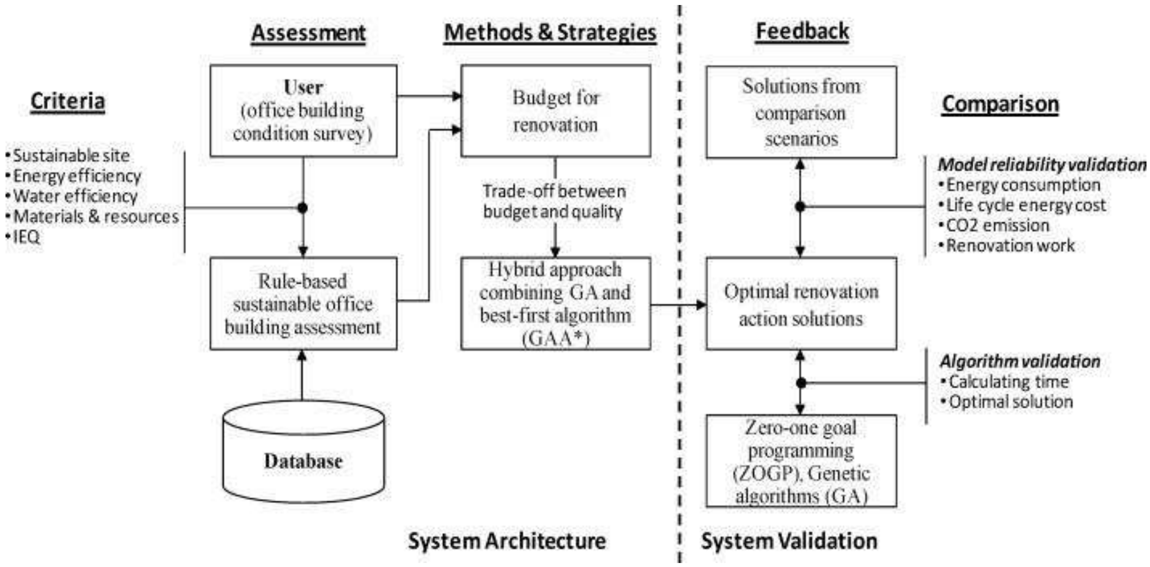

Figure 2. Architecture of decision support system (Juan et al., 2010, p. 292).

2.4 Current Use of BIM and Information Technologies in Retrofitting

2.4.1 Use of BIM

Building information modeling (BIM) is defined as the digital representation of the physical and functional characteristics of a facility that serves as a shared resource for information about that facility during its life cycle (NIBS, 2015). It has taken nearly two decades for BIM to be developed to its current state. In the last several years, the application of BIM tools has been pushed by a large number of architects, engineers, and consultants, and BIM use has recently become quite widespread in the construction industry (Borrmann, Konig, Koch, & Beetz, 2015).

The concepts of green buildings and environmental sustainability are quite common in the building sector. The use of BIM in sustainable design and construction is referred to as *Green BIM*. According to Krygiel and Nies (2008), Green BIM is BIM that supports aspects of sustainable design such as building orientation (for potential project cost reduction), building massing (for analyzing building form and building envelope optimization), daylighting analysis and water harvesting (for water needs reduction in the building), energy modeling (for calculating energy needs and analyzing how renewable energy options can contribute to low energy consumption), sustainable materials (for material needs reduction by using recycled materials and reusing materials), and site and logistics management (for waste and carbon footprint reduction). Green BIM has become a common concept in the construction sector over the last several years. Although Green BIM is used maximally in the initial stages of the building life cycle, it can be extended to the entire life cycle, including the post construction phases (i.e., operations, repair and maintenance, and demolition; Wong & Zhou, 2015). The inherent nature of the integration of building energy models makes BIM an ideal process for implementing sustainable design principles into the renovation and retrofitting of existing buildings (Hammond et al., 2014).

Building information technology assists in the identification of daylighting opportunities by using sensors to dim artificial lights or open window shades for natural light, thus reducing both the electrical lighting load and subsequent heating, cooling, and energy loads. In the building operation phase, in addition to the identification of daylighting opportunities, BIM is currently being used for the analysis of heating and cooling loads and selecting appropriate building equipment that may reduce energy use (Wong & Zhou, 2015). The use of BIM and other information technologies has revolutionized the building retrofit sector by making building retrofits more efficient and enabling the stakeholders to estimate their environmental and economic outcomes.

2.4.2 Building Data Collection Techniques

Any retrofitting or rehabilitation process is preceded by exhaustive documentation and analysis related to master planning, project requirements, and cost requirements, including information related to all the stakeholders involved with the project during all stages of its life cycle, such as architects, construction workers, and users (Linderoth, 2010).

In a retrofit project, stakeholders need baseline information to identify energy waste in the building, understand energy needs, set energy performance goals, create energy management plans, and prioritize potential upgrade opportunities for the non-efficient energy systems. Most important, baseline information helps to identify and avoid excessive peak energy use (Woo & Menassa, 2014).

Energy performance benchmarking provides this baseline information. One of the most important benchmarking options for building stakeholders who want an accurate understanding of a building's energy performance and consumption is sub-metering (G. Liu, 2011). The latest sensing technologies and wireless network technologies make sub-metering a cost effective approach to obtaining critical energy information (Pesovic, Jovanovic, Randjic, & Markovic, 2012).

Sensing devices, data loggers, and controllers are used to capture temperature, humidity, CO_2 emissions, and power consumption data for use in analyzing building performances at a more aggregate level (Woo & Menassa, 2014). For chilled water, domestic and reusable condense water flow meters are used (Spiegelhalter, 2014).

Currently, to gather building data in a digital format, a geographic information system (GIS) can be used, which is efficient for energy simulation and rehabilitation management. This type of system mainly uses two-dimensional representations (2D) of the entity under study (Heiple & Sailor, 2008). A three-dimensional (3D) representation of a building is more accurate and can also be used if a 3D geographic information system solution is followed (Ramos, Siret, & Musy, 2004). However, geographic information systems are designed for studying entities larger than buildings, such as cities (Heiple & Sailor, 2008).

Since the more realistic the model is, the more accurate the results are, key aspects such as the 3D geometry of the building should be as accurate as possible. For this reason, latest information technologies allow the generation of a building information model from a point cloud acquired with a laser scanner, an instrument that provides accurate representations of objects and facilities in a reduced amount of time (Huber et al., 2011; Tang, Huber, Akinci, Lipman, & Lytle, 2010). This system's measurement rates vary from 5,000 points per second, using the Trimble GX200, to 200,000 points per second, using the Faro Photon (Armesto-González, Riveiro-Rodríguez, González-Aguilera, & Rivas-Brea, 2010).

Building energy models based on BIM are currently being used to acquire real-time energy performance data such as energy consumption, temperature, CO_2 emissions, and humidity. Commercial buildings are equipped mostly with comprehensive building automation systems and building energy management and control systems that allow the use of their data in energy audits to help identify energy conservation opportunities (Ma et al., 2012).

2.4.3 BIM and Other Information Technology in Retrofit Projects

Advances in information technology have provided the platform for improving the way the energy performance of buildings is analyzed throughout their life cycles. One of the most important technologies is BIM, which allows the creation and use of coordinated, internally consistent, computable information about the design and construction of a building (Krygiel & Nies, 2008).

Several studies have recently emerged on the use of BIM in building retrofitting. Motawa and Almarshad (2013) developed a BIM-based knowledge sharing system consisting of two elements: a BIM system to gather and share data and a case based reasoning module for capturing knowledge. This system allows stakeholders to learn from preceding experience and to survey a building's full record, including its record of maintenance of different materials and components. The integration of knowledge management principles, embedded in case based reasoning systems, with information management principles, embedded in BIM systems, can transform current BIM applications into a new knowledge based BIM (Motawa & Almarshad, 2013; Motawa & Carter, 2013).

Hammond, Nawari, and Walters (2014) established the sustainable framework and best practices for green retrofitting. Their research shows that BIM integration helps to implement sustainable design principles into the renovation or retrofitting of existing buildings. Jiang et al. (2012) offered a server centric BIM platform for energy efficient retrofitting by establishing a set of RESTful programming interfaces to allow maintenance teams to access and exchange data, including information on security and data privacy issues.

The latest technologies are constantly replacing older ones in BIM and the retrofit sector. For example, laser scanning devices for recoding building existing conditions are preferred to simpler methods such as total station or photogrammetry. Laser scanning is faster and more accurate than most other scanning devices, especially in large scale projects (Lagüela et al., 2013). Some of the latest software and technologies being used for building retrofits are Autodesk Revit MEP, eQuest, and Green Building Studio Cloud Software for 2D and 3D modeling.

2.5 Benefits of Using BIM

Research has been conducted extensively on the benefits of implementing BIM in construction projects. These benefits can be divided categorically into qualitative benefits and quantitative benefits (Giel & Issa, 2013).

2.5.1 Qualitative Benefits of BIM

The benefits of BIM that improve the physical process of design and construction are called qualitative benefits (Giel & Issa, 2013). These qualitative benefits can be gained throughout a building's life cycle, from the initial conception of a construction project to final occupancy.

2.5.1.1 Benefits of BIM in the Preconstruction Phase

Implementing BIM can assist an owner or developer in determining the initial budgeting and feasibility of design options during the early preconstruction stages. It provides a schematic model linked to cost data that can act as an excellent estimation tool during the schematic design phase. It can also assist in understanding how a particular design option can meet functional, sustainable, and financial requirements (Eastman et al., 2011).

In the past, the process of communication and collaboration occurred using 2D documentation software where drawings produced by computer aided design (CAD) tools were limited to conveying information only visually to other parties (Holness, 2006). Today, BIM improves the overall visualization of a project and aids architects and engineers in conveying design ideas to owners. It also supports the communication and collaboration between different project disciplines (Giel & Issa, 2013).

Building information modeling facilitates the early collaboration of many design disciplines involved in a construction project (Eastman et al., 2011). Its tools allow architects and engineers to work on a building information model with a single central database and efficiently transfer design changes using files. The continuous collaboration between architects and engineers helps accomplish efficient design improvements (Bennet, 2008). Holness (2006) stated that a central database model, which can be used by each party of the project to input or extract information, dramatically improves the flow of communication. The continuous maintenance of a central database model used by many integrated disciplines is a more efficient process than repeatedly redrafting and resubmitting drawings from different disciplines. There is greater room for error in the traditional process of drawing and redrawing for changes in two dimensions, and the process is extremely time consuming. On the other hand, the design changes can be easily made in BIM. It can generate 2D documentation directly from a 3D model and make instantaneous changes to all corresponding views of the model. It also allows parametric rules to control the design components, which accelerates changes, leading to the development of accurate 2D drawings at any stage of design and the improvement of the overall efficiency of the process (Eastman et al., 2011).

Building information modeling allows the extraction of more accurate conceptual cost estimates for designers, who without BIM must depend on traditional methods of estimating unit cost per square foot. Due to the implementation of BIM, all parties have the information on cost implications before the bidding process begins (Eastman et al., 2011). Of all the benefits of BIM during the preconstruction stage, one of the greatest is its ability to link the energy analysis tools to a building model to improve the quality of design and make sustainable design decisions.

Within the context of construction, the major use of BIM is for conflict resolution and clash detection (Bennet, 2008). It facilitates the discovery of conflicts and clashes early in the project, thus reducing the number of change orders. Clash detection software like Autodesk's Navisworks assesses project components for possible structural and mechanical conflicts such as clashes between structural, mechanical, plumbing, and electrical systems that occupy the same space (Bennet, 2008).

Giel and Issa (2013) pointed out that many of the most expensive change orders in the history of building construction occurred due to construction conflicts and clashes that were not recognized during the preconstruction phase. Implementing BIM in a project can facilitate the discovery of construction clashes often before construction even begins and thus lessens the number of change orders.

2.5.1.2 Benefits of BIM in the Construction Phase

BIM's ability to perform quantity take offs and project scheduling is an excellent source of checks and balances for the contractors and estimators. The level of accuracy the models can achieve leads to better estimates and greater profit potential and also reduces bidding time and effort (Holness, 2006). Other benefits of BIM include implementing lean construction techniques, reducing on-site material waste, and improving the efficiency of on-site activities (Eastman et al., 2011).

Today, BIM is used to completely simulate the construction process in a virtual world. Site layout, space congestions, crew, and equipment organization and safety concerns are all easily represented in 3D (Eastman et al., 2011). Cost data and construction scheduling can also be linked to a building information model and provide a visual insight to construction phasing. Building information modeling can also improve issue tracking for the project managers. Thus, the requests for information (RFIs) and change order logs are assisted by model visualization, and a BIM-based single database makes the communication between architects, engineers, and contractors more efficient (Holness, 2006).

One of BIM's greatest abilities is building fundamental intelligence into drawings (Holness, 2006). The objects in BIM are smart and contain information such as mensuration quantities, phase of construction, and material type. The objects are editable with parametric properties that can be changed as required. Using traditional 2D tools such as AutoCAD, one of the major issues occurs in the discrepancy in rounded dimensions between design documentation and physical construction. This results in numerous dimensional discrepancies and leads to an increased number of RFIs during construction. However, BIM can eliminate this issue by providing an accurate scale and leaving no difference between the design and construction dimensions. Parametric modeling is often perceived to leave a greater potential for error, but in reality, it is an improvement of quality control and quality assurance compared to traditional methods (Certo, 2007).

Parametric modeling applied by BIM helps automatically generate accurate shop drawings as required by the contractors for supplemental information (Holness, 2006). That BIM can produce accurate shop drawings also allows larger elements of the design to be fabricated offsite, reducing construction cost, time, and rework (Eastman et al., 2011). According to Liu, van Nederveen, and Hertogh (2017), BIM has made the execution of construction tasks more efficient and more effective in later stages of the project. The use of BIM for collaboration among different stakeholders in a construction project has become an inevitable requirement due to the fragmented nature of the construction environment and the information required to be exchanged among various stakeholders (Isikdag & Underwood, 2010).

2.5.1.3 Benefits of BIM in the Post Construction Phase

Building information modeling can be used in the post construction phase to improve management and the operation of facilities (Eastman et al., 2011). It provides a more accurate record of a building. A traditional 2D as-built drawing often lacks the accuracy and detail required by future owners and facility managers, but a 3D building information as-built model can be supplied with the required information on every system, product, finish, and fixture, both inside and out (Madsen, 2008).

Building information models can be integrated with facility operation and management systems and thus allow for the continued maintenance of buildings during operations. Therefore, BIM can assist in the real time monitoring of control systems and provide an interface for sensors and the remote operating management of facilities (Eastman et al., 2011). According to Ani, Johar, Tawil, Razak, and Hamzah (2015), relying on paper based documentation proves difficult in preserving facilities for facility maintenance staff. Organizations using BIM in the operation phase of the building life cycle have the opportunity to use BIM as a knowledge repository and can document facility information needed for decision making by the facility managers (Golabchi & Akula, 2013). According to Aziz, Nawawi, and Ariff (2016), the benefits of BIM in facility management are apparent in areas such as effective operational costs, shortened time for decision making, resources for decision making, better documentation systems, collaboration and work flexibility, updated information, and clash detection.

Becerik-Gerber, Jazizadeh, Li, and Calis (2012) conducted a survey among facility owners and managers and showed that the most frequent application of BIM in the operation and maintenance phase is for locating building components. According to the survey results, the second and third most frequent applications of BIM are facilitating real time data access, and visualization and marketing. Other applications of BIM in operation and maintenance include checking maintainability, creating and updating digital assets, space management, and emergency management.

2.5.2 Quantitative Benefits of BIM

Qualitative benefits may be sufficient to prove the advantages of BIM to most industry professionals, but owners and developers respond better to quantitative units of measure, such as cost and schedule reductions (Giel & Issa, 2013). All parties in the construction process perceive different quantitative benefits from BIM use. For example, owners are impressed mainly with the potential reduction in time from project handover to turnover. Regardless, past research shows that the implementation of BIM can result in the reduction of the building life cycle's operation and maintenance costs by as much as 10–40% (Holness, 2006).

In addition to the many benefits previously discussed, BIM can help reduce the design time required by the architects and designers by 20–50%. Studies have shown that implementing BIM in a construction project can lead to a reduction in construction time and costs by as much as 20–40% and a reduction in rework to almost zero (Holness, 2006).

Barlish and Sullivan (2012) calculated the return on investment (ROI) from using BIM and showed savings of 5% of the total contractor cost and 2% of the total project cost. Won and Lee (2016) measured the ROI from using BIM with factors such as the prevention of rework due to design errors, and cost and time reductions caused by BIM-based quantity takeoffs. The results showed that BIM's ROI ranged from 27% to 400%.

2.5.3 Problems Identified Through the Use of BIM

Software used to create building information models can identify and terminate many major and minor issues in design and construction documents. According to Giel and Issa (2013), major issues identified by implementing BIM can be divided into five basic categories:

- Dimensional inconsistencies: AutoCAD and other 2D software may cause dimensional inconsistencies due to the rounding errors they make. Implementing BIM helps reduce the discrepancies that can arise between design sheets.
- Document discrepancies between disciplines: Discrepancies between different discipline sheets are common issues that can be mitigated using BIM. The use of 2D software for document preparation causes a greater proportion of CAD errors between design sheets.

Most inconsistencies are related to materials, notations, wall types, door and window installation schedules, and other factors. The variation between sheets constructed by different disciplines, particularly between architectural and structural drawings, can be identified in the RFI logs.

- 2D errors and omissions: 2D CAD errors are common in construction drawings. Many sheets lack the information required to accurately construct a model. There are often door, window, and wall types omitted from or mislabeled on the drawings. Requests for information are created to obtain the required information from the designers. Implementing BIM helps this information be obtained early in a construction project.
- Grid and column alignment issues: Gridline and column alignment issues are very common in construction projects. Implementing BIM helps to identify these issues early in a construction project.
- Direct clashes: Requests for information pertaining to direct conflicts between different systems, such as architectural, structural, plumbing, and mechanical systems, are very common in construction projects. Many of these issues generally result in change orders. These conflicts can be discovered using clash detection in building information models.

2.6 Potential Costs and Savings from Using BIM

Giel and Issa (2013) conducted two case studies to calculate the benefits of using BIM in construction projects. In one case study, the cost benefits of BIM amounted to approximately \$20,000, and in the second case study, the cost benefits of BIM amounted to approximately \$4,000,000. Barlish and Sullivan (2012) compared change order costs and schedule overruns in projects constructed with and without BIM. The research showed that the cost of change orders in projects with BIM was 42% lower than the cost of change orders in projects without BIM, and the schedule overruns were 67% lower in projects constructed with BIM.

Holness (2006) showed that using BIM in a construction project resulted in savings of approximately 15–40% of the total cost. Past research has shown that the initial investment in BIM averages at approximately 0.25–5% of the total construction cost for projects ranging from a total cost of $75–150 million dollars. Holness (2008) showed that the Construction Industry Institute estimates savings due to using BIM in construction projects at 3–7.5%. These savings were due mainly to improved coordination and reduced conflicts.

The use of BIM has also been successful in the construction of automotive plants. According to a study, BIM used in the construction of an automotive plant showed the elimination of an estimated 20% of sheet metal waste. It also assisted in the development of programs that were 15–25% faster, with a reduction of 25% of all the change orders and reduction of construction costs by 4–10% (Holness, 2008). A study by a construction company demonstrated the creation of a building information model from 2D construction documents provided by the architects. Thirty five conflicts were discovered in the project's building information model. The company was able to save $135,000 by using collision detection and investing $4,000 into the building information model in their unplanned experiment (Madsen, 2008).

2.7 Cost–Benefit Analyses

Ngulube (2011) defined cost–benefit analysis as the systematic collection of financial and technical data related to a given business function or situation. A cost–benefit analysis provides an economic framework for the evaluation of the feasibility of a proposed project or a project in operation (International Records Management Trust, 2006). Data collected and analyzed during the cost–benefit analysis support decision making about resource allocation and the most appropriate solution (David, Ngulube, & Dube, 2013).

A cost–benefit analysis compares the options in a given business function or situation and specifies the ROI, that is, the financial inputs and expected returns from a given project (International Records Management Trust, 2006). The results of a cost–benefit analysis help evaluate alternative options and can support a bid for resource allocation and management endorsement. Therefore, the scope and objectives of the proposed project for use in the cost–benefit analysis must be well defined (David et al., 2013).

2.7.1 Objectives of the Cost–Benefit Analysis

According to David et al. (2013), to understand the expected results from a cost–benefit analysis, it is important to understand the purpose and business objectives of performing one. Ngulube (2011) justifies the expected results of cost–benefit analysis by articulating expected benefits. Ngulube (2011) explains that the significance of any document management scheme in an organization is primarily evident in the use of available technology to reduce costs in the maintenance, retrieval, and storage of documented information whilst increasing the usability of the documented information. The use of available technology to reduce costs thus ensures transparency, accountability, economy, efficiency, and effectiveness of business operations.

2.7.2 Factors to be considered in a Cost Benefit Analysis

According to David et al. (2013), costs and benefits are the two major factors that should be considered when conducting a cost–benefit analysis. Costs that should be considered include the cost of maintenance and acquisition of equipment; the upgrade, enhancement, or redesign of current networks; the acquisition, maintenance, and testing of software; the development and delivery of training to users and support staff; the record’s conversion from the current system;

and the system administration. Even though costs that are intangible are not easy to quantify, they should still be identified as they can impact the overall costs of a project. The non-quantifiable costs should be acknowledged in the cost–benefit analysis, even if they may not be used in the calculations of the analysis (David et al., 2013).

On the other hand, the returns expected from a project are called benefits. Most benefits are expressed in terms of improvements and cost savings. Benefits can also be quantifiable and non-quantifiable. To be precise and to determine results, it is important to attempt to convert each benefit into a dollar figure (David et al., 2013). According to guidelines from the National Archives of Australia (2003), one should seek advice from financial staff to calculate benefits, and it is important to understand that secondary benefits may also be derived from a project.

2.7.3 Cost Analysis in Construction

Cost analysis methods in construction are involved in research related to ROIs during the preconstruction, construction, and post construction stages. Research related to cost estimates during other project stages also uses cost analysis methods.

According to Ahn et al. (2017), cost analysis methods such as regression analysis, artificial neural networks, and case based reasoning are used to enhance cost estimate outputs. Ahn et al. (2017) carried out a comparative study on various similarity measurement methods applied to cost models, and they estimated cost results in terms of their estimated accuracy and stability.

Mao et al. (2016) conducted a cost analysis for sustainable off-site construction. A multiple case study method and the identification of concrete systems were used as the primary elements of their research. They discussed the reasons for the cost difference between traditional projects and off site construction, including the cost types and change fluctuations.

Giel and Issa (2013) used a cost analysis method to calculate the benefits of BIM in construction projects. Two case studies were conducted in the research; each case study compared the cost of a project constructed using BIM to a project constructed without BIM. The first case study showed a cost benefit of approximately 0.2% of the total project cost for the owners, and the second case study showed that BIM may have prevented approximately 10% of the total cost of change orders.

Kaiser (2017) conducted a cost analysis on the offshore pipeline construction in the U.S. Gulf of Mexico. The aim was to understand the construction cost differences among projects from 1995 to 2014. Various costs such as the costs of materials, damages, labor, engineering, and surveys were included in the cost analysis study. The research showed the reasons for its large deviation in cost distribution among different projects. The cost analysis results showed a deviation pattern for the costs, and these reasons were identified according to this pattern.

Hosny, Ibrahim, and Fraig (2016) analyzed the costs of continuous flight auger piles construction under Egyptian operating conditions with unique marketplace factors. The methodology compared estimated costs with the actual costs of piles to determine the accuracy of the estimated costs. Sensitivity analysis was then performed on the cost estimates to study the effect of changes in each of the main costs and on the total cost. The research identified the most effective equipment on total cost of projects as the rig, loader, pump, pan mixer, and mini loader.

2.7.4 Return on Investment (ROI)

The concept of ROI is important for understanding cost savings due to use of BIM. It is one of the many ways to evaluate proposed investments. Return on investment compares the potential benefit or gain of an investment to how much the investment costs. It is usually calculated by taking a ratio of profits gained from a certain investment in a project to the total price of investment. According to Feibel (2003), ROI is a measure of investment profits and not a measure of investment size. It measures the percent return on an amount of capital expenditure. It can be calculated in simple terms using the following equation: ROI = (gain from investment – cost of investment) / cost of investment (Feibel, 2003).

Friedlob and Plew (1996) explained ROI as a comprehensive tool that normalizes dissimilar activities of different sizes and allows them to be compared. When applied to BIM used in construction projects, it is suggested that ROI be measured as a ratio of net savings to costs because the resulting potential savings are considered profit by contractors, designers, and other stakeholders (Giel & Issa, 2013).

Chapter 3: RESEARCH METHODOLOGY

This research aims to analyze the cost of using building information modeling (BIM) in building retrofit projects. Three primary objectives and the research methods for each objective are provided in Table 1.

Table 1. Research Objectives and Research Methods

Phase	Research Objective	Research Method
1	To identify the factors to be used to calculate the cost benefits of using BIM in building retrofit projects	• A review of existing literature was conducted to identify various factors that could be used to calculate cost benefits due to using BIM in retrofit projects. • A real-life retrofit project was selected. The project data were analyzed to determine which factors, previously identified through the literature review, could be used for the research.
2	To develop a systematic approach to cost analysis to quantify the cost benefits of using BIM in retrofit projects.	• A method was developed to determine the benefits of BIM for each factor identified in Phase 1 and to then quantify these benefits into a cost.
3	To perform a cost analysis to investigate whether there are	• The methodology developed in Phase 2 was applied to the real-life project. The cost

	economic benefits to using BIM compared to not using BIM in retrofit projects.	benefits due to using BIM and the fees required for implementing BIM in the real-life project were quantified and analyzed to evaluate the cost of using BIM in the project.

3.1 Phase 1: Factor Identification

In Phase 1 of the research, the goal was to identify the cost benefit factors (in the design, construction, and post construction phases) of a retrofit project. A review of existing literature was conducted to identify the factors for which the benefits of BIM could be calculated. Then, a real-life retrofit project was selected; the selection criteria included whether BIM was implemented during the design and construction phases of the project. The available project data were analyzed, the factors were finalized and could be used to calculate the benefits of BIM in the real-life retrofit project.

This research examined the cost benefits of BIM using factors such as requests for information (RFIs), change orders, and schedule overruns in the construction phase of the project. These factors were used in Phase 2 to develop the systematic cost analysis approach that was used later on in Phase 3 to analyze the costs related to BIM in a retrofit project constructed using BIM as compared to projects constructed without using BIM.

3.2 Phase 2: Development of the Cost Analysis Approach

In Phase 2 of the research, a systematic approach to cost analysis was developed to determine the benefits of the factors identified in Phase 1 and to then quantify them into a cost. One of the major benefits of using BIM is the reduction in change orders, and using BIM thus results in a decrease in costs and time delays for the owners. It can identify construction issues and conflicts early in the project and can thus decrease the number of change orders that may occur later due to undetected issues.

The chosen real-life retrofit project was designed and constructed using BIM, and the assumption was therefore that BIM preventable change orders were prevented because BIM was used in the project. The change orders that could have occurred had BIM not been used in the project were identified to calculate the benefits of using BIM. The RFIs for the project were analyzed by the author of this research to identify the RFIs that may not have been issued had BIM not been used in the project. These RFIs could potentially have led to change orders and thus could have caused cost increases or time overruns. The cost of these change orders was estimated and was identified as a cost benefit of using BIM. The entire process of the RFI analysis and change order estimation is provided in detail in Section 3.3.

3.3 Phase 3: Implementation of the Cost Analysis of the Retrofit Project

In Phase 3, the cost analysis approach was applied to the real-life retrofit project. The cost benefits of using BIM and the fees required for implementing BIM in this project were quantified and analyzed to evaluate the cost of using BIM in the project. The Department of Animal Sciences building at Colorado State University was selected for the case study. The selection criteria for the project were based on two factors: the project should be a retrofit or renovation project, and BIM should be used in the project. The project implemented BIM during the design as well as the construction phase. The methodology developed in Phase 2 of this research was implemented to determine the cost reductions due to the implementation of BIM in the Animal Sciences Building project. The construction project superintendent mentored the author throughout the research.

3.3.1 Retrofit Project Overview

The chosen real-life project was a renovation of the Animal Sciences Building at Colorado State University. The Animal Sciences Building is a three story classroom, laboratory, and office building on the Colorado State University campus. The basement mainly consists of offices, the main mechanical and electrical rooms, and two classrooms. The first floor primarily consists of office space, some classrooms, and small breakout conference areas. The upper floor is mainly laboratory space.

The building structure is concrete with a retrofitted steel structure in sections of the building modified during a prior renovation. The envelope of the building is a stone masonry facade with masonry block back-up walls.

The renovation project consisted of an interior renovation including fire alarm, mechanical, electrical, telecommunication, and audio visual systems; installation of a new sprinkler system and new finishes; installation of four new north windows; a new accessible north entry ramp; and an option for the replacement of the existing elevator. The existing building construction type and occupancy types were to be maintained.

The total gross area of the project was 40,117 gross square feet (GSF) divided into 14,503 GSF for the basement, 13,839 GSF for the first floor, and 11,775 GSF for the second floor. The project construction type was II-B, and the project occupancy type was B. The building had a full sprinkler system for fire protection.

With the help from the owners of the project (Colorado State University), the general contractor, and the architects, the available project data were collected and analyzed to determine the benefits of using BIM in the project. The general contractor for the project was a medium sized commercial general contractor, with annual revenue of approximately $200 million. They specialize in office, retail, multifamily residential units, and healthcare facilities. They provide multiple services in general contracting, preconstruction, project closeouts, and virtual design and construction.

The architectural firm is based in Wyoming. They specialize in high rise residential, commercial, healthcare, government, and interior design projects. The architectural firm specializes in value based decision making, using their full technological capabilities including the proven 3D BIM, life cycle cost analysis of materials and systems, and cost control and project scheduling software support.

The Animal Sciences Building was a 40,117 GSF building renovation project with an additional 3,000 GSF of new construction. The project implemented BIM during the design and construction phases. The project delivery method was negotiated bid and its final contract type was guaranteed maximum price. The schedule for the Animal Sciences Building project spanned roughly 18 months, and its final contract value summed to approximately $14.5 million.

3.3.2 Approach to Virtual Design and Construction

The general contractor of the project has been offering BIM services to its clients for over 8 years. Their efforts towards implementing BIM have been efficient and have continued to grow and improve with time. They have an in-house BIM department, and the BIM manager oversees all modeling tasks and coordination drawing. They worked in collaboration with the subcontractors to develop the building information model for this project. Their in-house virtual design and construction (VDC) manager oversees all modeling tasks, provides assistance in estimation and preconstruction efforts, and communicates with field personnel to create specific drawings from the models as required. The chosen software platform used for the Animal Sciences Building project was Autodesk Revit 2013 Architecture, Structure, and MEP. Autodesk Navisworks 2013 was used for clash detection in the project.

For the Animal Sciences Building project, the general contractor created a Revit model for coordination and to foresee potential conflicts that may arise in the field. The building information model was created once the drawings were received from the architects. The architects also created a building information model, but that model was not used by the general contractor. The general contractor and its subcontractor created their own building information models.

Many major issues were resolved during the initial modeling phase before the construction took place. There was no separate VDC related RFI log to aid communication between the general contractor's VDC department and the subcontractors. All the VDC related RFIs were included in the general RFI logs. Questions from subcontractors that could be answered by the general contractor were answered directly, and the questions requiring assistance from the architects or the owners were sent to them.

3.3.3 Data Collection Plan

The quantitative data collected for the retrofit project in Phase 1 included the following:

- original contract value,
- total number and details of requests for information (RFIs),
- total number and details of the change order requests (CORs),
- architectural drawings for the project, and
- charges for schedule overruns.

The fee for providing BIM services to the project was not defined separately in the project contract. For research purposes, the cost of BIM implementation was estimated at roughly 0.5% of the initial contract value (Giel & Issa, 2013).

In addition to this quantitative data, qualitative data were also gathered through the author's discussions with the project's superintendent. First, the issues discovered by BIM were thoroughly analyzed. This was accomplished through discussions with the project's superintendent and careful manual inspection of the project's VDC related RFI logs. These RFI logs provided all records of conflicts and issues discovered using BIM over the course of construction. Interpreting these logs assisted the author in understanding how BIM helped identify the issues. The assistance of the project superintendent helped identify the RFIs that could have been missed had BIM not been used. The project superintendent also helped clarify which RFIs would probably lead to cost increases and time overruns. In the end, all the RFIs that could have led to change orders if missed were identified by the author and validated by the project superintendent.

3.3.4 Analysis of RFIs and Change Orders

This research used mainly the information obtained through the project's RFI logs. These RFI logs provided the most accurate record of events and issues during the construction phase. The goal of the detailed analysis of these RFIs was to identify the RFIs that could have been missed had BIM not been used in the project. The RFI logs were provided by the general contractor of the project. The VDC related RFI logs were not segregated from other RFIs, and therefore, the first step was to identify the RFIs that were discovered by BIM.

According to the project superintendent, many issues were discovered by BIM before and during construction. The unresolved issues were converted into RFIs and sent to the architects for answers. The superintendent explained the issues to the author and provided a list of keywords to look for in the RFI logs. The following keywords were used to find the RFIs that contained BIM discoverable issues:

- *ceiling height*: BIM helped identify conflicts with overhead rough-ins and other structural components with the ceilings. All RFIs containing the keyword *ceiling height* were analyzed for BIM discoverable issues.
- *conflict*: All RFIs related to structural, mechanical, engineering, or plumbing conflicts were analyzed for BIM discoverable issues.
- *existing*, *cast in place, floor tilted*: The existing concrete floors and other structures had conflicts with the new structures, and BIM helped to discover these issues early in the project.
- *light fitting*: BIM helped identify conflicts with light fixtures in the ceilings, and all RFIs with the keyword *light fitting* were analyzed for BIM discoverable issues.
- *east wing basement*, *alternate 5*: BIM helped identify conflicts and issues in the East Wing Basement in alternate-5 regions. Any RFI with keyword *east wing basement* or *alternate 5* were analyzed for BIM discoverable issues.
- *plastered ceilings*: There were structural conflicts in several plastered ceilings, and all RFIs containing the keyword *plastered ceilings* were analyzed for BIM discoverable issues.

Along with the keywords provided by the project superintendent, major issues that can be identified by implementing BIM were also used. These issues can be divided into five basic categories (Giel & Issa, 2013):

- Dimensional inconsistencies in the construction documents
- Document discrepancies between disciplines
- 2D errors and omissions
- Grid and column alignment issues

- Direct clashes

The RFIs that could have been missed had BIM not been used in the project were discovered in four stages:

1. In the first stage, a list was created as suggested by the project superintendent. The list included the keywords related to issues discovered by BIM in the project.
2. In the second stage, RFIs were discovered using the five basic issues discoverable by BIM (Giel & Issa, 2013) and the keywords suggested by the superintendent of the project. Most RFIs were common in both.
3. In the third stage, each of the discovered RFIs was analyzed by the author to determine whether they could have been missed had BIM not been used in the project. The RFIs that could have been missed were then checked to determine whether they could have led to change orders. These change orders were checked to determine whether they could have led to cost or time overruns. The discussions with the project's superintendent helped determine which RFIs could have been missed without BIM use and could have led to probable change orders.
4. In the fourth stage, the RFIs identified were shown to the project superintendent for validation.

From a total of 303 project RFIs, 41 BIM-based RFIs were identified in the first stage using the list of keywords and five basic issues. However, not all 41 RFIs identified as BIM-based by the author were related to BIM. In the second stage, these 41 RFIs were discussed with the project superintendent who also checked them for BIM discoverable issues. Thus, the RFIs not related to BIM were removed by the project superintendent and their total was reduced to 33. In other words, out of 303 RFIs in the project, 33 RFIs were finally identified as BIM related. Among the 33 RFIs, only those that could have been missed by using 2D methods were selected. It was assumed that 2D methods would miss the issues related to construction element conflicts and the issues discovered by 3D visualization. Any RFIs with issues such as document discrepancies or dimension inconsistencies were also removed. Eleven RFIs out of 33 were thus found that could have been missed had BIM not been used in the project. From these 11 RFIs, 5 RFIs with the potential of causing rework were selected. Change orders causing rework lead to cost and time increases.

Once the five RFIs that could have been missed had BIM not been used were discovered, the next step was to identify the change orders that these RFIs could have led to. For every RFI submitted by the contractor, an answer was provided by the architects or the owners. All 33 BIM discoverable RFIs and the answers provided by the architects and owners were analyzed. The RFIs showing issues of direct conflict in structure or mechanical, electrical, or plumbing systems were likely to result in a change order. The RFIs to which the response from the architects suggested a change in construction were also likely to result in a change order. The change orders that could have been made had the RFIs not been filed were estimated after analyzing the responses to the RFIs and after discussion with the project superintendent.

3.3.5 Cost Analysis

Using the project data, the benefits due to implementing BIM were identified, and these benefits were converted into a cost that could have added to the project cost had BIM not been used. This cost included the cost of rework due to BIM preventable change orders and the cost related to schedule overruns during the project's construction phase. To estimate the benefits of BIM, the cost of rework and schedule overruns due to potential change orders was calculated according to Equation (1). All variables in Equation (1) represent dollar values.

$$B_{BIM} = B_{CO} + B_{SO} \quad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits of using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns.

The fee required for implementing BIM was subtracted from the total cost benefits of using BIM in the retrofit project. The net cost of BIM was calculated according to Equation (2). All variables in Equation (2) represent dollar values.

$$N_{BIM} = B_{BIM} - I_{BIM} \quad \text{(Eq. 2)}$$

where N_{BIM} is the net cost of using BIM, B_{BIM} is the total of the cost benefits of using BIM, and I_{BIM} is the fee required for implementing BIM.

The return on investment (ROI) from using BIM was calculated according to Equation (3).

$$\mathrm{ROI} = (N_{BIM} / I_{BIM}) * 100 \quad \text{(Eq. 3)}$$

where ROI is the return on investment from using BIM, N_{BIM} is the net cost of using BIM, and I_{BIM} is the fee required for implementing BIM.

Chapter 4: RESULTS

4.1 Factor Identification

A review of previous literature was conducted to identify the factors for which BIM benefits could be calculated. A list of these factors was prepared. The identified factors include reductions in change orders, requests for information (RFIs), schedule overruns, building energy costs, building maintenance costs, on-site material waste, and time saved due to better coordination among all project stakeholders. Only the factors that matched the data from the real-life project were selected. Based on the literature review and available project data, the factors identified to calculate the cost benefits due to implementation of BIM were

- reductions in cost due to prevented change orders, and
- reductions in cost due to the reduction in schedule overruns.

4.2 Development of the Cost Analysis Approach

A systematic approach to cost analysis was developed using the two identified cost benefit factors. Cost reductions due to prevented change orders and cost reductions due to decreased schedule overruns were calculated using project data.

The total BIM benefits were calculated according to Equation (1),

$$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}} \qquad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits due to use of BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns.

4.3 Implementation of the Cost Analysis Approach

The methodology developed in Phase 2 of the research was implemented in a real-life project. The results of this implementation are discussed in detail in this section.

4.3.1 Results of Analysis of RFIs and Change Orders

From a total of 303 RFIs, 41 BIM-based RFIs were identified. The 41 RFIs identified as BIM related were discussed with the project superintendent and were then reduced to 33 RFIs. Among the 33 RFIs that were discovered by BIM in the project, only those RFIs were selected that would have been missed by 2D methods. It was assumed that 2D methods would miss the issues related to construction element conflicts and the issues that were discovered by 3D visualization. Out of 33 RFIs, 11 RFIs were found that would have been missed had BIM not been used in the project. From these 11 RFIs, five RFIs were identified to have the potential of causing rework. Change orders for rework lead to increases in cost and time. The five RFIs are described in the following sections.

RFI 1

In the first RFI, many conflicts were discovered between structural components and a heating, ventilation, and air conditioning (HVAC) duct. They were discovered during BIM coordination. An RFI for the issue was created and sent to architects. The reply to the RFI from the architects suggested relocating the duct to the rooftop after the design team confirmed the relocation.

It was assumed that without BIM the conflict would not have been discovered, and therefore, the HVAC duct would have been placed as shown in the initial construction documents; as a result, conflicts with other structures would have occurred. Due to these conflicts, the duct would have been relocated as a change order. The cost of the duct relocation was estimated and was counted as a cost benefit due to using BIM.

RFI 2

The second RFI included a ceiling height congestion issue. The ceiling was conflicting with the overhead rough-ins. An RFI for the ceiling height congestion was created and sent to the architects. The reply to the RFI from the architects suggested lowering the ceiling by 8 inches.

It was assumed that without use of BIM the conflict would not have been discovered, and therefore, the ceiling would have been placed as shown in the initial construction documents; as a result, conflicts with the overhead rough-ins would have occurred. Due to these conflicts, the ceiling would have been relocated as a change order. The cost of the ceiling relocation was estimated and was counted as a cost benefit from using BIM.

RFI 3

In the third RFI, two ceiling conflicts were discovered:

a) An acoustic ceiling was conflicting with a fan coil unit. An RFI for the conflict was created and sent to the architects. The architects suggested dropping the ceiling by 8 inches.
b) A gypsum drywall ceiling in the hallway was conflicting with structural entities. An RFI for the conflict was created and sent to the architects. The architects replied that the ceiling should be lowered from 9 feet 0 inches to 8 feet 2 inches.

It was assumed that without use of BIM these conflicts would not have been identified, and therefore, the ceilings would have been placed as shown in the initial construction documents; as a result, conflicts with other structures would have occurred. Due to these conflicts, the ceilings would have been relocated as a change order. The cost of the ceiling relocations was estimated and was counted as a cost benefit due to using BIM.

RFI 4

In the fourth RFI, many conflicts were discovered between certain structures and the ceilings. In all typical rooms with fan coil units, the original ceiling height did not allow the installation clearance required for the fan coil units. Seven rooms were identified as having such conflicts. An RFI for the conflict was created and sent to the architects. The architects suggested dropping the ceiling by 4 inches.

It was assumed that without the use of BIM these conflicts would not have been identified, and therefore, these ceilings would have been placed as shown in the initial construction documents; as a result, conflicts with other structures would have occurred. Due to these conflicts, the ceilings would have been relocated as a change order. The cost of the ceiling relocations was estimated and was counted as a cost benefit from using BIM.

RFI 5

In the fifth RFI, a drywall conflict with an overhead waste pipe was identified during the mechanical system coordination. An RFI for the conflict was created and sent to the architects. The architects suggested shifting the drywall to the north by 6 inches.

It was assumed that without BIM, the conflict would not have been identified, and therefore, the drywall would have been placed as shown in the initial construction documents; as a result, conflicts with the overhead waste pipe would have occurred. Due to these conflicts, the drywall would have been relocated as a change order. The cost of the drywall relocation was estimated and was counted as a cost benefit from using BIM.

4.3.2 Cost Estimation for the Change Orders

Costs were estimated using RSMeans 2013, and the cost values used were adjusted according to the location of the project. Demolition and second installation costs were calculated for the change orders that would have occurred had BIM not been used. The maximum possible cost was estimated for all the change orders. It was also assumed that no material was reused while conducting change orders. Tables 2–6 show the cost estimates for the five RFIs.

Table 2 shows the cost estimate for a demolition and new installation of an HVAC metal duct. The duct size was 34 inches by 14 inches and was 60 feet long with 1-inch-thick duct liner. All information for the materials was taken from project specification details. The estimated cost of demolition was $254, and the estimated cost for the second duct installation was $4,662. Thus, the total savings due to the prevented change order related to RFI 1 were $4,916.

Table 2. Cost Estimate of Potential Change Order Due to RFI 1

RSMeans reference#	**Component description**	**Qty of duct**	**Qty per lb of duct**	**Unit**	**Material unit cost**	**Total material cost**	**Labor unit cost**	**Total labor cost**	**Total cost**
HVAC duct: demolition cost									
23 0505.10 1400	Selective demolition, duct	60.00		LF			$4.23	$253.80	$253.80
							Total demolition cost		$253.80
HVAC duct: second installation cost									
23 0505.10 1400	34”x34” metal duct, 28-gauge galvanized steel	480.00	374.88	LB	$0.69	$259	$4.87	$1,826.67	$2,084.33
23 3353.10 3344	Duct liner, fiberglass, 1” thick	480.00		SF	$0.60	$288	$4.77	$2,289.60	$2,577.60
							Total second installation cost		$4,661.93
							Total estimated cost		$4,915.73

Note. LF – Linear Feet, LB – Pound, SF – Square Feet

Table 3 shows the cost estimate for a demolition and new installation of an acoustic ceiling. The ceiling had an area of 107 square feet. All information for the materials was taken from project specification details. The estimated cost of demolition was $80, and the estimated cost for the second installation of the ceiling was $361. Thus, the total savings due to the prevented change order related to RFI 2 were $441.

Table 3. Cost Estimate of Potential Change Order Due to RFI 2

RSMeans reference#	**Component description**	**Qty of ceiling**	**Unit**	**Material unit cost**	**Total material Cost**	**Labor unit cost**	**Total labor cost**	**Total cost**
Ceiling Act-01: demolition cost								
09 05 05.10 1580	Selective demolition, suspended ceiling, 2’x4’ mineral fiber	107.00	SF			$0.75	$80.25	$80.25
						Total demolition cost		$80.25
Ceiling Act-01: second installation cost								
09 51 23.10 1110	Mineral fiber tile, lay-in, 2’x3’ ¾” fine texture	107.00	SF	$1.61	$172.27	$0.60	$64.20	$236.47
09 53 23.30 0310	Class A suspension system, 2’x4’ grid	107.00	SF	$1.61	$75.97	$0.45	$48.15	$124.12
						Total second installation cost		$360.59
						Total estimated cost		$440.84

Note. SF – Square Feet

Table 4 shows the cost estimate for a demolition and new installation of an acoustic ceiling and a gypsum board ceiling. The ceilings had areas of 185 square feet and 143 square feet, respectively. All information for the materials was taken from project specification details. The estimated cost of demolition was $252, and the estimated cost for the second ceiling installation was $2,229. The total savings due to the prevented change order related to RFI 3 were $2,481.

Table 4. Cost Estimate of Potential Change Order Due to RFI 3

RSMeans reference#	Component description	Qty of ceiling	Unit	Material unit cost	Total material cost	Labor unit cost	Total labor cost	Total cost
Ceiling ACT-01 and GPDW: demolition cost								
ACT-01								
09 05 05.10 1580	Selective demolition, suspended ceiling, 2'x4' mineral fiber	185.00	SF			$0.75	$138.75	$138.75
GPDW ceiling								
09 05 05.10 1580	Selective demolition, drywall on suspension system	143.00	SF			$0.79	$112.97	$112.97
						Total demolition cost		$251.72
Ceiling Act-01 and GPDW: second installation cost								
ACT-01								
09 51 23.10 1110	Mineral fiber tile, lay-in, 2'x3' ¾" fine texture	185.00	SF	$1.61	$297.85	$0.60	$111.00	$408.85
09 53 23.30 0050	Class A suspension system, 2'x4' grid	185.00	SF	$0.67	$123.95	$0.45	$83.25	$207.20
GPDW Ceiling								
09 29 10.30 2300	5/8" gypsum board	143.00	SF	$0.87	$160.95	$0.80	$148.00	$308.95
09 29 10.30 2300	5/8" gypsum board	143.00	SF	$0.87	$124.41	$0.80	$114.40	$238.81
09 29 10.30 2300	3 5/8"-wide 16 O.C.	143.00	SF	$0.37	$52.91	$0.60	$85.80	$138.71
09 81 16.10 3600	Sound attenuation blanket, 3"	143.00	SF	$5.80	$829.40	$0.68	$97.24	$926.64
						Total second installation cost		$2,229.16
						Total estimated cost		$2,480.88

Note. SF – Square Feet

Table 5 shows the cost estimate for a demolition and new installation of an acoustic ceiling. The ceiling had an area of 902 square feet. All information for the materials was taken from project specification details. The estimated cost of demolition was $677, and the estimated cost for the second ceiling installation was $3,040. The total savings due to the prevented change order related to RFI 4 were $3,716.

Table 5. Cost Estimate of Potential Change Order Due to RFI 4

RSMeans reference#	Component description	Qty of ceiling	Unit	Material unit cost	Total material cost	Labor unit cost	Total labor cost	Total cost
Ceiling Act-01: demolition cost								
09 05 05.10 1580	Selective demolition, suspended ceiling, 2’x4’ mineral fiber	902.00	SF			$0.75	$676.50	$676.50
						Total demolition cost		$676.50
Ceiling Act-01: second installation cost								
09 51 23.10 1110	Mineral fiber tile, lay-in, 2’x4’ 3/4” fine texture	902.00	SF	$1.61	$1452.22	$0.60	$541.20	$1,993.42
09 53 23.30 0310	25% recycled steel, 2’x4’	902.00	SF	$0.71	$640.42	$0.45	$405.90	$1,046.32
						Total second installation cost		$3,039.74
						Total estimated cost		$3,716.24

Note. SF – Square Feet

Table 6 shows the cost estimate for a demolition and new installation of drywall. The drywall had an area of 128 square feet. All information for the materials was taken from project specification details. The estimated cost of demolition was $91, and the estimated cost for the second drywall installation was $1,381. The total savings due to the prevented change order related to RFI 5 were $1,472.

Table 6. Cost Estimate of Potential Change Order Due to RFI 5

RSMeans reference#	Component description	Qty of wall	Unit	Material unit cost	Total material cost	Labor unit cost	Total labor cost	Total cost
Drywall: demolition cost								
09 05 05.10 1580	Selective demolition, drywall	128.00	SF			$0.71	$90.88	$90.88
						Total demolition cost		$90.88
Drywall: second installation cost								
09 51 23.10 1110	5/8" gypsum board	128.00	SF	$0.87	$111.36	$0.80	$102.40	$213.73
09 53 23.30 0310	5/8" gypsum board	128.00	SF	$0.87	$111.36	$0.80	$102.40	$213.73
09 22 16.13 1640	3 5/8"-wide 16 O.C.	128.00	SF	$0.37	$47.36	$0.60	$76.80	$124.16
09 81 16.10 3600	Sound attenuation blanket, 3"	128.00	SF	$5.80	742.40	$0.68	$87.04	$829.44
						Total second installation cost		$1,381.12
						Total estimated cost		$1,472.00

Note. SF – Square Feet

4.3.3 Estimation of Schedule Overruns due to the potential Change Orders

The time to complete each change order that could have occurred had BIM not been used was estimated and then quantified into a cost. The fine for schedule overruns in the project was $1,200 per day. Many factors affected the time involved in a change order, such as time taken by the architects to reply to the RFIs, the efficiency of the project team, and the time needed to procure required labor and materials. According to the project superintendent, the maximum time for the architects to reply to the RFIs was 7 days after an RFI was sent to them. The architects took longer to reply to the RFIs, and according to the project superintendent, the average response time for all RFIs was 25–30 days, and for one of the RFIs, the architects took 90 days to reply.

The time required for rework was estimated using RSMeans 2013 data. For estimation purposes, it was assumed only one labor crew would be used for each change order. Using more than one crew would decrease the time required for the rework and would give different results. Tables 7–11 show the estimated time needed for each potential change order.

Table 7 shows the estimated time for a demolition and new installation of an HVAC metal duct. The estimated time for the demolition was 7.14 hours, and the estimated time for the second duct installation was 94.34 hours. The total time reduction due to the prevented change order related to RFI 1 was 101.48 hours.

Table 7. Time Estimate of Potential Change Order Due to RFI 1

RSMeans reference#	Component description	Qty of duct	Unit	Lbs per SF	Qty. per lb of duct	Labor hrs/lb	Crew	Labor hrs total
HVAC duct: demolition time								
23 05 05.10 1400	Selective demolition, drywall	60.00	LF			0.12	1 clab	7.14
						Total demolition time		7.14
HVAC duct: second installation time								
23 31 13.13 0520	34x14 metal duct, 28-gauge galvanized steel	480.00	SF	0.781	374.88	0.10	Q-10	36.74
23 33 53.10 3344	Duct liner, fiberglass, 1” thick	480.00	SF			12	Q-14	57.60
						Total second installation time		94.34
						Total estimated time (hrs)		101.48

Note. LF – Linear Feet, SF – Square Feet

Table 8 shows the estimated time for a demolition and new installation of an acoustic ceiling. The estimated time for the ceiling demolition was 2.25 hours, and the estimated time for the second installation was 2.46 hours. The total time reduction due to the prevented change order related to RFI 2 was 4.71 hours.

Table 8. Time Estimate of Potential Change Order Due to RFI 2

RSMeans reference#	**Component description**	**Qty of ceiling**	**Unit**	**Labor hrs/lb**	**Crew**	**Labor hrs total**
Ceiling Act-01: demolition time						
09 05 05.10 1580	Selective demolition, suspended ceiling, mineral fiber 2'x4' on suspension system, including system	107.00	SF	0.021	2 clab	2.25
				Total demolition time		2.25
Ceiling Act-01: second installation time						
09 51 23.10 1110	Mineral fiber tile, lay-in, 2'x4' ¾" fine texture	107.00	SF	0.013	1 carp	1.39
09 05 23.30 0310	Class A suspension system, 2'x4' grid	107.00	SF	0.01	1 carp	1.07
				Total second installation time		2.46
				Total estimated time (hrs)		4.71

Note. SF – Square Feet

Table 9 shows the estimated time for a demolition and new installation of an acoustic ceiling and a gypsum board ceiling. The estimated time for the ceiling demolition was 7.03 hours, and the estimated time for the second installation was 13.41 hours. The total time reduction due to the prevented change order related to RFI 3 was 20.44 hours.

Table 9. Time Estimate of Potential Change Order Due to RFI 3

RSMeans reference#	**Component description**	**Qty of ceiling**	**Unit**	**Labor hrs/lb**	**Crew**	**Labor hrs total**
Ceiling Act-01 and GPDW: demolition time						
Ceiling Act-01						
09 05 05.10 1580	Selective demolition, suspended ceiling, mineral fiber 2'x4' on suspension system, including system	185.00	SF	0.021	2 clab	3.89
Ceiling GPDW						
09 05 05.10 0240	Selective demolition, drywall on suspension system, including system	143.00	SF	0.022	2 clab	3.15
				Total demolition time		7.03
Ceiling Act-01 and GPDW: second installation time						
Ceiling Act-01						
09 51 23.10 1110	Mineral fiber tile, lay-in, 2'x4' ¾ inch fine texture	185.00	SF	0.013	1 carp	2.41
09 05 23.30 0310	Class A suspension system, 2'x4' grid	185.00	SF	$0.01	1 carp	$1.85
Ceiling GPDW						
09 29 10.30 2300	5/8" gypsum board	143.00	SF	0.018	2 Carp	2.57
09 29 10.30 2300	5/8" gypsum board	143.00	SF	0.018	2 Carp	2.57
09 22 16.13 1640	3 5/8" wide 16 O.C.	143.00	SF	0.013	1 Carp	1.86
09 81 16.10 3600	Sound attenuation blanket, 3"	143.00	SF	0.015	2 Carp	2.15
				Total second installation time		13.41
				Total estimated time (hrs)		20.44

Note. SF – Square Feet

Table 10 shows the estimated time for a demolition and new installation of an acoustic ceiling. The estimated time for the ceiling demolition was 18.94 hours, and the estimated time for the second installation was 20.75 hours. The total time reduction due to the prevented change order related to RFI 4 was 39.69 hours.

Table 10. Time Estimate of Potential Change Order Due to RFI 4

RSMeans reference#	**Component description**	**Qty of ceiling**	**Unit**	**Labor hrs/lb**	**Crew**	**Labor hrs total**
Ceiling Act-01: demolition time						
09 05 05.10 1580	Selective demolition, suspended ceiling, mineral fiber 2'x4' on suspension system, including system	902.00	SF	0.021	2 clab	18.94
				Total demolition time		18.94
Ceiling Act-01: second installation time						
09 51 23.10 1110	Mineral fiber tile, lay-in, 2'x4' ¾ inch fine texture	902.00	SF	0.013	1 carp	11.73
09 05 23.30 0310	25% recycled steel, 2'x4' grid	902.00	SF	0.01	1 carp	$9.02
				Total second installation time		20.75
				Total estimated time (hrs)		39.69

Note. SF – Square Feet

Table 11 shows the estimated time for a demolition and second installation of drywall. The estimated time for the drywall demolition was 2.56 hours, and the estimated time for the second drywall installation was 8.19 hours. The total time reduction due to the prevented change order related to RFI 5 was 10.75 hours.

Table 11. Time Estimate of Potential Change Order Due to RFI 5

RSMeans reference#	Component description	Qty of wall	Unit	Labor hrs/lb	Crew	Labor hrs total
Drywall: demolition time						
09 05 05.10 0200	Selective demolition, drywall	128.00	SF	0.02	2 clab	2.56
				Total demolition time		2.56
Drywall: second installation time						
09 29 10.30 2300	5/8" gypsum board	128.00	SF	0.018	2 carp	2.30
09 29 10.30 2300	5/8" gypsum board	128.00	SF	0.018	2 carp	2.30
09 22 16.13 1640	3 5/8" wide 16 O.C.	128.00	SF	0.013	1 carp	1.66
09 81 16.10 3600	Sound attenuation blanket, 3"	128.00	SF	0.015	2 carp	1.92
				Total second installation time		8.19
				Total estimated time (hrs)		10.75

Note. SF – Square Feet

4.3.4 Discussion of Final Cost and Time Estimates

The total potential cost of change orders and estimated schedule overruns was calculated. As shown in Tables 1–5, cost was estimated for each potential change order due to the respective RFI. Details of material to be used were taken from the project specifications, and it was assumed that there was no reuse of materials during the rework due to change orders. Therefore, the cost estimates for the potential change orders were the highest possible.

For time estimates it was assumed that change orders would follow an 8-hour workday. The schedule overruns were calculated in days using the 8-hour workday assumption.

The total costs estimated for the potential change orders (RFI 1–RFI 5) are the following:

- RFI 1 = $4661.93 + $253.80 = $4,915.73

- RFI 2 = $360.59 + $80.25 = $440.84
- RFI 3 = $2,229 + $251.72 = $2,480.72
- RFI 4 = $3039.74 + $676.50 = $3,716.24
- RFI 5 = $1381.12 + $90.88 = $1,472

The total cost estimated from the change orders (RFI 1–RFI 5) is $13,025.53, and the addition of 5% contingency and 5% overhead to $13,025.53 amounts to $14,328.08, which equals to 0.1% of total project cost. This means that the project cost would have increased by 0.1% of the total project cost due to undetected conflicts had BIM not been used in the project.

The total times estimated in hours for the potential change orders (RFI 1–RFI 5) are:

- RFI 1 = 94.34 hours + 7.14 hours = 101.48 hours
- RFI 2 = 2.46 hours + 2.25 hours = 4.71 hours
- RFI 3 = 13.41 hours + 7.03 hours = 20.44 hours
- RFI 4 = 20.75 hours + 18.94 hours = 39.69 hours
- RFI 5 = 8.19 hours + 2.56 hours = 10.75 hours
- Schedule overrun due to RFI 1 change order assuming 8-hour workday = 13 days
- Schedule overrun due to RFI 2 change order assuming 8-hour workday = 1 day
- Schedule overrun due to RFI 3 change order assuming 8-hour workday = 3 days
- Schedule overrun due to RFI 4 change order assuming 8-hour workday = 5 days
- Schedule overrun due to RFI 5 change order assuming 8-hour workday = 2 days

According to the project's contract, the penalty to the general contractor for schedule overruns was $1,200 per day. In general, schedule overruns are discussed among stakeholders to understand the issues or people responsible for each change. In this research, it is assumed that these schedule overruns ultimately result in costs to the owner.

Schedule overruns due to change orders include the time required for the rework and the time required to process the change orders. Once the RFI is sent to the architects from the general contractors, the architects and owners decide whether a change order is required. Other negotiations such as cost of rework, time of rework, and person responsible for the change orders are also conducted among the owners, architects, and general contractors, and then the change orders are finalized. For this research, five scenarios were created to calculate the schedule overruns due to the change orders, and for each scenario, the total change order cost was calculated.

Scenario 1

In this scenario, only the time used for the rework required by change orders was used. It was assumed that no time was required to negotiate or finalize the change orders. It was also assumed that all rework due to the change orders occurred linearly and not simultaneously.

The cost reduction due to BIM preventable change orders is $14,328.08. The total time reduction due to BIM preventable change orders is 24 days. The penalty due to schedule overruns is 24 * $1,200 = $28,800.

The equation developed to calculate the total cost benefits due to use of BIM (Equation [1]) is

$$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}} \qquad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits due to using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns. Inputting $B_{\mathrm{CO}} = \$14,328.08$ and $B_{\mathrm{SO}} = \$28,800$ into Equation (1) gives

$B_{\mathrm{BIM}} = \$14,328.08 + \$28,800,$

$B_{\mathrm{BIM}} = \$43,128.08.$

The fee for using BIM in the project (I_{BIM}) was assumed to be 0.5% of the total project cost of $14.6 million, giving

I_{BIM} = 0.5% * $14.5 million,

I_{BIM} = $72,500.

The net BIM cost was calculated using Equation (2),

$N_{BIM} = B_{BIM} – I_{BIM}$ (Eq. 2)

where N_{BIM} represents the net cost due to using BIM, B_{BIM} represents the total of the cost benefits due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

N_{BIM} = $43,128.08 - $72,500,

N_{BIM} = - $29,371.92.

A negative value of a net BIM cost shows that BIM was not economically beneficial in this scenario.

The return on investment (ROI) from using BIM was calculated according to Equation (3),

ROI = (N_{BIM} / I_{BIM}) * 100 (Eq. 3)

where ROI represents the return on investment due to using BIM, N_{BIM} represents the net cost due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

ROI = ($29,372 / $72,500) * 100,

ROI = 40%.

As the value of N_{BIM} was negative, there was no ROI in this case, and the project suffered a loss of 40% from using BIM in the project. Therefore, in Scenario 1, the use of BIM in the project was not economically beneficial.

Scenario 2

In this scenario, the time used for the rework of change orders as well as the time required for negotiating and finalizing the change orders was calculated. It was assumed that all rework due to the change orders occurred linearly and not simultaneously.

The cost reduction due to BIM preventable change orders is $14,328.08, and the time reduction due to rework required by BIM preventable change orders is 24 days. According to the project contract, a 7-day period was selected as the time needed for the architect to answer any RFIs. For this research, this 7-day period was used as the time needed to negotiate and finalize a change order. The time reduction due to BIM preventable change orders for one change order is 7 days. The time reduction due to BIM preventable change orders for five change orders is 35 days. The total time reduction due to BIM preventable change orders is 24 days + 35 days = 59 days. The penalty due to schedule overruns is 59 days * $1,200 = $70,800.

The equation developed to calculate the total cost benefits due to use of BIM (Equation [1]) is

$$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}} \qquad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits due to using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns. Inputting B_{CO} = $14,328.08 and B_{SO} = $70,800 into Equation (1) gives

B_{BIM} = $14,328.08 + $70,800,

B_{BIM} = $85,128.08.

The fee for using BIM in the project (I_{BIM}) was assumed to be 0.5% of the total project cost of $14.6 million, giving

I_{BIM} = 0.5% * $14.5 million,

I_{BIM} = \$72,500.

The net BIM cost was calculated using Equation (2),

$N_{BIM} = B_{BIM} - I_{BIM}$ (Eq. 2)

where N_{BIM} represents the net cost due to using BIM, B_{BIM} represents the total of the cost benefits due to using BIM, and I_{BIM} is the fee required for implementing BIM. This gives

N_{BIM} = \$85,128.08 - \$72,500,

N_{BIM} = \$12,628.08.

A positive value of net BIM cost shows that BIM was economically beneficial in this scenario.

The return on investment (ROI) from using BIM was calculated according to Equation (3),

ROI = (N_{BIM} / I_{BIM}) * 100 (Eq. 3)

where ROI represents the return on investment due to using BIM, N_{BIM} represents the net cost due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

ROI = (\$12,628 / \$72,500) * 100,

ROI = 17%.

As the value of N_{BIM} was positive, the ROI in this scenario from using BIM was 17%. Therefore, in Scenario 2, the use of BIM in the project was economically beneficial.

Scenario 3

In this scenario, the time used for the rework of change orders was used. It was assumed that no time was required for negotiating and finalizing the change orders. It was also assumed that all rework due to the change orders occurred simultaneously, not linearly.

The cost reduction due to BIM preventable change orders is \$14,328.08. As all rework was done simultaneously, the time required for the longest change order would also be the total time for all the change order rework. The time reduction due to BIM preventable change order rework is 13 days, the total time reduction due to BIM preventable change orders is 13 days, and the penalty due to schedule overruns is 13 days * $1,200 = $15,600

The equation developed to calculate the total cost benefits due to use of BIM (Equation [1]) is

$$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}} \qquad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits due to using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns. Inputting B_{CO} = $14,328.08 and B_{SO} = $15,600 into Equation (1) gives

$B_{\mathrm{BIM}} = \$14328.08 + \$15600$,

$B_{\mathrm{BIM}} = \$29{,}928.08$.

The fee for using BIM in the project (I_{BIM}) was assumed to be 0.5% of the total project cost of $14.6 million, giving

$I_{\mathrm{BIM}} = 0.5\% * \$14.5$ million,

$I_{\mathrm{BIM}} = \$72{,}500$.

The net BIM cost was calculated using Equation (2),

$$N_{\mathrm{BIM}} = B_{\mathrm{BIM}} - I_{\mathrm{BIM}} \qquad \text{(Eq. 2)}$$

where N_{BIM} represents the net cost due to using BIM, B_{BIM} is the total of the cost benefits due to using BIM, and I_{BIM} is the fee required for implementing BIM. This gives

$\mathrm{N_{BIM}} = \$29{,}928.08 - \$72{,}500$,

$\mathrm{N_{BIM}} = -\ \$42{,}571.92$

A negative value of net BIM cost shows that BIM was not economically beneficial in this scenario.

The return on investment (ROI) from using BIM was calculated according to Equation (3),

$$\text{ROI} = (N_{\text{BIM}} / I_{\text{BIM}}) * 100 \quad \text{(Eq. 3)}$$

where ROI represents the return on investment due to using BIM, N_{BIM} is the net cost due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

ROI = ($42,572 / $72,500) * 100,

ROI = 58.8%.

As the value of N_{BIM} was negative, there was no ROI in this case, and the project suffered a loss of 59% from using BIM in the project. Therefore, in Scenario 3, the use of BIM in the project was not economically beneficial.

Scenario 4

In this scenario, the time used for the rework of change orders as well as the time required for negotiating and finalizing of the change orders was calculated. It was assumed that all rework due to the change orders occurred simultaneously, not linearly.

The cost reduction due to BIM preventable change orders is $14,328.08. As all rework was done simultaneously, the time required for the longest change order would also be the total time for all the change order rework. The time reduction due to BIM preventable change order rework is 13 days. According to the project contract, a 7-day period was selected as the time needed for the architect to answer any RFIs. For this research, this 7-day period was used as the time needed to negotiate and finalize a change order. The time reduction due to BIM preventable change orders for one change order is 7 days, the time reduction due to BIM preventable change orders for five change orders is 35 days, and the total time reduction due to BIM preventable change orders is 13 days + 35 days = 48 days. The penalty due to schedule overruns is 48 days * $1,200 = $ 57,600.

The equation developed to calculate the total cost benefits due to use of BIM (Equation [1]) is

$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}}$ (Eq. 1)

where B_{BIM} represents the total cost benefits due to using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns. Inputting B_{CO} = \$14,328.08 and B_{SO} = \$57,600 into Equation (1) gives

B_{BIM} = \$14,328.08 + \$57,600,

B_{BIM} = \$71,928.08.

The fee for using BIM in the project (I_{BIM}) was assumed to be 0.5% of the total project cost of \$14.6 million, giving

I_{BIM} = 0.5% * \$14.5 million,

I_{BIM} = \$72,500.

The net BIM cost was calculated using Equation (2),

$N_{\mathrm{BIM}} = B_{\mathrm{BIM}} - I_{\mathrm{BIM}}$ (Eq. 2)

where N_{BIM} represents the net cost due to using BIM, B_{BIM} represents the total of the cost benefits due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

N_{BIM} = \$71,928.08 - \$72,500,

N_{BIM} = - \$571.92

A negative value of net BIM cost shows that BIM was not economically beneficial in this scenario.

The return on investment (ROI) from using BIM was calculated according to Equation (3),

$\mathrm{ROI} = (N_{\mathrm{BIM}} / I_{\mathrm{BIM}}) * 100$ (Eq. 3) where ROI represents the return on investment due to using BIM, N_{BIM} represents the net cost due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

ROI = ($572 / $72,500) * 100,

ROI = 0.8%.

As the value of N_{BIM} was negative, there was no ROI in this case, and the project suffered a loss of 0.8% from using BIM in the project. Therefore, in Scenario 4, the project experienced neither ROI nor a loss due to the use of BIM in the project.

Scenario 5

In this scenario, the time used for the rework of change orders as well as the time required for negotiating and finalizing the change orders was calculated. It was assumed that all reworks that were similar in scope were conducted linearly and the reworks that were different in scope occurred simultaneously. Change orders due to RFI 1 were related to the relocation of an HVAC duct. Change orders due to RFI 2, RFI 3, and RFI 4 were related to the relocation of ceilings. Change orders due to RFI 5 were related to the relocation of drywall. It was assumed that change orders related to RFI 2, RFI 3, and RFI 4 occurred in linear fashion and change orders related to RFI 1 and RFI 5 occurred simultaneously with other change orders.

The cost reduction due to BIM preventable change orders is $14,328.08. The schedule overrun due to the RFI 1 change order, assuming an 8-hour workday, is 13 days. The combined schedule overrun due to the RFI 2, RFI 3, and RFI 4 change orders, assuming an 8-hours workday is 9 days.

The schedule overrun due to the RFI 5 change order, assuming an 8-hour workday is 2 days.

The time required for the RFI 1 change order was longer than the combined time required for the RFI 2, RFI 3, and RFI 4 change orders, as well as the time required for RFI 5. Thus, the total time of rework was the same as the time required for the RFI 1 change order.

The time reduction due to BIM preventable change order rework is 13 days. According to the project contract, a 7-day period was selected as the time needed for the architect to answer any RFIs. For this research, this 7-day period was used as the time needed to negotiate and finalize a change order. The time reduction due to BIM preventable change orders for one change order is 7 days, the time reduction due to BIM preventable change orders for five change orders is 35 days, and the total time reduction due to BIM preventable change orders is 13 + 35 days = 48 days. The penalty due to schedule overruns is 48 days * $1,200 = $57,600.

The equation developed to calculate the total cost benefits due to use of BIM (Equation [1]) is

$$B_{\mathrm{BIM}} = B_{\mathrm{CO}} + B_{\mathrm{SO}} \qquad \text{(Eq. 1)}$$

where B_{BIM} represents the total cost benefits due to using BIM, B_{CO} represents the cost benefits due to BIM preventable change orders, and B_{SO} represents the cost benefits due to reduced schedule overruns. Inputting B_{CO} = $14,328.08 and B_{SO} = $57,600 into Equation (1) gives

B_{BIM} = $14,328.08 + $57,600,

B_{BIM} = $71,928.08.

The fee for using BIM in the project (I_{BIM}) was assumed to be 0.5% of the total project cost of $14.6 million, giving

I_{BIM} = 0.5% * $14.5 million,

I_{BIM} = $72,500.

The net BIM cost was calculated using Equation (2),

$N_{BIM} = B_{BIM} - I_{BIM}$ (Eq. 2)

where N_{BIM} represents the net cost due to using BIM, B_{BIM} represents the total of the cost benefits due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

N_{BIM} = \$71,928.08 - \$72,500,

N_{BIM} = - \$571.92.

A negative value of net BIM cost shows that BIM was not economically beneficial in this scenario.

The return on investment (ROI) from using BIM was calculated according to Equation (3),

$ROI = (N_{BIM} / I_{BIM}) * 100$ (Eq. 3)

where ROI represents the return on investment due to using BIM, N_{BIM} represents the net cost due to using BIM, and I_{BIM} represents the fee required for implementing BIM. This gives

ROI = (\$572 / \$72,500) * 100,

ROI = 0.8%.

As value of N_{BIM} was negative there was no ROI in this case, and the project suffered a loss of 0.8% due to the use of BIM in the project. Therefore, in scenario 5 the project experienced neither return on investment nor a loss due to the use of BIM in the project.

These scenarios show different cost results. Scenario 1 and Scenario 3 show an economic loss due to the use of BIM in the retrofit project. Scenario 2 shows an economic gain due to the use of BIM in the retrofit project. Scenario 4 and Scenario 5 show BIM benefits nearly equal to the BIM fee and thus have resulted in no gain and no loss due to the use of BIM in the project.

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

Based on the available project data, this research calculated the cost benefits due to the implementation of BIM in a retrofit project and performed an analysis of BIM related costs in a retrofit project. Though the benefits were calculated based on only two factors, the cost analysis in three of the five case scenarios proved that BIM technology is a worthy investment for the owners as well as the general contractor and the designers involved in the construction project. Although measurable savings did exist due to reduced change orders and reduced schedule overruns, it was difficult to quantify them in an unbiased fashion due to the limitations of this research. Thus, the calculated cost benefits to the owner due to BIM could have varied based on the data available.

The BIM related request for information (RFI) on the real-life retrofit project were analyzed and the results found that the major issues discovered due to the implementation of BIM consisted of conflicts among building structures/systems. Had these issues not been resolved before construction, major rework may have ensued. A total of 11 issues were detected that may not have been detected if 2D methods instead of BIM had been used. Among these 11 issues, 5 had high chances of leading to change orders. The cost of these five probable change orders was estimated at $14,328. This research shows a project cost increase of 0.1% of the total project cost due to undetected conflicts had BIM not been used in the project. The five change orders would have also resulted in schedule overruns. The schedule overruns due to the change orders, assuming they occurred linearly, were estimated to be 24 days. The increase in the project cost due to these schedule overruns was estimated to be 0.2% of the total project cost. According to the contract, the architects were required to answer an RFI within 7 days from the issue of that RFI, but according to the project superintendent, in many cases, the architects took longer than 7 days.

Five different scenarios were created to analyze the time required to finalize a change order. In Scenario 1 and Scenario 3, there was no return on investment and the project suffered an economic loss due to the use of BIM in the project; in Scenario 2, there was a return on investment of 17% due to the use of BIM in the project; and in Scenario 4 and Scenario 5, benefits due to BIM were almost equal to the fee of implementing BIM, and therefore, there was neither any return on investment nor any loss due to the use of BIM in the project.

This research analyzed the costs due to the implementation of BIM on a retrofit project. While quantifiable evidence of BIM's benefits was identified in this research, the measurement of BIM's actual savings was a much more difficult task. Multiple assumptions were used during the identification of these benefits in the research. The research analyzed cost due to the implementation of BIM in the project, and the results support the argument that BIM can help save cost and time to the owners.

This research shows that even though BIM use has an important role in preventing change orders and schedule overruns, the cost prevention depends on factors shown in the different scenarios in the research, and therefore, it is difficult to identify the accurate benefits of BIM. From the research results, it can be concluded that large and complex projects could result in larger BIM benefits due to change orders and schedule overruns.

5.1 Research Limitations

During this research, multiple limitations arose during the collection and analysis of available project data. One of the major limitations was the unavailability of separate VDC related RFI logs. These RFIs were identified and later verified by the project superintendent, but there is still a chance that VDC related RFIs were missed. The missed VDC related RFIs could have led to change orders and thus could have increased the total estimated cost. Also, the project superintendent helped the author in understanding and identifying the RFIs related to BIM and in the prediction of change orders due to the RFIs. The project superintendent's perspective could be biased towards his company's use of BIM in the project. Therefore, the involvement of the project superintendent was also a limitation in this research.

Another limitation was in the calculation of the potential change order costs. As no definite method was available, a cost estimation of the reconstruction work was done using the RS Means 2013 cost data according to the project timeline. This cost estimation method may use numbers different from what would have been used by the general contractor. In addition, for the reworks, the maximum probable cost was calculated assuming no material was reused. For example, to relocate the acoustic ceilings, some undamaged ceiling tiles could be reused, but it was assumed that all material that was used for the rework was new.

The schedule overrun calculation was the most complicated task as a change order has multiple stages that must be approved, and work can only start after the approval. Once the issue is detected, an RFI is sent to the architects who then decide on and reply as to whether a change order is required. The time between the issue identification and the start of rework was simulated in this research using different scenarios; however, it was still uncertain how much time the architects and owners may require to finalize a change order.

Another limitation was the real-life project used in this research. The project was informative, but the project was more of a renovation than a retrofit project.

It should be also noted that only those benefits were calculated that could not have been identified by 2D methods. It is possible that there were change orders that could have been prevented by 2D methods in the project. Use of BIM would also have identified these change orders, but for this research, only those issues were considered that could not have been identified by 2D methods. The total benefits due to BIM could have been larger than calculated.

5.2 Recommendations

There are numerous benefits of using BIM for all stakeholders involved in all project stages, from schematic design to the owner's final acquisition of a building. This research attempted to justify the importance of BIM by using some of the benefits of BIM outlined in Chapter 2: Literature Review. In this research, the benefits of using BIM were quantified into a cost, and BIM's potential value to the project was evaluated. However, this study had some limitations.

If this study were conducted again, the methodology would be slightly changed. Instead of using one real-life retrofit project, this research should be applied to more retrofit projects of different building types. This could allow checking whether the methodology developed in this research is suitable for use in different retrofit projects. In addition, if this research methodology is reused, the real-life projects selected should be a retrofit project with no functional or area changes. This could allow the calculation of the reduction in operational energy consumption in a retrofit project due to the use of BIM. This BIM-based energy modeling can assist designers in selecting the optimal retrofit solution. The optimal retrofit solution during the building operation stage can reduce the energy usage of the building, and this energy saved could be quantified into a cost benefit from using BIM.

Given more time and resources, this research could be broadened to address the BIM benefits in a more detailed and accurate manner. A comparison case study of retrofit projects should be done. Instead of using a retrofit project constructed using BIM and analyzing it assuming BIM was not used during the project's construction, a comparison of two retrofit projects should be done. A retrofit project constructed using BIM should be compared to a retrofit project constructed without using BIM. The retrofit projects selected for the comparison should be similar in project scope, size, cost, and type of retrofit. This comparison study could result in the calculation of larger BIM benefits.

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LIST OF ABBREVIATIONS

BIM	Building information modeling
BEM	Building energy modeling
VDC	Virtual design and construction
AEC	Architecture/Engineering/Construction
RFI	Request for information
CO	Change order