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A METHODOLOGY FOR CONTRACTOR CLASH DETECTION USING BUILDING INFORMATION MODELLING ON COMMERCIAL CONSTRUCTION PROJECTS

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SUMMARY: *Despite contractors adopting building information modelling reporting positive results on profitability and return on investment, there is little standardization in the way building information modelling is being adopted in the industry. This research proposes the application of failure mode and effects analysis as part of a methodology aiming to conduct clash detection using building information modelling and evaluate the impact of doing so on the constructability of commercial projects and the return on investment to contractors. It applies it to a case study of a commercial construction project designed using building information modelling. The methodology involved conducting clash detection analysis using building information modelling software and evaluating clashes detected using failure mode and effects analysis. It also involved analyzing the project's actual requests for information and change orders to investigate whether they addressed issues that were visible in the design models, would have been detected as clashes and could have been prevented. The methodology also compared the results from the clash detection and failure mode and effects analysis processes to the ones from analyzing the project's requests for information and change orders to determine the extent to which these processes could have predicted constructability issues. It finally entailed calculating the project's return on investment by determining its direct cost savings, indirect costs and the cost of adopting building information modelling. Failure mode and effects analysis proved to be an efficient platform for organizing and presenting clash data and highlighting critical issues. It identified several design issues that would have prevented 4.8% of the project's requests for information and 7% of design-related change orders. The latter would have reduced the cost of design-related change orders by 9% and total project costs by 0.1%., resulting in a 127% return on investment. This moderate return on investment is generally consistent with the ones reported in some research studies conducting similar detailed assessments of direct project savings, but in contrast with other studies using less rigorous assessments and reporting drastically higher values.*

KEYWORDS: *Building Information Modelling, Change Orders, Constructability, Contractor, Failure Mode and Effects Analysis, Requests for Information, Return on Investment*

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1. INTRODUCTION

Throughout the past decade, building information modelling (BIM) has seen a rapid rise in its use within the construction industry, with over 70% of the community having adopted some form of BIM as of 2012 (McGraw-Hill Construction, 2012). BIM technology enables the creation of accurate, data-rich, three-dimensional digital representations of buildings (Reinhardt and Klancnik, 2009). Models are created and developed throughout the design phase to provide the data to support the project throughout its construction phase. BIM also accommodates many of the functions needed to model a building's lifecycle, including the ability to store component operation and maintenance data (Reinhardt and Klancnik, 2009).

Early research in the field shows that contractors adopting BIM are reporting positive returns on investment (ROIs) (Giel and Issa, 2013). One aspect in which BIM appears to be useful is in detecting clashes where parts of the buildings may intersect and identifying their locations prior to actual construction to avoid schedule delays and cost overruns due to requests for information (RFIs) and change orders (COs).

Despite the surge in the use of BIM, there is little standardization in how the clash detection process is implemented (Azhar, 2011). There is in particular no standard method for conducting clash analysis using BIM and determining the ROI of the process. This is despite contractors identifying this lack of standardized method as the greatest factor affecting BIM benefits (McGraw-Hill Construction, 2012). There are also issues with the validity of the methods used to conduct clash analysis using BIM and determining its ROI.

The overall goal of the research was to develop and validate a methodology based on the use of failure mode and effects analysis (FMEA) that enabled contractors to conduct clash detection analysis using BIM. The methodology should also enable them to evaluate the impact of doing so on the constructability of commercial construction projects and the ROI to contractors. The research investigated whether:

- FMEA provided an appropriate methodology for the classification, management and analysis of clash detection results in commercial construction projects.
- BIM's implementation in clash detection analysis improved the constructability of commercial projects during the construction phase, resulting in a decreased volume of RFIs and COs issued at this phase.
- BIM's implementation in clash detection analysis resulted in a positive ROI to contractors.

The research validated the methodology by applying it to a real-life case study of a \$9.5M four-storey commercial building. The methodology involved implementing BIM to conduct clash detection on this project and using FMEA to determine the impact of the BIM clash detection process on the volume of RFIs and COs issued during construction, and resulting costs and cost savings.

2. LITERATURE REVIEW

A thorough literature search was conducted to review the use of building information modelling (BIM) in the construction industry and the resulting ROI to contractors. The review also aimed to provide an overview of the history, strengths and use of the technique of failure mode and effects analysis (FMEA) in the construction industry.

2.1 Building Information Modelling

The most comprehensive and cited BIM study in construction is the one by McGraw-Hill Construction (2012). Several other studies investigated specific BIM applications in construction. Farnsworth et al. (2014) studied the frequency and benefits of BIM use in commercial construction. Azhar (2011) evaluated current trends, benefits, and risks related to contractors' adoption of BIM. Hanna et al. (2013) evaluated the use of BIM by electrical and mechanical contractors. Several reports and studies, such as the National BIM Survey International BIM Report (2013) benchmarked the adoption of BIM across various countries. Costa and Grilo (2015) as well as Grilo and Jardim-Goncalves (2011) investigated the use of BIM to support the construction e-procurement process and improve stakeholder collaboration.

In the McGraw-Hill Construction (2012) study, contractors found BIM to be most useful for constructability analysis and jobsite planning and logistics. Eastman et al. (2011) perceived BIM to be most useful for 1) constructability analysis and clash detection, 2) quantity takeoff and cost estimating, 3) construction analysis and planning, 4) integration with cost and schedule control and other management functions, 5) offsite fabrication, 6) guidance and tracking of construction activities, and 7) handover and commissioning. In Farnsworth et al. (2014), BIM was found to improve communication, scheduling, coordination, visualization, and clash detection. Costa and Grilo (2015) found BIM-based e-procurement to reduce the time and effort involved in information management activities despite its high cost and steep learning curve. Grilo and Jardim-Goncalves's (2011) BIM-based, e-procurement framework was shown to overcome many technological barriers associated with e-procurement. Nevertheless, BIM required significant changes to the workflow and project delivery processes (Hardin, 2009). Contractors identified the lack of clearly defined deliverables and processes as the greatest barrier to taking full advantage of it (McGraw-Hill Construction, 2012).

A review of the literature shows no industry-accepted method for determining building information modelling's (BIM) return on investment (ROI). Many of the studies computing ROIs did not provide enough information about their data collection and analysis methods (Lee et al., 2012). Many typically determined ROIs based on "perceived returns" which often included cost savings that would have been incurred without using BIM. Furthermore, they used the volume of RFIs as an indicator of savings which may not be an adequate assumption given that the number of RFI's on a given project can vary greatly depending on the project's characteristics. Thus, fewer RFIs do not necessarily translate to a project with a higher ROI. They also considered cost savings to be the total value of all COs regardless of the portion of these costs that would have still been incurred had BIM been used.

McGraw-Hill Construction (2012) surveyed BIM users in the industry who admitted to not having a standard method for measuring their own ROIs. Only 5% of respondents perceived their own ROIs to be greater than 100%, with the majority believing them to be less than that. Azhar (2011) estimated the ROI for ten projects to range between 140 to 39,900%. The study used the clash detection results to estimate cost savings in labour and materials should each clash have been detected prior to construction.

Lee et al.'s (2012) method for calculating the ROI of BIM implementation was based on savings from design errors that would have been uncovered using BIM only and not using traditional drawing-based methods. This method, when applied to a $583M urban rehabilitation project in Seoul, Korea, resulted in project savings of $1,455,325 and a ROI of 64%. Had all design errors been taken into account, including those detected using traditional methods, they would have resulted in savings of $3,862,260 and a ROI of 335% for the same project. These results show how different methods can lead to drastically different results, reinforcing the need to standardize existing ROI calculation methods.

Another study by Giel and Issa (2013) found that BIM implementation during the planning and preconstruction phases led to ROIs between 16 and 1,654%. The study based its calculation of ROI on the cost of issues within the projects' RFIs, and the proportion of the cost of COs and schedule delays that could have been avoided using BIM. It estimated that the projects' RFIs and COs would have decreased by 34 to 68% and 37 to 48% respectively using BIM for the six projects investigated in the study. The study also considered indirect costs caused by delays associated with preventable RFIs and COs, including consultant fees, general conditions, administration fees and interest charges.

Barlish & Sullivan (2012) did not calculate ROIs but identified metrics that can be used to measure BIM benefits, dividing them into return metrics and investment metrics. Return metrics consider the quantity of RFIs, the cost value of COs and schedule variations whereas investment metrics consider design and construction costs including the cost of implementing BIM. The study applied these metrics to a total five projects and reported an average 42% reduction in the cost COs, 50% reduction in RFIs and 5% reduction in overall project cost following BIM implementation. The study also found a 31% increase in design costs because of architectural and engineering costs, a 34% increase in design cost due to 3D modelling and a 5% reduction in construction costs.

Clash detection is a parametric modeling tool that analyzes the proximity of physical objects in a model. Hard clashes involve two objects overlapping and occupying the same space. Soft clashes occur when the distance between two objects is less than recommended (Eastman et al. 2011). Clash detection can be accomplished using stand-alone BIM software, such as Autodesk Navisworks or Solibri Model Checker. This software allows for the integration of multiple models or file types and contains advanced tools for clash detection, animation and scheduling. The functionality and effectiveness of this software has been reviewed extensively in the literature (e.g. Lee et al., 2015; Liu and Issa, 2014).

Leite et. al. (2011) investigated the impact of the model Level of Development (LOD) on clash detection results. The study noted that the chosen LOD should reflect the purpose of the model, that more detailed modelling does not necessarily mean more modeling work and that more detailed modelling can lead to improved accuracy and improved decision-making. Leite et al. (2011) also highlighted the need to filter irrelevant clashes when investigating clash detection results.

2.2 Failure Mode and Effects Analysis

Failure mode and effects analysis (FMEA) is a step-by-step quality control technique that requires the knowledge of experts in the field for them to be able to identify potential risks in a product or process; rank them in order of priority; and reduce their probability of occurrence (Yu and Lee, 2012). The technique determines the risks of greatest concern and that need pre-emptive action through the generation of a risk priority number (RPN) for each risk (Yu and Lee, 2012).

The technique was first conceived in the 1940s by the United States Armed Forces Military and developed further by the aerospace and automotive industries (Tague, 2005). Even though it was originally developed for industrial purposes, it has been used in a variety of other contexts (Palady, 1995; Patricio et al., 2013). Nevertheless, its basic terminology remains the same.

The strengths of FMEA lie in its robust quantitative risk evaluation approach that define the severity of a risk's effects, its probability of occurrence and the detectability of its controls. FMEA considers both quantitative and qualitative inputs, in the form of engineering calculations and experts' feedback respectively (Afshari et al. 2013). The technique can also be used to evaluate a pre-existing list of failures, making it ideal for evaluating risks uncovered using the building information modelling (BIM) clash detection process.

Limitations of FMEA include the subjectivity involved with defining and rating the severity of a risk's effects, its probability of occurrence and the detectability of its controls (Yu and Lee, 2012). They also include the assumption that these three parameters have equal importance and that different combinations of them may produce the same RPN value even though they may have very different implications, causes and controls (Pillay and Wang, 2003).

The use of FMEA in the construction industry remains limited. A review of the literature shows how Layzell and Ledbetter (1998) adopted FMEA to anticipate issues that may occur with cladding systems. Rhee and Ishii (2003) used it to select design alternatives. Carbone and Tippett (2004) adopted it to evaluate project risks; whereas Kim and Kim (2007) implemented it to identify cost-increasing factors in skyscraper construction. Yu et al. (2008) used it to assess safety risk factors on a construction site.

3. RESEARCH METHODOLOGY

This section describes the methodology used for this research and depicted in Fig. 1. It includes a description of the case study and of the clash detection and FMEA processes used as part of it. The section also explains the methods used to compile and analyze the collected construction data, and compare the results stemming from the FMEA process to the ones derived from the analysis of the construction data. The section finally describes the method used to calculate the return on investment (ROI) for the case study.

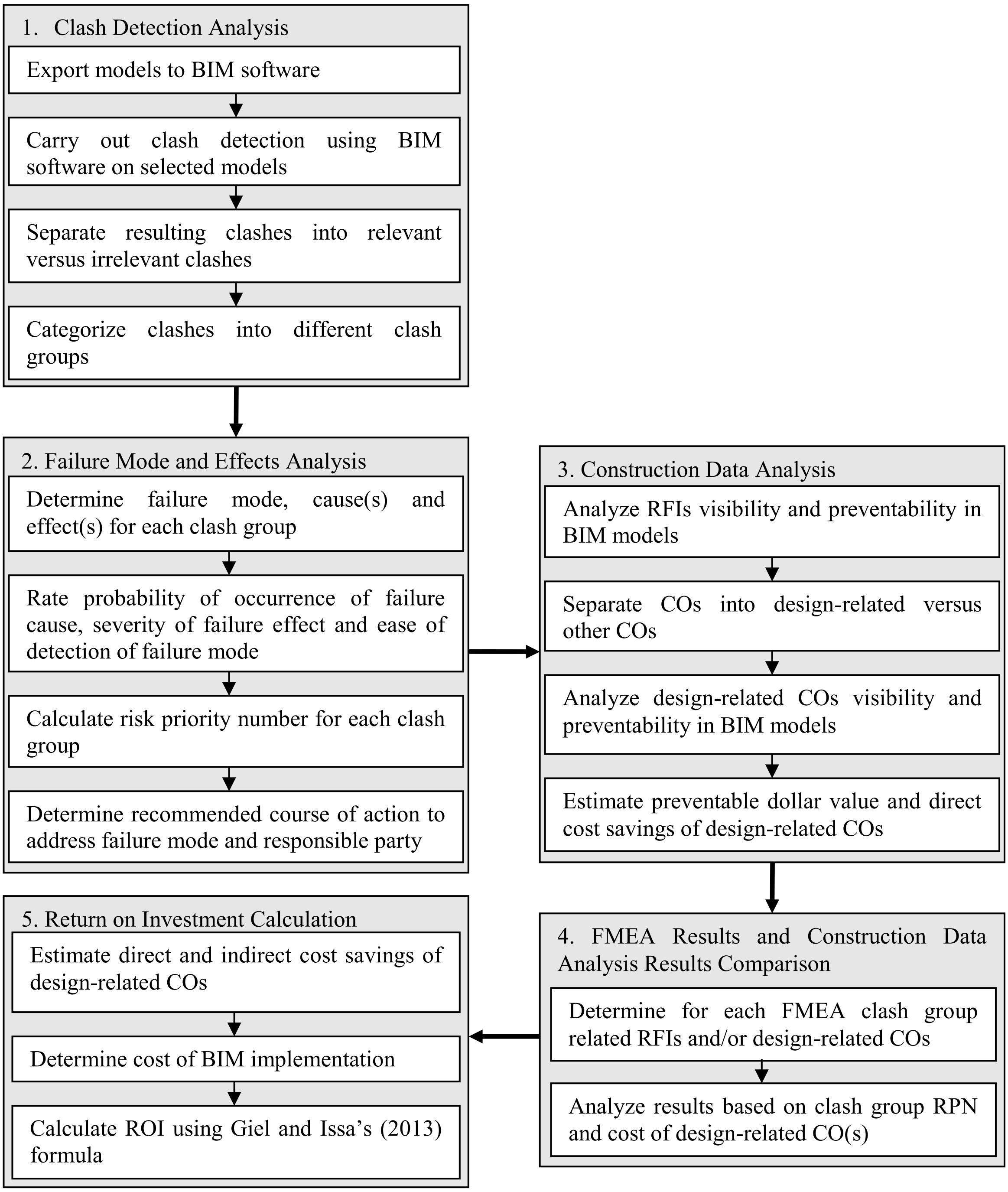

Fig. 1: Research Methodology

3.1 Project Case Study

The project involved the construction of a new 36,000 ft^2, four-storey commercial structure that included both retail and commercial office space in Manitoba. The structure included concrete grade beam on pile foundations, and is composed primarily of structural steel framing and concrete topping on metal deck. The contract used a construction management approach, and although the architectural model, structural model and combined mechanical and electrical model were conducted using the BIM software: Autodesk Revit, the contractor did not have access to them during construction. The architectural and structural models were developed to LOD 300;

however, the majority of the combined mechanical and electrical model was only at LOD 200. All final drafting and construction on site drawings used traditional two-dimensional drawings.

3.2 Clash Detection Process

The methodology involved collecting three model files of type ".rvt" (Autodesk Revit) for the three models from the architect and mechanical and electrical engineering consultant. The models were accessed using Autodesk Navisworks Manage 2013 software, and appended to a common Navisworks File Set (.nwf), so that they could be viewed and analyzed as a combined building model. Clash detection was carried out using Navisworks' built-in Clash Detective utility. Three separate clash tests were conducted: 1) Architectural Model versus Structural Model (AS), 2) Architectural Model versus Mechanical/Electrical Model, (AME) and 3) Structural Model versus Mechanical and Electrical Model (SME)

The software was set to detect only hard clashes, with a tolerance of 1mm. The three tests resulted in a total of 5,029 individual clashes. The data available for each clash included its location (i.e. level and gridlines), the item name for the two clashing components, and the "clash distance", indicating the maximum length of the overlap occurring between the two clashing components. For each clash test, a first-pass visual evaluation of each individual clash was conducted to separate irrelevant clashes (i.e. clashes that were only expected to occur because of the model LOD and are not real) from relevant ones (i.e. real physical clashes that may require follow-up action). The analysis involved grouping clashes representing the same modelling error in multiple locations, clashes in the same location, or clashes caused by a common irregularity.

3.3 Failure Mode and Effects Analysis

This research adopted the perspective of the contractor when detecting and evaluating clashes and recommending corrective actions to resolve them. A standardized Microsoft Excel spreadsheet, referred to as the "Failure Mode and Effects Analysis (FMEA) Control Sheet" was developed to report, track and evaluate clashes. Each clash group resulting from the clash detection process was assigned a reference number and entered as a line item within the control sheet. Reference numbers were coded according to the models included in the clash test. For example, clash groups from the architectural model versus structural model test were assigned reference numbers beginning with letters AS, whereas clashes from the architectural model versus mechanical and electrical model test were assigned reference numbers beginning with letters AME. The following information was also recorded for each clash group: the models and components involved, a general description of it, and the number of individual clashes within it.

The research involved reviewing each clash group to determine the specific failure mode that each group represented and its effects, and determine the severity of these effects, focusing on cost and schedule effects in particular. It also entailed rating the probability of occurrence of the failure mode due to the identified failure cause, and the likelihood that the complications would be detected using typical project control methods. The risk priority number (RPN) used to rank failure modes was then calculated for each clash group by multiplying the severity, occurrence and detection ratings. Finally, the likely course of action to be implemented to resolve any complications and the party responsible for implementing it were determined for each clash group whenever possible. Table 1 includes the descriptions and definitions adopted in this research for the three different ratings.

Table 1: FMEA severity, probability of occurrence and detection ratings

Rating	Description	Definition
		Severity
9	Extremely high	Failure impact could be greater than the entire contingency.
7	High	Failure impact could be greater than 50% of the contingency.
5	Low	Failure impact could be 15% of the contingency.
3	Minor	Failure impact could be 5% of the contingency.
1	None	Failure should not impact the contingency.
		Probability of Occurrence
9	High	Failure mode will inevitably occur unless design is altered
7	Moderate	Failure mode will likely occur unless design is altered
5	Occasional	Failure mode may occur unless design is altered
3	Remote	Failure mode will occur in isolated incidents unless design is altered
1	Unlikely	Failure mode will not occur except under exceptional circumstances
		Detection
9	None	Failure Mode cannot be detected.
7	Low	Failure Mode cannot be detected using construction documents or visually but can be uncovered through a detailed review by experienced staff.
5	Moderate	Failure Mode can be inferred from construction documents or visually and can be uncovered through a detailed review by experienced staff.
3	Good	Failure mode is apparent on construction documents or visually and can be uncovered based on a detailed review by moderately experienced staff.
1	High	Failure Mode is apparent on construction documents or visually and can be uncovered based on a cursory review by inexperienced staff.

3.4 Construction Data Analysis Method

Construction records for the case study project were made available by the general contractor. The data included detailed summaries of the project requests for information (RFIs), proposed changes, and approved change orders (COs).

The 105 project RFIs were reviewed to determine their preventability had the contractor had access to the BIM models. Every RFI was deemed preventable if it was visible and verifiable within the models. A preliminary review of the 136 project COs revealed that many were not a result of design issues or related to the BIM models. All COs were divided into the following groups:

- Physical design issues: representing changes relating to design errors or omissions that should have been included in the building information models.
- Specification revisions: representing changes relating to project specifications and that are not related to the building information models.
- Unforeseen site conditions: representing changes due to unforeseen conditions such as subsurface obstructions.
- Accounting changes: representing changes due to the reassignment of costs from the contractor to the owner or the refund of contingency and cash allowances.
- Owner discretionary changes: representing owner-initiated changes to increase or reduce project scope and that are not a result of design errors or omissions.

Only physical design issues were within the scope of BIM, therefore only COs falling in this group were analyzed further to determine whether they were visible in the BIM models and flagged during the clash detection process. If so, they were assumed to be preventable. If the complication associated with a CO scope was visible in the models but not flagged during clash detection, then it was assumed that the CO may have been prevented. The probability of preventing it was based on how visible the CO complication was in the BIM model. A review of these COs showed that one out of four would have likely been captured through visual inspection; therefore, a prevention rate of 25% was taken into account when estimating the direct cost savings stemming from preventing these COs.

3.5 Comparison of Failure Mode and Effects Analysis Results and Construction Data Analysis Results

The complete FMEA control sheet was compared to the results from the analysis of construction-related RFIs and COs. This was to evaluate the effectiveness of the FMEA process at predicting actual constructability issues and their impacts, and thus the effectiveness of FMEA as a leading indicator of constructability.

For each clash group item listed in the FMEA Control Sheet, the RFI and CO logs were reviewed to identify related, corresponding RFIs and COs. A summary table was prepared, listing every FMEA clash group item with their RPN, together with their related RFI and CO and the cost impacts of the corresponding change. These clash groups' RPNs were then analyzed further to determine their reliability at predicting the cost impacts of the related COs.

3.6 Return on Investment Calculation Method

The research used the method by Giel and Issa (2013) and filters by Lee et al. (2012) to calculate the ROI for the study. This method was selected due to its comprehensive consideration of both the direct savings associated with prevented rework and the indirect savings associated with additional design work, construction schedule extension, and financing interest charges. The formula used to calculate the ROI is:

$$\mathrm{ROI} = \frac{(\text{Direct Savings} + \text{Indirect Savings}) - \text{Cost of BIM}}{\text{Cost of BIM}} \times 100$$

Direct Savings included only cost savings related to preventable COs. These were estimated on a case by case basis using the actual description and detailed cost breakdown for each CO.

Indirect Savings included costs associated with:

- Consultant fees: calculated as 8% of direct costs, except on COs, where a minimum charge management cost of \$300 applied to each change (The Royal Architectural Institute of Canada, 2009). The above percentage and fee assume that each CO will require a minimum of 3 hours to administer regardless of cost. The formula used to calculate consultant fees is:

$$\text{Consultant Fees} = \text{Direct Costs} \times 8\% + (\text{Number of Changes Under } \$3750 \times \text{Minimum Charge})$$

- General conditions costs (GCC): these were incurred by the contractor and derived from the project data. They were approximately \$30,000 per month, assuming 21 working days per month. An extra 3 days on average were assumed to be lost and thus added to the project schedule to implement the preventable COs. The GCC for that time lost is calculated as follows:

$$\text{GCC for Days Added} = \text{Monthly GCC} \times \frac{\text{Number of Days Added}}{21 \text{ Working Days per Month}}$$

- Administration fees and interest charges (AFIC): construction projects are typically paid for by short-term loans that are replaced by a long-term mortgage once construction is complete. A 4.5% financing interest rate was assumed for this project (Canadian Mortgage and Housing Corporation, 2015). Because changes can occur at any stage during the project, the interest is assumed to be incurred over 50% of the project duration on average, which in this case is 9 months. Therefore, the calculation is as follows:

$$\mathrm{AFIC} = \text{Direct Costs} \times \frac{\text{Interest Rate}}{12 \text{ months}} \times (\text{Project Duration } \times 50\%)$$

The Cost of BIM included:

- Staff Salaries: a total of 7 working days or 56 hours at an hourly rate of $90 was assumed for the case study clash detection and failure mode and effects analysis (FMEA) processes. The calculation of staff salaries is:

$$\text{Staff Salaries} = \text{Hourly Rate for BIM Personnel} \times \text{Number of Hours Spent on Clash Detection and FMEA}$$

- Software and hardware costs (SHC): including the annualized cost of the software (up-front cost of $11,500 annualized over 10 years), software subscription (annual cost of $2,400), and additional hardware upgrades required to run one seat of the software ($800 annualized over 5-year life of computer system). It was assumed that the BIM software was used on four projects per year, with the annual cost shared equally between these four projects. Thus, the formula for calculating these costs will be:

$$SHC = \frac{\text{Annual Software Cost} + \text{Annual Software Subscription Costs} + \text{Annual Hardware Costs}}{\text{Number of Projects Using Software Annually}}$$

- Training and database setup costs (TDSC): The research assumed 2 working days or 16 hours approximately to train a project team member to use Navisworks for clash detection and set up the project database and analysis methodology at an hourly rate of $90. Since Navisworks training courses are typically offered as one day courses, the research assumed a day spent on software training and another on setting up the database and methodology. Therefore, these costs are:

$$TDSC = Hourly\ Rate\ for\ BIM\ Personnel \times Training\ \&\ Setup\ Hours$$

4. RESULTS & DISCUSSION

This section presents the results of the clash detection analysis, the FMEA, and the construction data analysis. A comparison is then conducted between the FMEA results and the construction data analysis results before the ROI for the case study is finally calculated.

4.1 Clash Detection

Tables 2, 3 and 4 summarize the clash groups resulting from the clash detection analysis between the architectural and structural models (AS); the architectural, and mechanical and electrical models (AME); and the structural, and mechanical and electrical models (SME) respectively. Every table shows the clashing components for each clash group, a description of the clashes within that group and the number of detected clashes within it.

None of the clashes between the architectural and structural models in Table 2 were considered relevant as they related to floor and wall penetrations, or structural members embedded in walls. Such clashes were expected within the models' LOD.

Table 2: Architectural versus structural clash summary

Group	Clashing Components		Description	Instances
AS1	Horizontal Framing or Floor Component	Vertical Framing or Wall Component	Floor and wall penetrations by structural members	2227
AS2	Wall Component	Structural Framing	Structural framing element running within a wall	503
AS3	Miscellaneous Specialty Item	Structural Framing	Bathroom accessories interfering with structural framing	2

The majority of the clashes between the architectural, and mechanical and electrical models in Table 3 were also irrelevant, as they related to floor and wall penetrations or embedded items. However, there were also relevant clashes between mechanical and electrical items and the 400 level and 200 level ceilings.

Table 3: Architectural versus mechanical and electrical clash summary

Group	Clashing Components		Description	Instances
AME1	Horizontal Framing or Mechanical/ Electrical Item	Vertical Framing or Mechanical/Electrical Item	Floor and wall penetrations by mechanical/electrical pipes and conduits.	1722
AME2	Wall Component	Mechanical Pipe or Electrical Device	Mechanical pipes or electrical receptacles/devices embedded within a wall	159
AME3	Light Fixture	Wall	Light fixtures penetrate walls	16
AME4	Mechanical/Electrical Component	400 Level Ceiling	Ductwork, heat pumps, lighting, and cable trays interfering with 400 Level ceiling	39
AME5	Mechanical/Electrical Component	200 Level Ceiling	Ductwork, lighting, and cable trays interfering with 200 Level ceiling	15

Table 4 shows that many of the clashes between the structural, and mechanical and electrical models occurred because of piping and conduit passing through structural beams, and mechanical and electrical components penetrating structural floors. These clashes were irrelevant and only occurred because of the model's low LOD. Other clashes such as duct sections interfering with structural slabs, and radiators interfering with cross-bracing were real, relevant ones.

Table 4: Structural versus mechanical and electrical clash summary

Group	Clashing Components		Description	Instances
SME1	Structural Beam	Pipe, Conduit or Ductwork	Mechanical/electrical components routed through steel beams	193
SME2	Structural Floor or Wall	Mechanical/Electrical Component	Structural floor and wall penetrations by mechanical/electrical pipes and conduits.	100
SME3	Vault Ceiling - Structural Slab	Mechanical Component	Multiple horizontal duct sections interfering with structural ceiling slab.	35
SME4	Structural Cross – Bracing	Radiators	Radiators interfere with structural cross-bracing at window locations	7
SME5	300 Level Floor Structure	Mechanical/Electrical Component	Multiple horizontal duct sections interfering with structural floor.	11

4.2 Failure Mode and Effects Analysis

The research involved assessing each clash group using FMEA, resulting in the FMEA Control Sheet. Given the size of the sheet, only a sample of it showing two of the thirteen clash groups is depicted in Fig. 2.

Among the thirteen clash groups, five (AS1, AS2, AME1, AME2, and SME2) had very low risk priority numbers (RPNs) (i.e. below ten). These represented clashes caused by penetrations through walls and floors. These clashes were irrelevant and only occurred because of software limitations and the models' low level of development (LOD). The software does not recognize the void space between studs in a wall where the pipes or columns are located and considers walls as solid elements, leading to many of these irrelevant clashes. The model LOD also makes it difficult to model each individual floor and wall penetration. As such, no corrective action is required for these clashes.

Ref	Models	Components 1	Components 2	Description	Instances
AS1	Architectural / Structural	Horizontal Framing or Floor Component	Vertical Framing or Wall Component	Floor and wall penetrations by structural members	2227
AS2	Architectural / Structural	Wall Component	Structural Framing	Structural framing element running within a wall	503

Ref	Failure Mode(s)	Effects of Failure	Severity Cost	Severity Schedule	Severity Average
AS1	Interference	Coordination of openings required	1	1	1
AS2	Interference	None	1	1	1

Ref	Cause(s) of Failure	Probability Rating	Detection Rating	RPN	Solution Assigned to	Recommended Solution
AS1	Openings for penetrations through floors and walls were not modeled	2	3	6	No Solution Required	Monitor penetrations requiring coordination between trades
AS2	Software limitation (items must occupy same space but are not recognized as acceptable during clash detection)	1	1	1	No Solution Required	N/A

Fig. 2: Sample of FMEA control sheet

Two groups (AS3 and SME1) had relatively low RPNs (15 and 13.5 respectively). These involved clashes between a bathroom accessory and a structural member, and between mechanical piping and structural beams. These clashes can be easily resolved through a cursory review that would ensure that the bathroom accessory is shifted slightly, that piping penetrates beams where necessary and that bulkheads are provided.

Clash group SME4 had an intermediate level RPN of 42. This group included instances of radiators interfering with exposed structural cross-bracing. A review is necessary to confirm if the radiators can remain at these locations with a revised offset, or if they need to be relocated.

Three groups (AME4, AME5 and SME5) had a high RPN of 87.5. These groups included many clashes between heating, ventilation and air conditioning components, and ceilings on the 200 and 400 levels; and between heating, ventilation and air conditioning components and the 300 level structural floor. They require a detailed review by both the architect and mechanical designer to determine whether the ducts should be resized or relocated or whether the ceiling height should be adjusted.

Clash group AME3 had an RPN of 98. This included instances of light fixtures interfering with walls. A review by the electrical engineer is required to determine the correct location and orientation of each fixture.

Clash group SME3 had the highest RPN at 100. This involved clashes between multiple horizontal duct sections and a concrete ceiling for a bank vault. The mechanical design did not appear to recognize that the isolated concrete structure existed. A review by the mechanical consultant is needed to determine the correct duct location and ceiling height.

Overall, RPN values were low in comparison to the maximum possible score of 1,000. The severity ratings did not exceed 2.5 for any of the groups, indicating no significant threats to the budget and schedule. The architectural and structural models were relatively well coordinated, and showed no significant clashes. Of the five highest ranked clash groups, four involved heating, ventilation and air conditioning components, and one involved lighting, reflecting less coordination between the mechanical and electrical models.

4.3 Construction Data Analysis

The section shows the results of the analysis of the project's construction data focusing on its requests for information (RFIs) and change orders (COs).

4.3.1 Requests for Information

As shown in Table 5, approximately 16% of all RFIs addressed issues that were visible in the models. Only 5% of them could have been prevented through the use of building information modelling (BIM).

Table 5: RFI analysis results

Classification	Number of RFIs
Visible in models and preventable using BIM	5
Visible in models but not preventable using BIM	12
Not visible in models and not preventable using BIM	88
Total	105

Three of the five fully preventable RFIs enquired about various dimensions and elevations. These were caused by drafting errors that led to missing or incomplete dimensions. In each case, the BIM models showed the correct dimensions. The remaining preventable RFIs addressed ceiling height issues causing interferences at various locations. These were visible in the BIM models and could have also been resolved prior to construction.

The twelve RFIs that had visible issues in the models but were not fully preventable were primarily design issues, with components present in the models but not detailed to the extent that would make the issues apparent visually or through clash detection. Further, these items required consultant-directed changes and therefore would have resulted in a RFI regardless. A detailed review of them showed that four of them could have been addressed in the design phase using BIM rather than during construction.

4.3.2 Change Orders

The case study project recorded a total of 136 change orders (COs), equalling \$516,355. Forty-five (33%) of them were design related, with their value accounting for only 21% of all COs' value. Fig. 3 depicts the distribution of these changes by dollar value. Three of the 45 design-related COs (7%) were detected using BIM and had a total value of \$11,588. An additional 4 (9%) were visible in the models but did not result in clashes. Seven (15%) should have been visible in the models based on the models' LODs but were not because of inconsistencies and omissions within them. The remaining 31 (69%) were not visible within the models' LOD. Fig. 4 shows the distribution of design-related COs by dollar value.

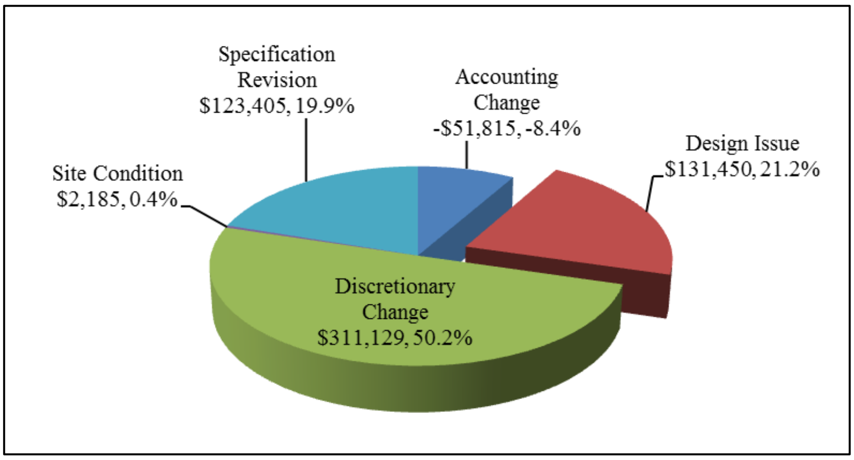

Fig. 3: Distribution of Total COs by Dollar Value

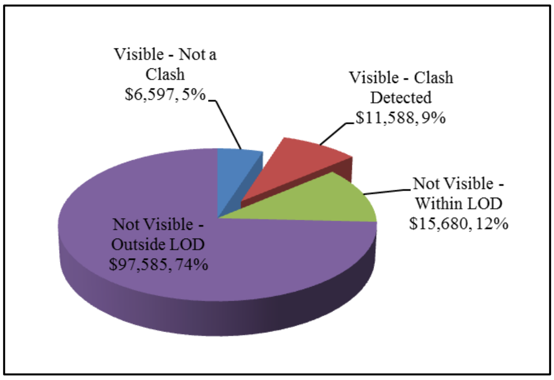

Fig. 4: Distribution of Design-Related COs by Dollar Value

A detailed review of the three preventable COs showed that they revolved primarily around interferences between the 400 level ceiling and mechanical items or windows. The majority of these issues could have been prevented through earlier coordination of the mechanical layout and the architectural plans; however, approximately 25% of the bulkheads required for them may have still been required under the original bid to optimize the mechanical equipment and window arrangement. This is equivalent to approximately $2,500 of steel stud and drywall work that could have not been prevented. This makes the overall preventable value of these three COs $11,588 and thus their estimated direct savings $9,088.

The four COs with issues that were visible in the models but did not result in clashes were also reviewed. Two of them, accounting for 48% of their total value, were the result of relocating walls and ceilings to accommodate design revisions. These included significant rework and very little added scope; therefore, 100% of their cost was considered preventable. The remaining two COs included added steel stud and gypsum board scope because of the furring out of walls to accommodate mechanical items. In both cases, the walls being furred out had already been constructed. Nevertheless, it would have been more cost efficient to construct a single thicker wall rather than construct the original wall and an additional furring wall. As such, the cost of the furring walls, estimated at 50% of the cost of these changes could have been prevented, making the overall preventable value of these four COs $4,882 and thus their estimated direct savings $1,221 assuming a prevention rate of 25%.

Table 6 provides a summary of the COs' actual values, preventable values and direct cost savings. Approximately, 77% of the COs' total value was considered preventable, amounting to direct savings from implementing BIM of $10,309 or 57% of the COs' total value. These savings were equivalent to only 0.1% of total project costs.

Table 6: Actual dollar values, preventable dollar values and direct cost savings of preventable COs

Method of Prevention	COs	Actual Value	Preventable Value	Prevention Rate	Direct Savings
Clash Detection	3	$11,588	$9,088	100%	$9,088
Visual Inspection	4	$6,597	$4,882	25%	$1,221
Total	7	$18,185	$13,970	-	$10,309

The seven COs related to items that were not modeled, but should have been based on the models' LOD, were also investigated in detail. Of them, only one would have been discovered by clash detection, while the others would have required visual inspection. The potential savings from preventing these COs was not considered, as the case study was limited to the actual models produced by the design team.

4.4 Comparison of FMEA Results and Construction Data Analysis Results

Table 7 presents the failure mode and effects analysis (FMEA) clash group entries, ranked according to their risk priority numbers (RPNs), with the corresponding, relevant request for information (RFI) and change order (CO), and cost impact. In general, the table shows a relationship between the FMEA results and constructability data. None of the irrelevant clash groups led to any RFI or CO. Four of the thirteen clash groups led to five RFIs, whereas one clash group resulted in all three preventable COs. All seven clash groups with RPNs of 15 or lower did not lead to any RFIs or COs whereas three of the five clash groups with RPNs of 87.5 or higher resulted in four RFIs and three COs. This demonstrates the clash detection and FMEA processes' ability to predict clashes that may lead to significant constructability issues during construction. In the case of clash groups AME3 and SME5, it appears that the significant clashes with those two groups were detected using conventional methods and resolved prior to construction, which explains why they did not result in any RFI or CO.

Table 7 - FMEA versus construction data analysis results comparison

REF #	DESCRIPTION	CAUSE(S) OF FAILURE	RISK PRIORITY NUMBER	RFIs	CHANGE ORDERS	
					QTY	COST
SME3	Multiple horizontal duct sections interfering with structural ceiling slab.	Ductwork height did not account for 200mm thick concrete ceiling above bank vault.	100	1	0	$0
AME3	Light fixtures penetrate walls	Light fixtures are incorrectly located or oriented	98	0	0	$0
AME4	Ductwork, heat pumps, lighting, and cable trays interfering with 400 Level ceiling	Ceiling height did not account for exact dimensions of HVAC components above, or HVAC components oversized	87.5	2	3	$11,588
AME5	Ductwork, lighting, and cable trays interfering with 200 Level ceiling	Ceiling height did not account for light fixture height or exact dimensions of HVAC components above, or lights	87.5	1	0	$0
SME5	Multiple horizontal duct sections interfering with structural floor.	Ductwork elevation not coordinated with slab elevation and thickness.	87.5	0	0	$0
SME4	Radiators interfere with structural cross-bracing at window locations	Radiator offset from wall did not account for exposed cross-bracing	42	1	0	$0
AS3	Bathroom accessories interfering with structural framing	Specialty item's location did not account for cross-bracing in wall	15	0	0	$0
SME1	Mechanical/electrical components routed through steel beams	Mechanical/electrical components not detailed to avoid beams, or penetrations through beam not detailed	13.5	0	0	$0
AS1	Floor and wall penetrations by structural members	Openings for penetrations through floors and walls were not modeled	6	0	0	$0
AME1	Floor and wall penetrations by mechanical/electrical pipes and conduits.	Openings for penetrations through floors and walls were not modeled	6	0	0	$0
AME2	Mechanical pipes or electrical receptacles/devices embedded within a wall	Software limitation (items must occupy same space but are not recognized as acceptable during clash detection)	6	0	0	$0
SME2	Structural floor and wall penetrations by mechanical/electrical pipes and conduits.	Openings for penetrations through floors and walls were not modeled	6	0	0	$0
AS2	Structural framing element running within a wall	Software limitation (items must occupy same space but are not recognized as acceptable during clash detection)	1	0	0	$0

4.5 Return on Investment

As shown in Table 6, preventable COs would have provided direct cost savings of $10,309 to the project. Indirect savings are calculated assuming that four COs were prevented: three from clash detection and one from visual inspection. Given that the total value of these four COs was $11,588 and that three of those four COs were lower than $3,750, estimated consultant fee savings amounted to $1,785. GCC savings equalled $4,286, whereas AFIC savings totalled $348 assuming direct cost savings of $10,309 for the project.

The cost of implementing building information modelling (BIM) includes the cost of staff of $5,040, software and hardware costs of $900 and training and database setup costs of $1,440, bringing the total cost to $7,380. These values amounted to a return on investment (ROI) of 127%, making it a worthwhile methodology to undertake despite its cost savings representing only 0.1% of total project costs.

This ROI was derived almost exclusively from preventing one design issue: the improper coordination of ceiling heights with mechanical items and windows, which resulted in three COs totalling $11,588. The largest of these changes, with a value of $11,060, was in fact the second most expensive CO of the 45 design-related COs. These results demonstrate how dependant high ROI values are on catching costly changes. Because the clash detection process did not prevent a significant volume of costly COs for this specific project, the ROI was relatively small.

This ROI was very similar and in line with the values reported by BIM users in McGraw-Hill Construction (2012). No details were provided on how those BIM users calculated their ROIs though. Nevertheless, it was very different from the 16% to 1,654% range reported by Giel and Issa (2013) despite both studies using the same method for calculating ROIs. One difference is that this study did not quantify the cost of preventable RFIs unlike Giel and Issa's (2013), thus the lower value. Moreover, in looking at the six projects investigated by Giel and Issa (2013), three of those had ROI values between 15% and 109%. Two had ROIs of 300% and 376% because of schedule savings of 60 days because of BIM versus 3 days only for this project, thus their higher ROI values. The last project with an ROI of 1,653% included very costly COs, a significant portion of which could have been avoided due to BIM and schedule savings of 426 days, thus its very high ROI value.

This ROI was also drastically different from the ROIs reported by Azhar (2011) which ranged between 140 and 39,900%. This is not surprising given that Azhar (2011) focused on cost savings that would have been avoided had BIM clashes been detected earlier regardless of whether these clashes were detected using traditional methods or not. It did not take into account whether these clashes were avoided during actual construction or not, and whether they led to costly RFIs and COs or not, thus raising questions about the accuracy of its values. This is in contrast with Lee et al.'s (2012) ROI value of 64% which took into account whether these clashes would have been avoided using traditional methods, and thus led to values that were more conservative than Azhar (2011), and more in line with this study's.

5. CONCLUSIONS

FMEA proved to be an effective and useful platform for organizing and presenting clash data. While somewhat subjective, the initial screening and grouping of clashes was an important step that allowed thousands of individual clashes to coalesce into manageable groups. For this specific case study, it would not have been feasible or efficient to evaluate each individual clash without grouping them. Once clashes were grouped, the FMEA culminated into a control sheet that provided concise data and a prioritization scheme that would allow project teams to direct efforts to the most critical issues. This being the case, it is important to remember that the methodology was applied to a single project, making its validation dependant on that one project. Additional projects should be evaluated using the developed methodology to further test its validity and reliability.

Of the five groups with the highest RPNs, three resulted in RFIs and one in multiple COs. Generally, the issues that did not result in RFIs or COs related to items that were improperly modeled and thus could not be built the way they were modelled. These issues were addressed later in the project's 2D construction drawings and specifications before actual construction. There was a need to rely on these traditional drawings and specifications in this case given the low LOD of this project's BIM models. That is why there is a need in future projects to use BIM models with higher LODs prior to actual construction.

This research showed that the developed methodology improved the constructability of commercial projects, as evidenced by the decreased volume of RFIs and COs had BIM been used. It resulted in a positive return on investment (ROI) to contractors, leading to positive cost savings that outweighed the cost to implement it. This being the case, the real actual ROI cannot be deterministically defined as this ROI is based on estimates of costs and cost savings incurred from implementing BIM. It is also difficult to determine which of these costs and cost savings are directly related to BIM and which are not. Therefore, the real ROI may be different than these estimated values. This ROI can also vary greatly depending on the number and value of design issues that may lead to RFIs and COs and the probability of detecting them using BIM. It can also be affected by factors such as the project type, its location, the stakeholders involved, existing drawings and project specifications, existing site conditions, the level of informal communication between the contractor and consultant and the models' LODs. Other factors such as the learning curve associated with implementing BIM, the extent to which BIM is used on a particular project and the availability of actual versus estimated cost data will also impact the results. Therefore, the ROI results should be read with those limitations in mind.

This methodology also uncovered a limited number of design issues for this specific project. This number would have been greater had this methodology been applied to a larger project, increasing in turn its value as an evaluation and benchmarking tool. The low LOD of the BIM models available for the case study project, particularly for the mechanical and electrical model, also resulted in several false positive irrelevant clashes. Because of that, project stakeholders could not rely on them and relied instead on traditional, 2D construction drawings, thus skewing the constructability and ROI analysis results and reinforcing the need to use BIM models with a LOD of at least 300 to avoid these issues. The lack of detail in the available documentation for the RFIs and COs, such as limited descriptions or missing references to other documents or site instructions made it difficult to assess the relationship between these RFIs and COs, and the detected clashes.

As the trend towards Integrated Project Delivery and full building information modelling (BIM) implementation (i.e. 100% modeled using BIM) continues to rise, the onus remains on general contractors to adapt to the BIM environment and improve related skills. This is in order for them to not only take advantage of what BIM has to offer, but to also add value to the project team through clash detection and design and constructability coordination. To date, early adopters of the technology have been quick to promote its successes. In order to separate marketing material from scientific data and provide credible evidence to construction stakeholders making the decision to implement BIM, existing research needs to generate consistent and validated methods for conducting clash detection analysis and determining potential ROIs. This and other research studies in the field are generating such methods and producing a body of knowledge that suggests positive ROIs from implementing BIM. Nevertheless, the size of those returns remains a subject of contention. This is because project cost savings can account for as little as 0.1% of a project's total costs as shown in this research, making it difficult at times to justify the use of BIM and of the developed methodology. Given how a number of project factors can affect the size of those cost savings, further research should determine how these factors affect these savings and the ones that are most likely to benefit from BIM use.

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