AMERICAN UNIVERSITY OF BEIRUT

MODELING THE COST OF CLASHES IN CONSTRUCTION PROJECTS USING BUILDING INFORMATION MODELING

by
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AN ABSTRACT OF THE THESIS OF

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Building Information Modeling is a new approach that is taking the construction industry by storm. Current research is not holding back on showing all the benefits of BIM when it comes to construction budgets. One of the main tools of BIM is clash detection. It is the process of identifying conflicts and constructability issues before the project reaches the construction phase. On any project, clashes are bound to happen and their causes are numerous. This research aims at modeling the cost of clashes in construction project using Building Information Modeling. It assesses how clashes affect the cost and of projects depending on whether they were detected prior or after construction. A tool is devised to generate the cost of clashes. The model is also illustrated with a real life scenario. Both the model and tool can be used by project managers in the industry as a decision making tool to manage clashes on construction projects.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

A. Introduction

Construction projects are becoming more and more complex with unconventional architecture and shortened delivery schedules. Traditional technologies are no longer able to cater for this advancement. In recent years, many technological advances have taken place paving the road for Building Information Modeling. Nowadays, 3D and 4D models can be created and the number of dimensions is expected to increase with the progression of research. The benefits of BIM are rapidly and widely being recognized. The Stanford University Center for Integrated Facilities Engineering indicated that with BIM, projects can witness up to 40% elimination of unbudgeted changes, 3% cost accuracy, up to 80% reduction in time needed to generate cost estimates, 7% reduction in schedule and high savings on budget through clash detection (Staub-French & Khanzode, 2007). Clash detection is the process of identifying conflicts and constructability issues between systems and solving them before they reach the construction site (Tommelein & Gholami, 2012). These benefits, among other drivers such as governmental policies, are increasing the number of BIM-assisted projects. Once the project is done, an analysis of the benefits of BIM ranks clash detection as the number one benefit (Ghanem & Wilson, 2011).

Prior studies have documented BIM-assisted projects and have attempted to put a number on the savings made from the identification of clashes. Some provide the return on investment using BIM and other provide a dollar value for the clashes (Giel, Issa, & Olbina, 2010). However, these numbers are speculations of what could have been the cost of those clashes, based either on previous similar site conflicts or on an analysis of cost avoidance (Azhar, 2011). They do not relate to the clash itself and its characteristics. These numbers on their own are obsolete because they do not provide any helpful insight on how to improve construction projects. Furthermore, previous literature fail to show how the numbers were derived.

This study acknowledges the before mentioned gap and attempts to derive a way to model the cost of clashes in construction projects from the detection of the clash till its resolution. It identifies the factors that directly and indirectly affect the cost of a clash. Those factors are then used to derive a tool which helps in estimating this cost. Finally, the model is illustrated on a real life example.

B. Literature Review

1. BIM and Clash Detection

The definitions of BIM are as numerous as the sources defining them. The National Building Information Model Standard Project Committee defines BIM as “a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (*The national BIM standard.*2013). BIM is hence a process that is implemented from the beginning of the project. The shared knowledge trait makes it a great tool to foster communication and coordination between all team members. It is used to improve several aspects of the project delivery such as planning, scheduling, designing and detecting clashes. As a result, more countries mandate that major construction projects be delivered using BIM. The United Kingdom is making Level 2 BIM mandatory on all publicly funded projects starting 2016, meaning that “BIM applications are used with fully integrated model collaboration” (Lester, 2014). These levels relate to the maturity level of BIM used on projects and range from Level 0 to Level 3. Level 0 represents unmanaged 2D papers used for exchange of information. Level 1 is defined as the use of managed 2D or 3D drawings to define standards and provide common project data such as data structures or formats. Level 2, as explained earlier, may include 4D and 5D schedule and cost elements to maximize collaboration (Eadie, Odeyinka, Browne, McKeown, & Yohanis, 2013) . Finally, Level 3 represents a fully integrated and collaborative process whereby BIM is used for project lifecycle management (Lester, 2014). In Australia, the government adopted a similar policy (Eadie et al., 2013). In the European Union, it has been compulsory since the beginning of 2014. Most recently, the United Arab Emirates (Dubai in particular) regulate that clash detection is to be applied on buildings over 40 floors or more that 300,000sqft as well as all government projects (Arabian Industry, 2014)

Clash detection is not a new concept; it was already done with 2D shop drawings, however the process was much more exhaustive. During coordination meetings, each trade contractor brought his 2D drawings preferably on transparent paper. At this point, not all drawings are submitted at the same level of detailing. For instance, the HVAC and piping systems may be sized but not the electrical systems. Drawings are then laid on top of each other on a light table and each element in a system was tracked to see if it violates other elements or systems (Staub-French & Khanzode, 2007). The model had to be imagined in a 3D space. Evidently, this procedure is time consuming, inefficient and suboptimal because not all clashes will be retrieved. In fact, at least half of the clashes are missed using 2D drawings for clash detection (Hartmann, 2010).

With the emergence of 3D CAD drawings, clash detection remained ineffective, but less than with 2D drawings. Even with these models, clashes still had to be retrieved manually by an Engineer. Of course, 3D models provide a better visualization of the structure than 2D models, but they still required extensive work. Clash detection could not be automated with 3D models because the latter were not parametric models, i.e. they did not recognize sold objects such as beams, columns or MEP elements. Models were 3D representations of plans and elevations and were defined by geometric shapes such as lines and circles (Azhar, Nadeem, Mok, & Leung, 2008). Hence, detection would have returned many meaningless clashes and forgone the important ones. It was not until technology could transform 3D models into parametric models that it was possible for clash detection to become automated (Lester, 2014).

Clashes arise because each trade prepares its model separately, usually based on the architect's model. Clash detection can be performed on each model in order to remove internal clashes within the same system. However, when all models are later integrated into one composite master model, conflicts are bound to exist. At this stage, clash detection is executed on the works of the "Last Designers", the team members which complete the design right before construction or at the beginning of the detailing phase (Tommelein & Gholami, 2012). The results of this process should be documented, along with their causes and solutions, in order to prevent them from happening again and allow the conflict resolution process to be more effective (Staub-French & Khanzode, 2007).

With BIM, the integration of all trade models is made easier; and with all the models combined in one place, clash detection is the most effective yet. This might help reduce clash instances because when one change is introduced to a model, all participants can be notified about it and adjust their work accordingly instead of being oblivious to the modification which make models more prone to conflicts (Ghanem & Wilson, 2011). The steps required to be able to perform clash detection are represented in Figure 1 below.

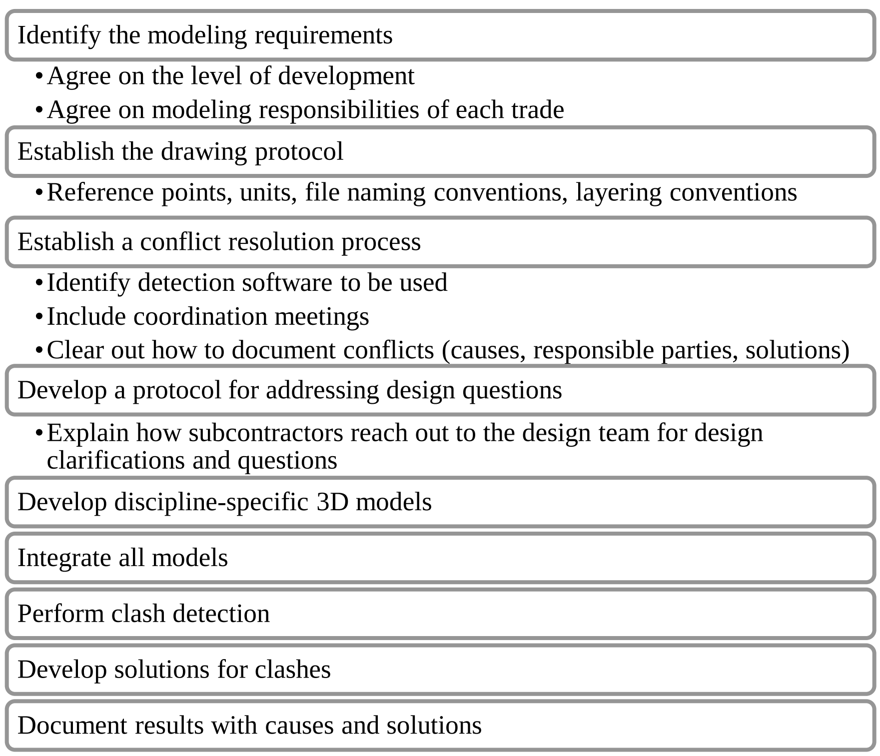

Figure 1: Steps for performing clash detection (Staub-French & Khanzode, 2007)

2. Types of clashes

There are several ways to classify a clash. For instance, some define them by the nature of their existence, others based on the impact they cause. When defined by their nature, clashes fall under three major categories. There are *hard clashes* which refer to two building elements occupying the same space and physically crashing into each other. For example, a hard clash arises when a pipe runs through a beam. Then there are *soft clashes*, also referred to as clearance clashes, which are caused by elements that require a certain buffer zone or clearance for installation, operability or safety and find this tolerance breached by other components, such as a valve who does not have enough room to be operated because they were never detected earlier with traditional clash detection. It is believed that soft clashes are one of the real opportunities that BIM has brought along. Finally, *time clashes*, or 4D clashes, are clashes pertaining to scheduling and construction sequence. They can relate to crews' work locations, material orders, temporary equipment locations and movements. For example, a time clash can be caused when a temporary lift material is not relocated before the construction of the stairs which is set to occupy the same place (*Clash detection in BIM modeling.*2012).

Some previous studies have also classified clashes based on their impact. In other words, they define them by the processes used to solve them. Gijezen et al. (2010) took the above classification a step further by defining relevant and irrelevant clashes. According to them, a clash is relevant when, if undetected, would cause a change order during the construction period, such as a ventilation system which does not fit in the false ceiling. They also acknowledge that sorting clashes into relevant and irrelevant is a cumbersome process that can be facilitated using a Work Breakdown Structure (WBS) as their research suggests.

Finally, Liete et al. (2011) also separates relevant clashes into two subcategories: true positives and false negatives. The first type refers to conflicts that were identified as clashes and were really a clash. The second type refers to real clashes that were not identified, perhaps due to errors in modeling or a low level of development. All retrieved clashes are also divided into true positives and false positives. False positives are clashes which are detected but are not really relevant. For instance, a repetition of the same clash across a different floor or different area on the same floor is considered as a false positive because it is not a new clash but a mere repetition of a previous one. Liete et al. (2011) used this classification in order to measure both the precision and recall rates of clashes. A representation of this classification is represented in Figure 3 below.

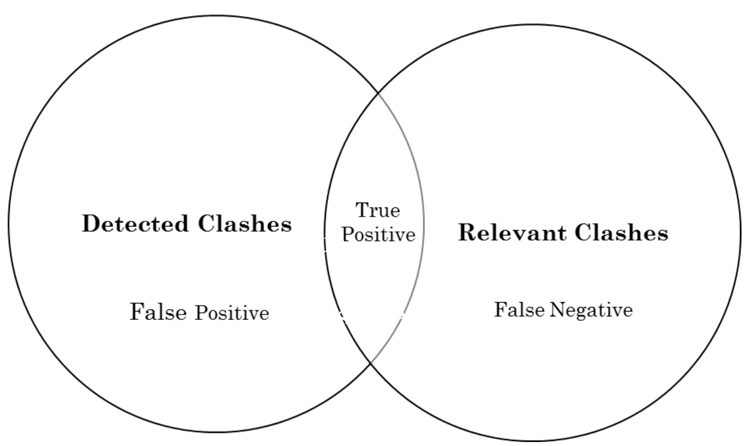

Figure 2: Venn diagram classifying clashes

3. Causes of clashes

The causes of clashes are first and foremost human errors. As long as the models are generated by employees, then they are prone to errors and the output of the process will be as good as the input. Human errors can be mistakes, slips and lapses of attentions or omissions and they are natural byproducts of the limitations of the human physiological and psychological systems (Love, Edwards, Han, & Goj, 2011).

Second, the causes of the clashes depend on their type. There are a lot of clashes that are caused because the model is at a lower level of development and hence rough dimensions or locations are used. When exact dimensions are later available, clashes are bound to happen. Other clashes show construction or operability concerns and are inserted there in order to forcefully open a conversation with the other party involved and discuss alternative designs and detailing, especially when design is too complex (Tommelein & Gholami, 2012). Time clashes are caused by errors in the sequencing of activities or in the schedules. A careful revision of the site layout and schedules can help solve them, or eliminate them from the start. Soft clashes arise from failing to model the buffer zone or clearance around an element. This lack of insertion is done either because a project is still at a low LOD, to show design intent or to preserve the tolerance required by the element (Tommelein & Gholami, 2012). Finally, the causes of hard clashes stem for the biggest part from the nature of design. Its complexity and uncertainty pave the road for hard clashes to occur. Elements can be vaguely represented (low LOD) either because exact specifications are not yet available or because they are too complex and may need to be modeled by other disciplines or trades. Another cause for hard clashes is from the lack of specified design rules, specifically those related to “how specialty systems are to be developed relative to others so as to avoid invading each other's space" (Tommelein & Gholami, 2012). This is bound to cause clashes especially in mechanical floors and service areas.

Hard clashes can also be caused by design and modeling errors, which make the input of the model faulty. On the D^3 City Project in Seoul, Korea, a $583 million urban project with several buildings including malls and offices, it was found that 83.54% of design errors result in hard clashes (Lee, Kwangho, & Won, 2012).

4. Impacts of clashes

Conflicts affect all stages of project delivery. If undetected, clashes jeopardize the cost, time and safety of projects. The most impacted criteria are schedule, change orders, RFIs and project's budget (Barlish & Sullivan, 2012). The more the clashes between trades, the more these impacts increase. On site, clashes decrease productivity because of the stop-and-go which results from solving conflicts on site and hence increasing the rework rates. On the BIM-assisted Camino Project in California, USA, productivity was almost 30% higher than estimated (Staub-French & Khanzode, 2007). Conflicts also reduce the chance of prefabrication because of the risk that prefabricated elements might not fit during construction and hence companies prefer to assemble on site to have the freedom to manoeuver around systems in case of clashes (Hartmann, 2010). Since constructability issues cannot be detected before construction, clashes impose the use of a skilled labor force on sites in order to work around the clashes once they happen and think of alternative configurations to solve them. Finally, there is a loss of opportunity to improve safety performance because at any point the work plan, logistics and work areas are subject to change once a clash happens. Needless to say, all of these construction issues are bound to delay the project and its turnover and incur extra costs (Staub-French & Khanzode, 2007).

The performance of clash detection at the end of the design phase fosters communication between cross-functional teams and provides solution for clashes before they reach the construction site. This results in the identification of design errors and prevention of negative design iterations and loops which cause a lot of waste in terms of time (Ballard, 2000).

5. Previous projects

Previous literature has documented several construction projects that have used clash detection during their design phase. The results are summarized in Table 1. For the sake of this research, the savings reported in this table are the ones resulting from the implementation of clash detection only and not from the use of all features of BIM on the project. The cost of BIM represents the head costs such as the cost of the software, training of the employees to use it, the loss of productivity at first before the learning curve picks up and the adaptation of the software to the company's needs. It may also include the cost of hiring BIM experts or outsourcing the process (Staub-French & Khanzode, 2007).

Earlier practices show that BIM in general was executed on large scope projects with huge budget and built-up area. The most important thing to note is that usually the cost of using BIM on a project amounts to a fraction of the total budget. The savings are much greater, hence, the net savings offset the cost of using BIM. As it can be seen, the results of clash detection help prevent contractors and clients from incurring extra costs that can sometimes reach millions of dollars. This result is further elaborated in Table 2.

Savings, other than on budget, include fewer requests for information, especially RFI which would result in conflicts on site, as well as a dramatic decrease in the number of change orders.

Table 1: Summary of previous projects which used clash detection

Name of the Project	**Description**	**Location**	**Project Cost**	**Cost of BIM**	**Savings from clash detection**	**References**
The Camino Medical Group	Medical building facility – 25,000sqft with a 1,400sqft parking building	California, USA	$100 Million	N/A	-69% of RFIs were for clarification -Only 2 RFIs related to field conflict issues -Zero change orders	(Staub-French & Khanzode, 2007)
The Sequus	Pilot plant facility – 20,000sqft	California, USA	$6 Million	N/A	-60% fewer RFIs than expected -Only 1 change order	(Staub-French & Khanzode, 2007)
Valley of Performing Arts Center	**Building to accommodate all types of artistic performances – 168,000sqft**	**California, USA**	**$100 Million**	**$80,000**	**-$5 Million saved from detection of 2,000 clashes** **-75% of RFIs were clarifications only**	**(Ghanem & Wilson, 2011)**

Table 1 (Cont'd)

Hilton Aquarium	Hotel and parking structure – 484,000sqft	Georgia, USA	$46 Million	$90,000	-$600,000 saved from detection of 590 clashes -1143 hours saved on schedule	(Azhar, 2011)
One Island East	Commercial building – 1,517,711sqft	Hong Kong, China	$300 Million	N/A	-over 2,000 clashes identified	(Azhar et al., 2008)
Central Los Angeles Area New Learning Center 1	Three school campuses – 685,000sqft	California, USA	$320 Million	N/A	-$4M saved from the detection of 100,000 clashes	(Kuprenas & Mock, 2009)
Healthcare Expansion Project	Expansion of a healthcare facility- 110,000sqft	North Carolina, USA	$44 Million	$44,000	-$220,000 saved from the detection of 560 clashes	(N. Lu & Korman, 2010)

In 2007, the Center for Integrated Facility Engineering at Stanford University reported the return on investment (ROI) values of 10 United States BIM-assisted projects that were done by Holder Construction (Giel et al., 2010). The results are summarized in Table 2 below.

Table 2: BIM ROI of Holder Construction (Azhar, 2011)

Year	Cost ($M)	Project	BIM Cost ($)	Direct BIM Savings ($)	Net BIM Savings	BIM ROI (%)
2005	30	Ashley Overlook	5,000	135,000	130,000	2,600
2006	54	Progressive Data Center	120,000	395,000	232,000	140
2006	47	Raleigh Marriott	4,288	500,000	495,712	11560
2006	16	GSU Library	10,000	74,120	64,120	640
2006	88	Mansion on Peachtree	1,440	15,000	6,850	940
2007	47	Aquarium Hilton	90,000	800,000	710,000	780
2007	58	1515 Wynkoop	3,800	200,000	196,200	5160
2007	82	HP Data Center	20,000	67,500	47,500	240
2007	14	Savannah State	5,000	2,000,000	1,995,000	39900
2007	32	NAU Sciences Lab	1,000	330,000	329,000	32900

The results show that compared to the savings emerging from the use of BIM on projects, the return on investments are at least double the cost of the process. The range is very wide because it is a function of the project scope and budget. Indeed, more technical projects with larger built-up areas may show higher detected clashes and hence higher savings on costs.

C. Problem Statement and Significance

As it can be concluded from previous studies on the topic, the implementation of BIM on construction projects, specifically the process of clash detection, results in major benefits when it comes to savings on budget and schedule.

However, current practices imply that the benefits of clash detection are to be measured by calculating the return on investment (ROI) on the project. This is an aftermath measure, as the project would already be done. It provides no insight on the impact of these clashes and how to measure them. Furthermore, assessing what would have the ROI been if BIM was not used is usually done by comparing the project to one similar in size that was implemented traditionally (Giel et al., 2010). This comparison can become difficult when no projects with equivalent characteristics exist. Researchers on a case study done in Hong-Kong to assess the cost-benefit analysis of BIM chose two nearly identical residential buildings and for comparison purposes, they ignored the foundations parts to reduce unpredictably, adjusted prices for inflation because the projects were three years apart and adjusted the timeline of both projects so they were both studied from the beginning of design till the same time in the construction phase, i.e. at 85% completion (W. Lu, Fung, Peng, Liang, & Rowlinson, 2014).

Therefore, this study proposes to model the cost of a clash in construction projects. Instead of just showing what the cost is, it sheds the light on how different characteristics of hard clashes inflate the budget in different ways. Furthermore, in order to come up with the model, clashes are studied not only based on their characteristics but also on the solution they require.

The study is significant because as it can be seen from the McLeamy curves in Fig. 3 below, the ability to make changes and impact cost is very low during the construction phase and the price of these changes is very high. Since clash detection is done in the earliest stages, more changes can be done at a significantly lower price.

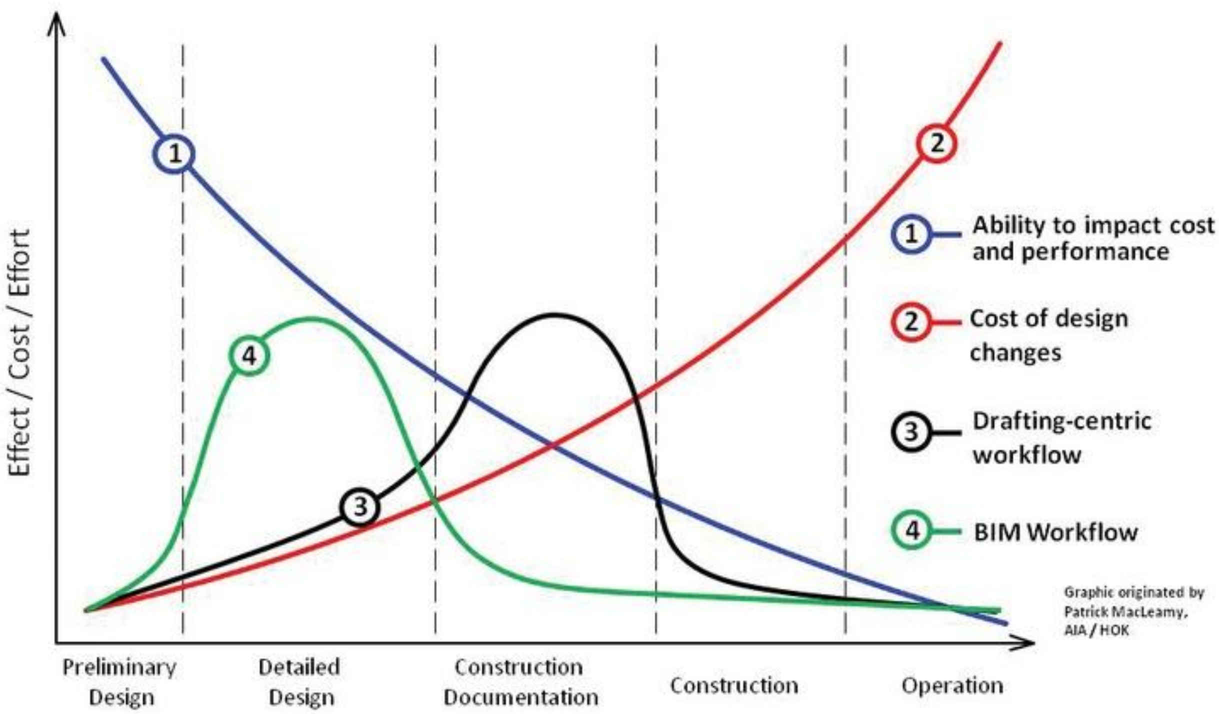

Figure 3: McLeamy curves showing the effort and effect of change in BIM vs traditional projects

Furthermore, the proposed model can be used as a decision making tool by project managers to prioritize clashes, decide which ones to solve during the design phase and which one to postpone to the construction phase. This helps them reduce the overall project cost and duration. The tool becomes more useful when it is fully automated.

D. Research Questions

The questions that the research attempts to answer are the following:

- How to derive the cost of a clash?
- How do the characteristics of clashes relate to their impacts?
- How do clashes affect the cost of a project?

CHAPTER II

METHODOLOGY

A. Research method

The research method focuses more on the qualitative aspect of hard clashes even though a quantitative analysis on one example will be done. In order to reach the study goals, the following methodology was adopted.

The first step consisted in analyzing the data of a case study and sorting its clashes. Revit models, 2D drawings and clash detection reports of the projects are used for analysis. In order to understand the nature and distribution of clashes on the project, they were sorted by type, by volume and by building.

Then, representative samples of clashes were examined. They are selected in a way to be representative of all clashing instances on this project and cover all types of clashing elements, volumes and locations. This helps include all factors that come into play when assessing the impacts of clashes on cost.

The study of several clash cases leads to the development of a model for pricing clashes. This model identifies how characteristics of clashes affect cost in different ways. It recognizes the fact that there are several cost families and each includes several cost factors that increase differently depending on the clash. Furthermore, clashes were later assigned into different categories based on the solutions they require. It was also shown how each category drives the cost of the project in a different way whether the clash materialized on site or if it is detected prior to construction.

Finally, a tool was developed which generates the cost of clash based on all the factors identified in the model. It was created using Microsoft Excel and requires the manual input of the price of factors previously identified. The model and the tool were both illustrated with a real life scenario. In fact, a clash example involving several disciplines was used in order to test the model and find its cost prior and during construction.

The careful analysis of the representative sample as well as the delimitation of all the cost factors affected will lead to a classification of clashes based on how each escalates the cost of a project in its own way. This tool can be used by project managers in order to understand which clashes are the most important to focus on and solve.

B. Scope of Work and Limitations

The major objective of this research is to provide a model that assesses the cost of clashes in construction projects. This is important because, as previous studies have shown, early identification of clashes can prevent the project from running late and over budget. The specific objectives that this research aims to reach are as follows:

- *Understanding the characteristics of clashes:* how are these clashes distributed along the project areas? What is their volume? Which trades cause the most clashes? These characteristics provide means for taking preventive measures as well as choosing the adequate solution for each clash.
- *Understanding the cost implications of clashes.* How can we quantify the cost of a clash? What is the proper process to do so? Which cost factors are affected?

- *Studying how the characteristics of clashes relate to their impacts.* Depending on the characteristics mentioned above, each clash will have a different potential solution and hence a different impact when it comes to cost. The results will clearly show the relationship between clash description and effects.

The research is based on a specific case study that helped develop the model. Specific assumptions and conditions have been made for the pricing of the clash taken as an example and some time factors have been excluded. While the example cannot be generalized, the model can be. In fact, it also takes into account a category of clashes which was not encountered in the case study. However, it only addresses how clashes impact the cost of a project and excludes the impacts on time, quality and safety, although some time factors have been addressed because of their interaction with cost factors. Finally, this study only focuses on the impacts of hard clashes and excludes soft and time clashes. The latter need further assessment and are more complex in nature.

C. Case Study

This research is based on the clash detection done on a project which consists of four towers. Two of them are a hotel and contain a podium entrance, meeting rooms, business centers besides the rooms, restaurants pools and leisure centers. The other two towers are private residences and sky villas also equipped with the same leisure facilities. The towers are 16 and 17 stories high respectively and sit on four basements mainly allocated for parking spaces. The built up area of this project is 126,500 m^2 and the estimated budget is at $300 million. Technical studies were done in 2012 and the completion date is set to the first quarter of 2016.

The clash detection process was outsourced to a third party. This project is not fully BIM integrated. It started as a traditional project. Then, the company converted the 2D CAD drawing into 3D Autodesk Revit models, coordinated the models, generated clash reports and modified the models based on the design consultants input after they reviewed the clashes. They used Revit plug-ins (clash detection manager tools) and Autodesk Navisworks when needed to perform the clash detection.

The drawings produced by the designers as well as the elements modeled are summarized Table 3 below.

Table 3: Summary of modeled elements

Drawing	Modeled Elements
Architectural	Architectural walls, ceiling and floors
Structural	Slabs, beams, columns, structural foundations
Mechanical/Electrical/Plumbing	HVAC systems, plumbing systems, fire systems, lighting systems, power systems
Coordination	Architectural, structural and MEP components

The clash detection process revealed a total of 4767 clashes across the entire project. The results were summarized in reports which included a description and pictures of each element causing a clash, their location and the volume of the clash. A sample report is included in Appendix I. After correcting the models, the total number of clashes was reduced to around 200. They were not solved by the designers and instead were coordinated on site.

The case study is relevant because it is based on a project located in the Middle East. It is a medium size commercial project which is more representative of the type of projects constructed in this area. Furthermore, it is also complex in its nature because it is a hotel and hence includes many services. It is more complex than a residential project and less complex than other types of commercial projects such as hospitals.

This research is particularly significant because of the nature of the obtained data. In fact, not only the total number of clashes on the project was obtained, but also all the clash reports. This allows for a thorough analysis of the clashes and hence provides a more accurate model and a detailed breakdown of the cost of clashes.

CHAPTER III

RESULTS

All 4767 clashes were sorted based on their location, volume and trades involved. The first step is to understand how clashes were distributed along the project areas. Figures 4 and 5 show this distribution. The term B0 refers to the four basements of all buildings, B02 refers to both hotel buildings and the term B03 refers to the apartment buildings.

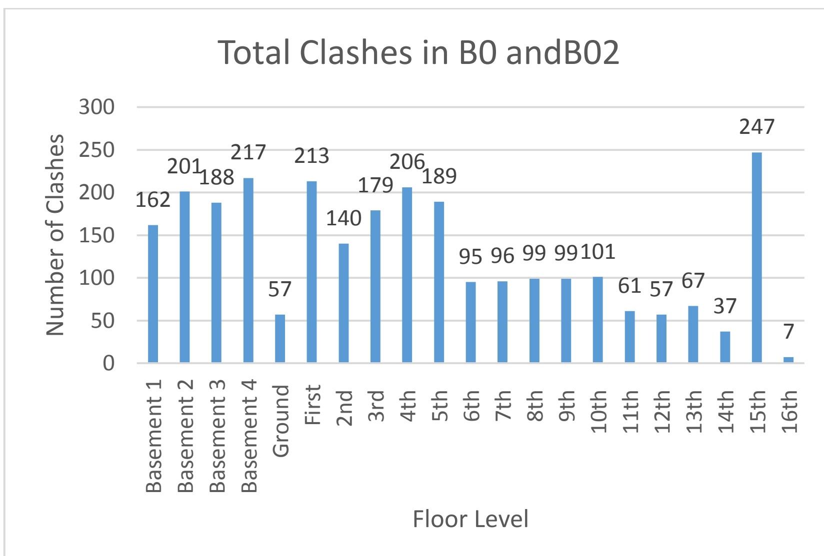

Figure 4: Total clashes in B0 and B02

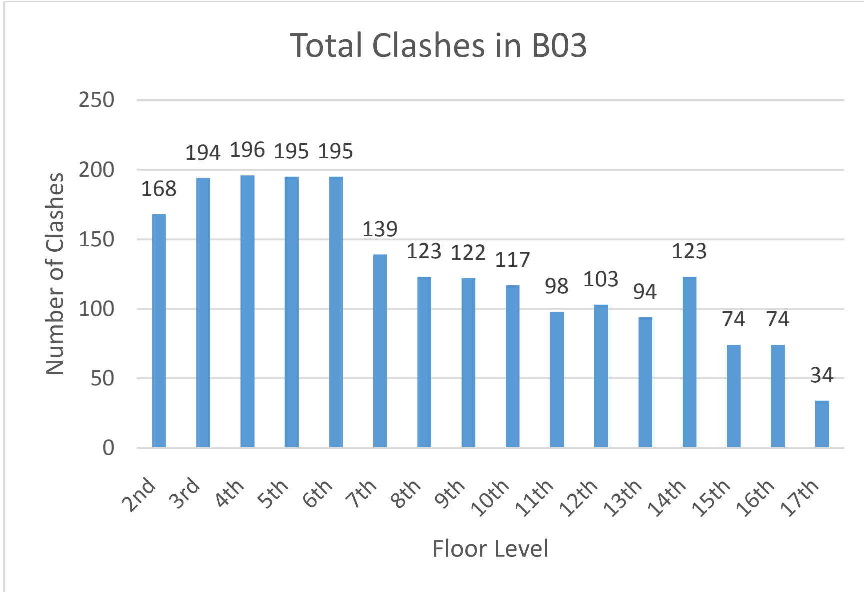

Figure 5: Total clashes in B03

As it can be seen, clashes are not evenly distributed. The 15th floor (B02) stands out with the most clashes, followed by the basements and the first floors. In complex B03, the first floors also reveal the most clashes. A thorough analysis of the floor plans might give an explanation to some of these discrepancies, while other remain random. For instance, the 15th floor in the hotel building is a mechanical floor that hosts a lot of installations and equipment circulation elements which would explain the high number of clashes. The first floor also hosts a larger amount of clashes because it houses conference rooms and some leisure amenities, which require a lot of mechanical and electrical installations.

Clashes were then sorted into five intervals based on their volume in cubic meters. The results are shown in Figure 6.

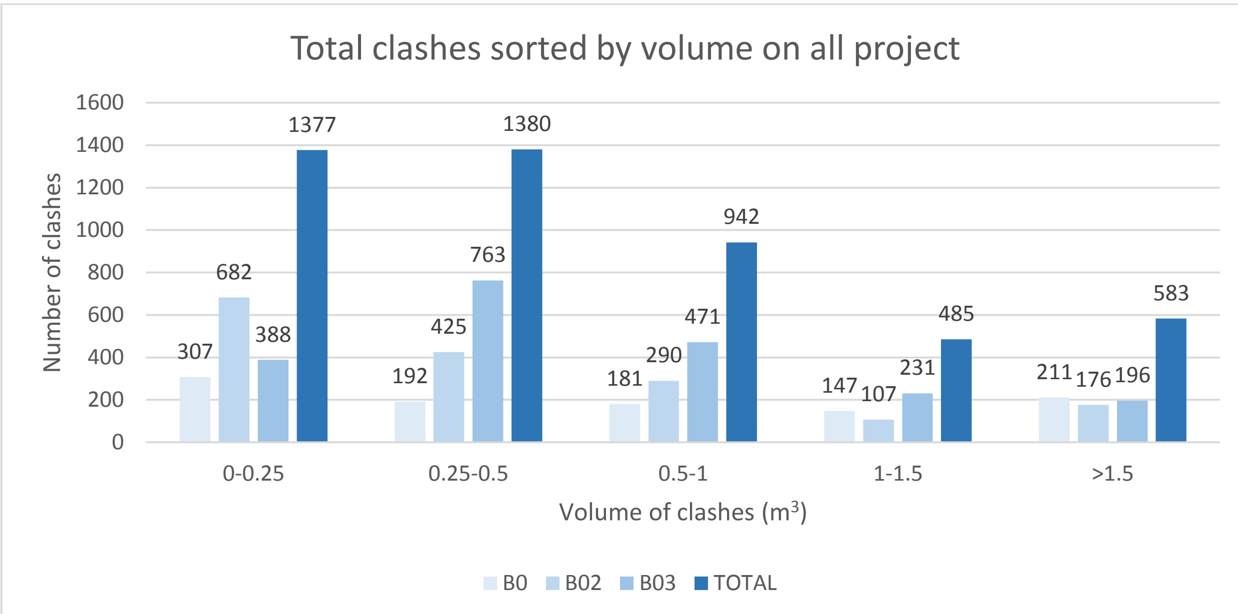

Figure 6: Sorting of clashes by volume

It can be noted that smaller clashes are more common than larger ones. Later investigations showed that in the case of the project, most of these clashes were between ducts and false ceilings where the false ceiling has a relatively small thickness (approximately 70mm).

Finally, clashes were also sorted according to the trades involved. The MEP elements were further divided into mechanical and electrical, with the mechanical parts including plumbing. There were no clashes detected within the structural and architectural systems. However, there were clashes among the mechanical one. More than half of retrieved clashes (51.3%) were between the architectural and the mechanical models, followed by clashes within the mechanical trade. The results are summarized in Figure 7 below. The results seem to confirm the fact that mechanical elements are the main causes of clashes on construction projects. This is because the MP trade includes a lot of elements that clash with each other and that causes clashes with the architectural system because the models are developed separately and hence no communication exists between both trades in order to share information such as clearances and dimensions which would help avoid these clashes.

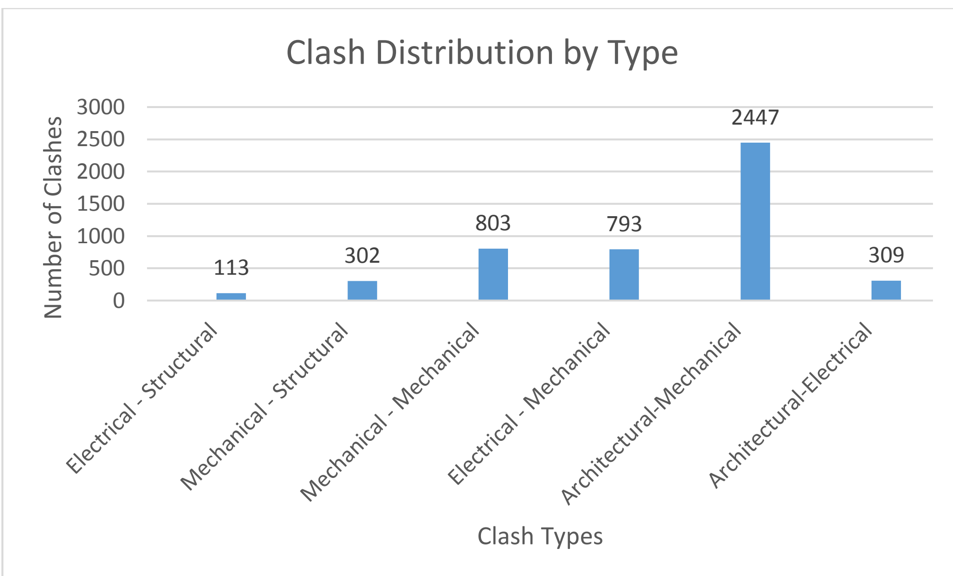

Figure 7: Clash distribution by trade

CHAPTER IV

MODEL FOR ASSESSING THE COST OF A CLASH

A. General Process Map

The preliminary results obtained show that there are some clashes between trades themselves, in this case the mechanical and plumbing. While they are relatively smaller in number compared to other types of clashes (16.8%), they are till important and can be fixed before doing clash detection on the master model. Therefore, the process map depicted below shows an optimized clash detection process. It proposes running an intradisciplinary detection process before submiting the models for compiling in order to eliminate clashes within trades first. This helps reduces coordination costs and time loss because each trade can solve them seperately. After these clashes are addressed, the master model can now be compiled and clash detection is run again.

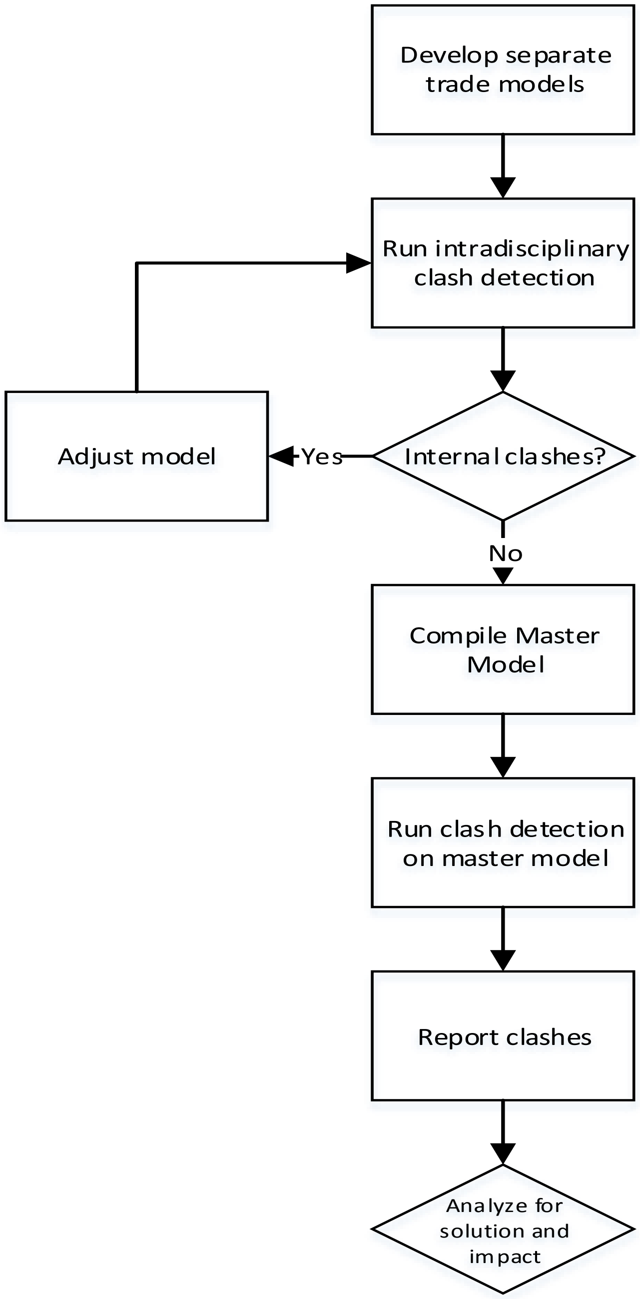

Figure 8: General process map

B. Proposed Model

The first phase of the model, depicted in Figures 9 and 10, shows the steps that have to be done once a clash is reported in order to be able to assess its impact.

A detected clash can have multiple redundancies, which means that it can be repeated at the same location across several floors. This arises from the fact that most buildings have typical floors that are replicated. Tracking the repetitions is done either by inspecting the same location at different floors or by checking the clash reports for clashes that have the same volume. The number of redundancies is important because the cost of one clash is multiplied by the number of times it is repeated and also because solving it once may eliminate all instances. Hence, this serves to group clashes and spend less time solving them.

The next step is to inspect the clashing elements. If a duct is clashing with a pipe at a certain grid section, it would be useful to follow the duct to see if it clashes with other pipes or other elements at different locations. A study of all the clashes an element causes can lead to finding the optimal solution. In some cases, one solution can solve all of them. For example, in the case where a cable tray is hitting a structural column than a duct, both clashes can be solved together whereby the cable tray is moved horizontally away from the column and bent below the duct. The first part of the framework is shown in Figure 9.

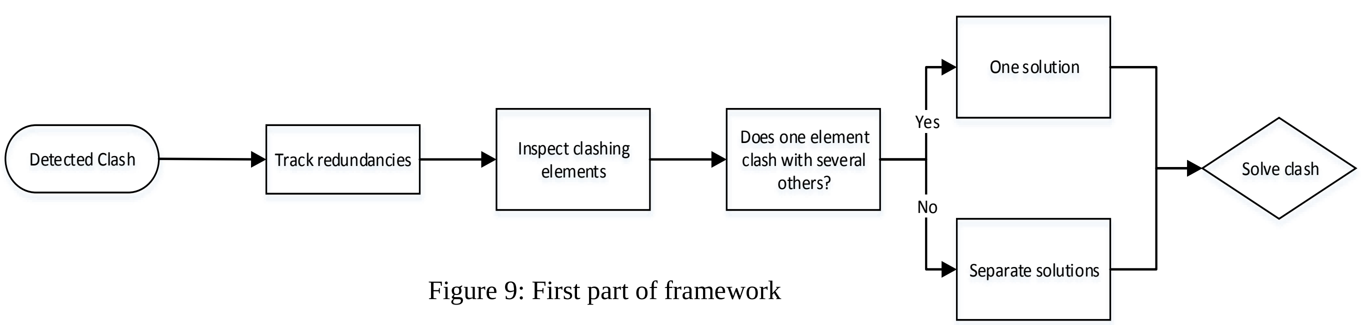

Figure 9: First part of framework

Then, a solution for the clashes is sought. This depends on the type of clashes. In this study the focus is on hard clashes only as previously mentioned. It also depends on the trades involved in the clashes and their numbers. The more trades involved, the more design hours and engineers are required and the higher the cost of the clash would be if it materialized on site. The volume of the clash should also be considered. Small volumes may be indicative of a design error and may be solved by relocating or lowering elements. However, big volumes of clashes showing elements hitting each other through their entire cross section highlight a bigger issue and should be carefully addressed by project managers. In such cases, a redesign of an entire floor or section might be needed. The last step to consider while seeking a solution is to assess the significance of the location of these clashes. Clashes on typical floors tend to be repetitive. However, locations such as mechanical floors are very problematic and impact the budget and duration of construction projects greatly because they host a lot of elements as well as expensive equipment. A detailed way each of these types drive up the cost of the project is presented later on. The second part of the framework is shown in Figure 10.

After all these characteristics are identified, designers or consultants in charge can proceed with solving the clashes. It is important to note that the choices shown in the framework are not mutually exclusive, but are represented this way for more clarity. Once a solution is available, it is crucial to make sure that it does not cause another chain reaction of clashes somewhere else. Therefore, the process of solving clashes is cumbersome and very specific. At this point, it should also be noted that to derive a solution for a clash, a certain hierarchy has to be adopted. For example, a structural change is usually the last resort while solving a clash. This is further elaborated in the discussion part. An order is necessary because once the proposed tool is fully automated to propose a solution on its own, a hierarchy would prevent it from entering in an endless loop of solution.

The characteristics of the clashes along with their solution are what determine how they will impact the construction project. It has already been established that they have a direct influence on cost, time, quality and safety. In this study, the focus is shifted towards cost only though it will include some time aspects in the way they relate to cost. Once the impact is assessed, project managers can now know which clashes have high impacts and are able to make more informed decisions when it comes to managing them.

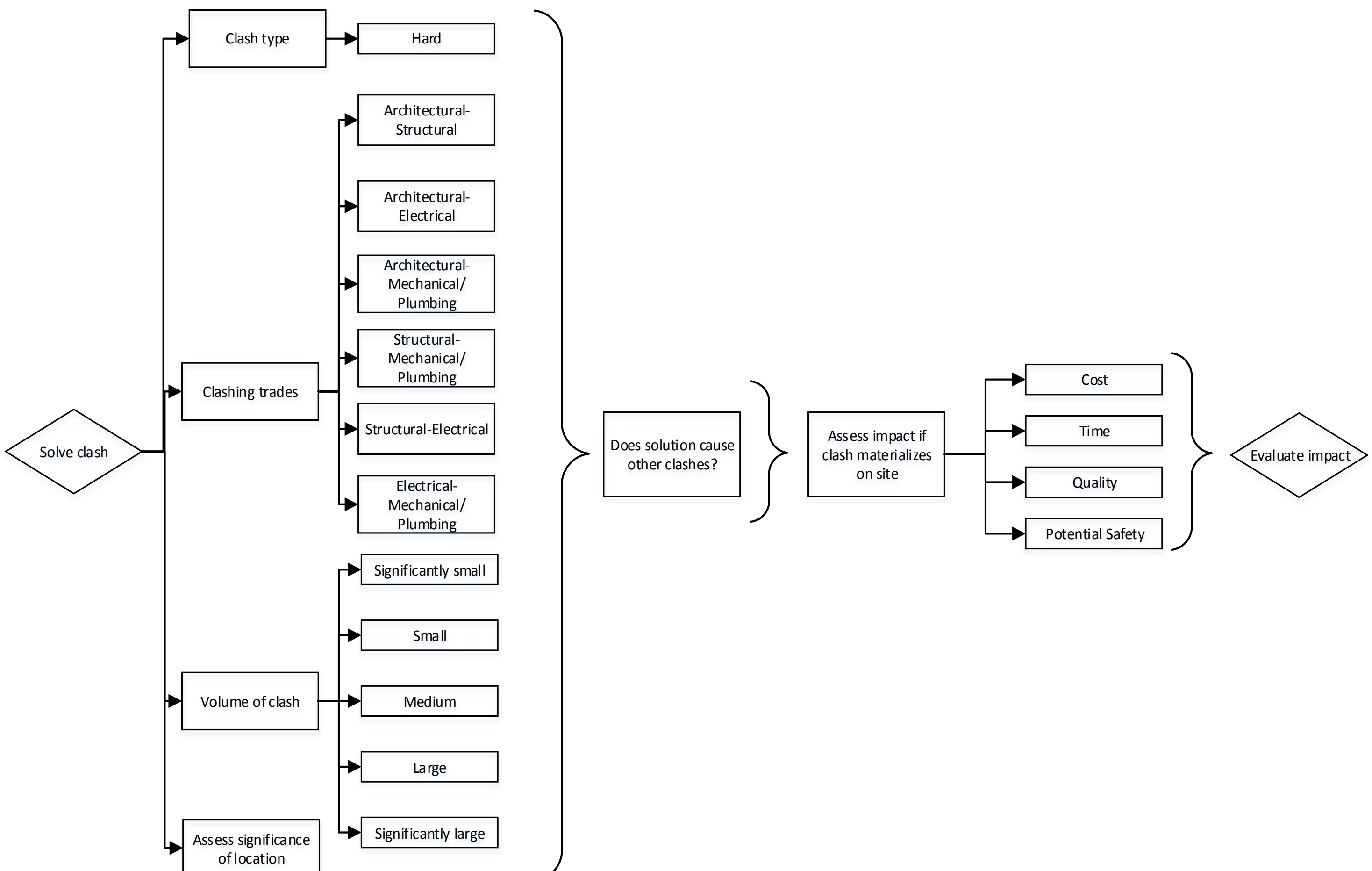

Figure 10: Second part of framework

After studying a set of different clashes and trying to figure out a solution to solve them, the following cost impacting factors were established. With every clash, there are cost associated with construction, others with design and overhead, and costs related to time implications and workforce behavior.

When a clash materializes on site, its construction cost is dependent on the type of element it is (duct, beam, etc..), how many times it is repeated or how many other clashes it is causing as well as the material it is made of. The latter is important because it also relates to another feature which is rework. By the time the clash reveals itself on site, the element has already been installed. If the solution entails removing it, then it becomes wasted material that has already been paid for besides the fact that rework requires labor which adds to the cost. Furthermore, in some cases, solving a clash on site requires the recruitment of skilled labor or a specialized workforce to deal with the changes especially if the solution is too complex. They might also need to use more equipment for removal and replacement or specialized ones for the solution that may or may not be readily available on site and it also increases the construction cost.

Solving clashes causes design and overhead costs. First and foremost, a solution has to be designed for the clash. The more trades colliding with each other, the more engineers are required, at least one for each trade. The more elements are involved in the clash, the more time the engineers might take in order to derive a solution. First, they would have to meet after the issue was raised to them in order to get information about the clash. Then each engineer would revise his model in order to see what the options he can adopt are. They would later meet for another time and lay their options in order to find an optimal solution. Furthermore, design time is increased because they have to make sure that their solution does not cause a chain reaction of clashes somewhere else. The more time the engineers spend devising the solution, the more the cost of design increases. Moreover, if additional or different material are required, they may need a long procurement period. This lead time halts the construction process and introduces idle time in the construction process. All of this contributes to delays and added overhead expenses since proper documentation has to be done.

Finally, there are factors that increase the cost because they are associated with both the construction and the design process. They are mainly related to time implications and workforce behavior. The delays arising from variation orders and requests for information as well as from the disruption of activity flow increase overhead expenses. The more the solution is complex and entails rework and the more time it takes to be derived and implemented, the more disruption will happen. Furthermore, if a labor crew is pausing work awaiting the solution and is later asked to work overtime it will result in a decreased morale and hence a decreased productivity. This also increases the cost since overtime adds to the overhead expenses and labor costs on one hand and a decreased productivity means the crew will have to work more hours and hence be paid more. A summary of all factors is shown in Table 4.

Table 4: Factors impacting cost

	Family of cost factors	Factors	Cost item	Price
Cost	Construction cost (C)	Type of element	C1	(price/unit)*(number of units)
		Number of instances	C2	
		Type of material	C3	
		Rework	C4	(labor wage/time)*(number of workers)*(time)
		Recruitment of specialized workforce	C5	(labor wage/time)*(number of workers)*(time)
		Need of specialized equipment	C6	(operation fees/time)*(operating hours)
	Design and overhead costs (D)	Redesign hours	D1	(designer wage/hour)*(number of design hours)
		Procurement time of new material	D2	(total delay time)*(liquidated damages/day)
		Increase in overhead expenses	D3	
Cost	Costs related to time implications and workforce behavior (T)	Decreased productivity	T1	
		Delays from RFIs and VOs	T2	
		Disruption to activity flow	T3	
		Delays due to rework	T4	

The total construction costs is:

$$C = n * \sum_{i=1}^{6} C_i$$

where C_i is the cost of each factor related to construction and n is the number of times the clash is replicated. For each instance of the clash, the construction costs remains the same.

The total design and overheads costs is:

$$D = \sum_{j=1}^{3} D_j$$

where D_j is the cost of each factor related to design and overhead expenses. In this case, the number of instances is not accounted because the solution is independent of the number of instances. It depends on the complexity of the clash.

The total cost related to time implications and workforce behavior is:

$$T = \sum_{k=1}^{4} T_k$$

where T_i is the cost of each factor in this family.

Finally, the total cost of the clash is the summation of the total of each family of factors:

$$Total\ cost = C + D + T = n * \sum_{i=1}^{6} C_i + \sum_{k=1}^{3} D_j + \sum_{k=1}^{4} T_k$$

It is important to note that all of these factors are not mutually exclusive, they all relate to each other in a way or another. Combined, their effect is one; the project budget will be overrun.

This model has limitations in the way that the cost of the time implications has to be estimated and entered manually instead of it being generated automatically.

C. Automated tool and model validation

Previous literature, while stating approximate costs of clashes, failed to show how the final number was obtained. Considering all the above mentioned factors, a cost breakdown will be shown in the following example. The proposed tool is an automated interface that will help price the cost when all the necessary data has been extracted from the model. It is illustrated using a real life scenario from the case study.

1. Limitations and assumptions for the example

The actual interaction between time and cost implications are relatively hard to price. For this matter, the delays due to variation orders, requests for information, decrease in productivity and its associated overhead expenses have been excluded.

The prices of material and labor were obtained from a local contracting firm and the solution was validated by their engineers. Therefore, the prices and the methods are specific to the firm and the country and cannot be generalized. One working day amount to an 8 hour shift. The labor crew required for each change is formed of a skilled labor and a helper.

2. Description of the example

Figure 11 shows a 3D view of a clash from the first floor.

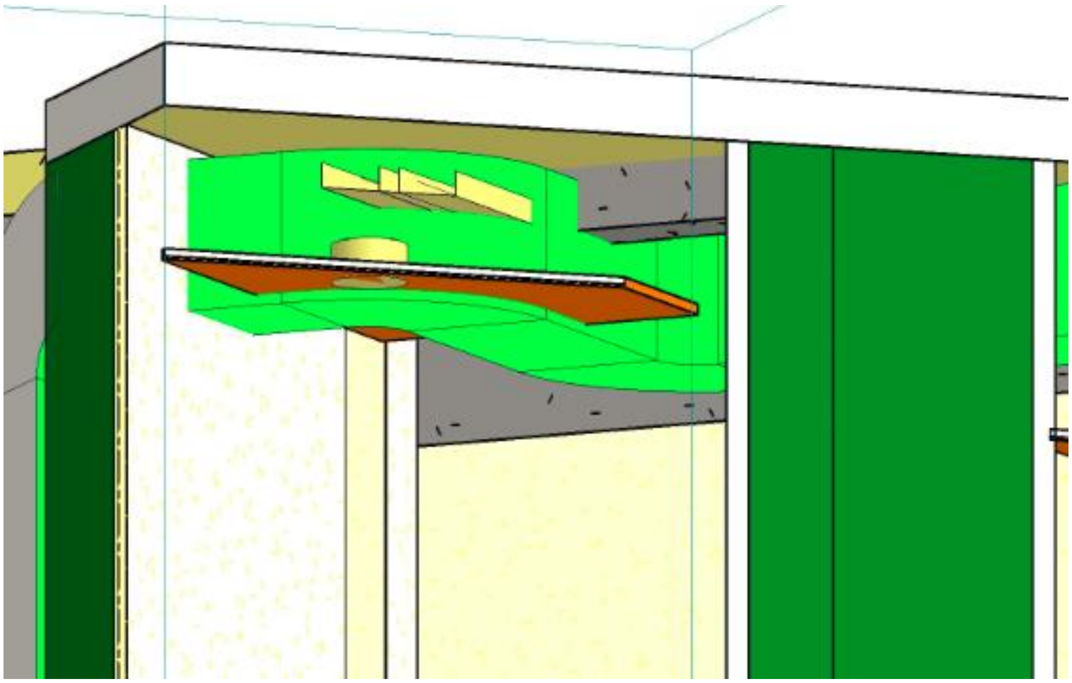

Figure 11: 3D view of clash example

There are four elements causing clashes:

- An HVAC duct with a structural beam, with a volume of 1.272 m^3.
- The same duct with the false ceiling, with a volume of 0.318 m^3.
- A cable tray with the duct, with a volume of 0.473 m^3.
- The same cable tray with the structural beam, with a volume of 0.211 m^3.

The total volume of clashing elements is 2.274 m^3. A fifth element has to be added which is the cables conveyed by the cable tray. In case the tray needs extension, then longer cables should be ordered. If a drop or a junction is to be installed on the path of the tray, then the material has to be checked to see if it is flexible to bend with the path of the cable tray or not.

3. Proposed solution

In order to draft a solution for this clash, an architect, a mechanical and an electrical engineer should collaborate. The estimated time they require is three days in order to coordinate the solution and check that no further clashes are caused by it. Even though one of the elements in this clash is a beam, changes to the structural framing system is usually the last resort in solving clash because it will require a complete new structural analysis if it is caught before construction. In the case where the clash materializes on site, the beam would be the first element to be installed so other elements have to be worked around it.

Three changes are required for this clash to be solved. At first, the duct has to be resized in order to fit in the false ceiling after lowering it, while keeping the same output. Based on the input from the contracting company, ducts are assembled on site from aluminum sheets and are priced by kilogram of material. The original duct is 800mm by 600mm and has to be replaced for 2 meters run. From this method, it is assumed that the same weight of sheets will be used for the new duct. One and a half working days are required for the dismantling and reinstallation of the element.

Second, the false ceiling has to be lowered because the duct cannot be reduced in size further or else its output will be reduced. Based on the drawings, the false ceiling area is 16 m^2. Two days are needed for the removal of installed elements and rework.

Finally, the cable tray has to be rerouted under the beam and a drop has to be added in order to lower the cable tray below the duct. This will increase the length of cable tray needed as well as that of the cables. Due to lack of information, the cables are assumed to be of a flexible type that will bend with the drop of the cable tray.

This clash is estimated to cause a total delay of five days: three days for drafting the solution and redesigning, and two days of delays due to the rework on the construction site. Assuming that this activity is only near critical and does not affect the critical path, a total delay of one day to the construction sequence is considered. This delay will then be multiplied by the amount of liquidated damages that applies per day, as commonly stipulated in construction contracts.

4. Cost

Each factor from the model impacting the cost is computed into the automated cost calculator. The total cost is the summation of the cost of each factor, if the clash were to materialize on site.

The first step is to input the clash characteristics, as seen in Figure 12 below. This interface can combine several clashes at the same time, if they can be solved together. The number of instances if the clash repeats itself is required, in order to multiply the clash by it as well as the number of clashing elements and trades. The latter number is important because when this tool is more automated, it will create a loop that will fill all the required inputs for all clashing elements. For this example, the number of elements is four.

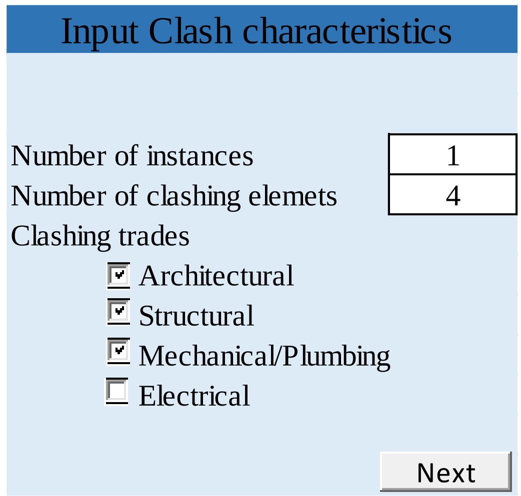

Figure 12: Step 1 of the automated calculator

The next step is to input the cost, based on the breakdown in Table 4. The first step is to input the construction costs, then design costs and finally overhead costs. The same process is repeated for each element. The entire breakdown is shown in Appendix II.

Input Construction Costs - Element 1

Type: Duct

Existing Material	
Unit (kg)	50
Price/Unit	6

New Material	
Unit	50
Price/Unit	6
Crew size	2
Skilled labor	1
Wage ($/hr)	5
Hours	12
Helper	1
Wage ($/hr)	4
Hours	12
Labor Cost	108
Extra Equipment	0
Total	708

Next

Figure 13: Construction costs of element 1

Input Design Costs-Element 1

Type	Number	Wage($/hr)	Hours
☑ Architect	1	18.75	24
☑ Mechanical Eng.	1	18.75	24
☑ Electrical Eng.	1	18.75	24
☐ Structural Eng.			

Next

Figure 14: Design costs of element 1

Input Overhead Costs - Element 1	
Delays due to Engineering (days)	3
Delays due to Construction (days)	2
Delays due to new material procurement (days)	0
Delays due to VO/RFI (days)	-
Total Critical Path Delay	1
Liquidated Damages ($/per day)	4000
Increase in Overhead Expenses (per day)	-
	Next

Figure 15: Overhead costs of element 1

When all of the information has been filled, the total cost figure is automatically generated (Fig. 16). For this example, the cost of this clash, if it were to materialize on site, excluding the costs due to variation orders, requests for information and overhead expenses and assuming that no procurement of new material is needed, is approximately 7000$.

Total Clash Cost	
Total Construction Cost	1667.5
Total Engineering Cost	1350
Total Overhead Costs	4000
Clash Cost	**7017.5**

Figure 16: Total cost of a clash on site

Figure 17 below shows what the clash costs when it is detected prior to construction. The difference between the two totals is that the previous one is an additive sum of all elements while the second one is a differential sum. In fact, when a clash is detected prior to construction, the labor cost is excluded because it was already accounted for in the budget. What is taken into account is the difference in the price of the old and new material as well as the redesign cost. Time implications, procurement delays and costs related to workforce behavior are all excluded because detection is happening in the early stages of the project life cycle and hence these factors do not carry an impact yet. Since a period of clash assessment and solving follows the process of clash detection, it is assumed that no delays will be caused to the schedule from the coordination meetings that take place to solve clashes. The complete cost breakdown is shown in Appendix III.

Total Clash Cost	
Total Construction Cost	34.5
Total Engineering Cost	1350
Total Overhead Costs	0
Clash Cost	**1384.5**

Figure 17: Total cost of clash prior to construction

As it can be seen by comparing both totals, a big part of the cost is impacted by liquidated damages. Furthermore, the total delay penalized by liquidated damages is caused by several clashes and not just one. However, even if this effect is excluded, the cost of a clash if it were to be detected on site is still high because of the construction costs.

CHAPTER V

DISCUSSION

The analysis of representative sets of clashes revealed that each clash impacts the project's budget and schedule differently depending on the solution it requires. Table 5 below explains this difference. It covers conflict between two trades, three or more trades and those involving equipment. It also tries to tackle all the possible solutions that can be derived during coordination meetings. Finally, it accounts for the hierarchy in solving clashes which was previously discussed.

Table 5: Solution of clashes based on clashing trades

Clashes between	**Tentative Solution**
Structural vs mechanical (beams, columns, slabs, etc.) vs. (ducts, pipes, etc.)	• A structural change is usually the last solution provided. • If the need arises, a change of material (from concrete to steel etc.) may be helpful. • If all else fails, a complete redesign of the structural framing system is required. • Mechanical elements can be rerouted, relocated or resized to solve the clash. With resizing and relocation, new material has to be ordered.
Structural vs electrical (beams, columns, slabs, etc.) vs. (cable trays, lighting fixtures, communication devices etc.)	• Cable trays are the most common causes of clashes. They can be rerouted or lowered with drops and junctions. This also entails the ordering and use of extra material.

Table 5 (Cont'd)

Architectural (false ceiling, floors, etc.) vs. mechanical and/or electrical	• A first solution is to reroute or relocate electrical or mechanical element. • In cases where architectural elements such as false ceiling do not provide enough clearance to fit all MEP elements and resizing them or relocating them is not an option, a change in elevation or thicknesses of the architectural elements can be considered. If clashes materialize on site in this case, a removal and replacement of the architectural elements is required
Structural vs. architectural and mechanical and electrical	• Clashes including several trades are more common. • Solution is more complex and involves a combination of the solution mentioned above.
Clashes involving equipment	• Equipment usually is installed on site at the later stages sometimes when finishing is being done. • Relocating equipment can be a solution but it will provide dead spaces and requires extra material for the circulation of the equipment. • Ordering smaller units of the equipment while conserving the output or the load of the original one means time is lost for procurement and money is wasted because the original equipment will not be useful anymore. • Trying to make space for the equipment in its original location by enlarging the room or the facility it is in. This requires the demolition of what is already built as well as a study on the feasibility of this solution on all levels (structural analysis, rerouting already installed MEP elements, etc.)

While the solution remains the same whether the clash was detected prior or after construction, the way the cost is impacted differs. It is wrong to assume that clash detection eliminates entirely the extra costs incurred from clashes if they were to materialize on site. Some items remain present even if conflicts were discovered during the design phase. However, their impact is less significant. Table 6 below show which factors are affected depending on where the project is with respect to its lifecycle. A simple clash is a conflict between two trades, for example between a structural element and a mechanical one. A complex clash is one which involves more than two trades or several elements from each one. Finally, a clash involving equipment was not detected in this project due to drawings being on a lower level of development and hence did not include equipment. An example of such a conflict is in order because this category was not encountered in the case study. A clash of this type can happen when an air handling unit (AHU) does not fit into its assigned room. Several tentative solutions exist to remediate this. The unit can be relocated into another room. However, this would mean that a dead space now exists in its original location and more elements for circulation are needed. On another hand, smaller units may be ordered with their total output equaling the original one. This entails that the previously bought equipment is wasted. Finally, the room, which was already constructed, may be demolished and extended if the surrounding space allows for this. It is important to note that this type of clashes blasts all type of costs and has major time implications leading to delays and liquidated damages.

The table shows that some cost items are impacted whether the conflict is detected prior or during construction. However, the impact is much greater on site and it would drive the cost up considerably. For example, the cost of material when a clash is detected during the design phase is limited to the difference in prices between the original material and the new one, if the new one is more expensive. On the other hand, once the clash materializes on site, the cost become additive because the original material has already been ordered and paid for. It should also be noted that even if the same items are impacted whether the clash is simple or complex, the impact increases with the complexity, i.e., the more complex the clash, the greater the implications.

Table 6: Cost items affected by clashes prior to and during construction

Clash case	**Impact on cost**	**Cost items impacted if clash detected**	
		Prior to construction	**On site**
Simple clash	• Cost is mostly incurred from design hours because material volume is small. • If clash is detected on site, this cost is greater.	C1, C2, C3 D1,	C1, C2, C3, C4 D1, D2, D3 T1, T2, T3, T4
Complex clash	• Cost is incurred from redesigning but it is higher than the previous case. • Cost is also incurred on site from the ordering new material, dismantling old elements and labor costs.	C1, C2, C3 D1, D2	Greater costs of: C1, C2, C3, C4, C5, C6 D1, D2, D3 T1, T2, T3, T4

Table 6 (Cont'd)

Clashes involving equipment	• Prior to construction, extra cost is incurred from redesigning. • On site, extra costs arise from idle time during procurement of new equipment, redesigning, rework, labor and the cost of unused equipment.	C1, C2, C3 D1, D2	C1, C2, C3, C4, C5, C6 D1, D2, D3 T1, T2, T3, T4

A considerable fraction of the cost is driven by the time factor. As it can be seen from the detailed example, the liquidated damages increase the way in a significant way. Furthermore, some of the time factors, T1 to T3, were disregarded and not quantified. The more complex the clash, the more complicated the solution becomes and time consuming; hence more cost items come into play.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

Clash detection, a tool of Building Information Modeling, is the process of identifying constructability issues on a project before the construction phase. Clashes are bound to happen and their causes are numerous. While they affect the cost, time, quality and safety, the focus of this study was mainly cost.

Clashes on a specific case study were analyzed in order to understand all their characteristics. Then, a model breaking down the cost of these clashes was developed. An automated tool was created which helps price each cost factor derived from the model in order to generate the final cost of a clash. The model was illustrated with a real life clash example from the case study. Based on the model, it was established that different scenarios of clashes have different implications on cost.

While the real life example cannot be generalized, the model can be and it accounts for a category of clashes that was not encountered in the case study. It can be used as a decision making tool by project managers when it is fully automated to prioritize clashes, decide which ones to solve during the design phase and which one to postpone to the construction phase. This helps them reduce the overall project cost and duration.

Future research may look at soft and 4D clashes and assess their impacts on the project. It may also keep investigating the impact of hard conflicts when it comes to time separately from cost, quality and safety. Finally, it may also improve on the tool by fully automating it and by finding a model that would help estimate the time implications of clashes in order to find a more accurate cost estimate.

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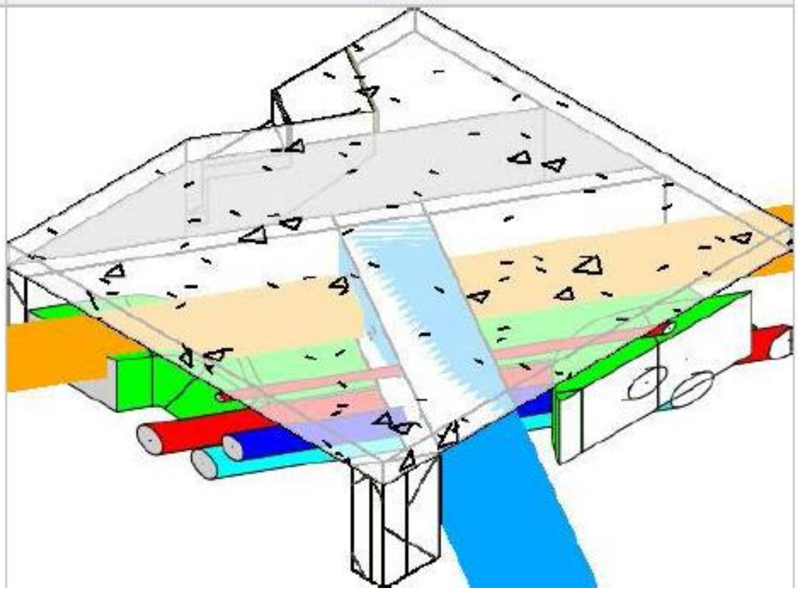
APPENDIX 1: CLASH REPORT

displayId	element1Id	element2Id	element1Type	element2Type	grid1	grid2	versionId	statusId	level	levelDistance	gridDistance	volume
1	2035845	486988	CableTray	Structural Framing	HO-7	HO-N	346	Pending	LL05	2.9400	2.0595	0.23837400037006

viewName	myPhoto
View3D	

APPENDIX 2: FULL COST BREAKDOWN PRIOR TO CONSTRUCTION

Input Construction Costs - Element 2

Type: False Ceiling

Existing Material	
Unit (m^2)	16
Price/Unit	20

New Material	
Unit	16
Price/Unit	20
Crew size	2
Skilled labor	1
Wage ($/hr)	5
Hours	16
Helper	1
Wage ($/hr)	4
Hours	16
Labor Cost	144
Extra Equipment	0
Total	784

Next

Input Construction Costs - Element 3

Type	Cable tray			
Existing Material			New Material	
Unit (m)	1.5		Unit	3
Price/Unit	18		Price/Unit	18
			Crew size	2
			Skilled labor	1
			Wage ($/hr)	5
			Hours	8
			Helper	1
			Wage ($/hr)	4
			Hours	8
			Labor Cost	72
			Extra Equipment	0
			Total	153
				Next

Input Construction Costs - Element 4

Type	Cables		Labor cost included	Yes
Existing Material			New Material	
Unit (m)	1.5		Unit	3
Price/Unit	5		Price/Unit	5
			Extra Equipment	0
			Total	22.5
				Next

APPENDIX 3: FULL COST BREAKDOWN DURING CONSTRUCTION

Input Construction Costs - Element 1

Type: Duct

Existing Material	
Unit (kg)	50
Price/Unit	6

New Material	
Unit	50
Price/Unit	6
Crew size	0
Skilled labor	0
Wage ($/hr)	0
Hours	0
Helper	0
Wage ($/hr)	0
Hours	0
Labor Cost	0
Extra Equipment	0
Total	0

Next

Input Engineering Costs-Element 1

Type	**Number**	**Wage($/hr)**	**Hours**
☑ Architect	1	18.75	24
☑ Mechanical Eng.	1	18.75	24
☑ Electrical Eng.	1	18.75	24
☐ Structural Eng.			

Next

Input Overhead Costs - Element 1

Delays due to Engineering (days)	3
Delays due to Construction (days)	2
Delays due to new material procurement (days)	0
Delays due to VO/RFI (days)	-
Total Critical Path Delay	1
Liquidated Damages ($/per day)	0
Increase in Overhead Expenses (per day)	-

Next

Input Construction Costs - Element 2

Type: False Ceiling

Existing Material	
Unit (m^2)	16
Price/Unit	20

New Material	
Unit	16
Price/Unit	20
Crew size	0
Skilled labor	0
Wage ($/hr)	0
Hours	0
Helper	0
Wage ($/hr)	0
Hours	0
Labor Cost	0
Extra Equipment	0
Total	0

Next

Input Construction Costs - Element 3

Type	Cable tray		
Existing Material		**New Material**	
Unit (m)	1.5	Unit	3
Price/Unit	18	Price/Unit	18
		Crew size	0
		Skilled labor	0
		Wage ($/hr)	0
		Hours	0
		Helper	0
		Wage ($/hr)	0
		Hours	0
		Labor Cost	0
		Extra Equipment	0
		Total	27

Next

Input Construction Costs - Element 4

Type	Cables	Labor cost included	Yes
Existing Material		**New Material**	
Unit (m)	1.5	Unit	3
Price/Unit	5	Price/Unit	5
		Extra Equipment	0
		Total	7.5

Next

Total Clash Cost

Total Construction Cost	34.5
Total Engineering Cost	1350
Total Overhead Costs	0
Clash Cost	**1384.5**