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DECISION MAKING PROCESSES FOR BIM SOFTWARE SELECTION IN THE U.S. A.E.C. INDUSTRY: DEVELOPING A UNIFIED, STREAMLINED FRAMEWORK.

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**DECISION MAKING PROCESSES FOR BIM SOFTWARE SELECTION
IN THE U.S. A.E.C. INDUSTRY: DEVELOPING A UNIFIED,
STREAMLINED FRAMEWORK.**

by

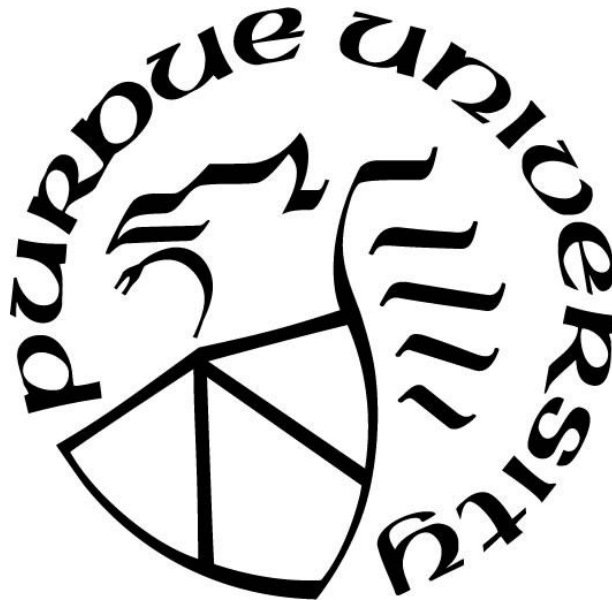
Richelle Fosu

A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy



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West Lafayette, Indiana

December 2017

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GLOSSARY

MCDMM – Multi-criteria decision-Making Methods refer to decision making methods used in support of decision making in a variety of situations and scenarios (Toloie-Eshlaghy & Homayonfar, 2011).

DSS – Decision Support Systems - DSS are interactive systems designed to support decision-making problems by utilizing “...data, models, visualizations and user interface to solve semi-structured or unstructured problems.” (Poletto, de Carvalho, & Costa, 2015, p. 14).

Functional criteria - According to Baharom, Yahaya, and Tarawneh (2011), functional attributes refer to services and capabilities that the software is expected to offer to its users.

Non-functional criteria – Non-functional attributes on the other hand, refer to those not linked with the specific behavior of the software (Baharom, Yahaya, & Tarawneh, 2011).

LIST OF ABBREVIATIONS

BIM – Building Information Modeling

AEC – Architectural Engineering and Construction

MEP – Mechanical Electrical and Plumbing

GC – General Contractors

DSS – Decision Support System

WBDSS – Web Based Decision Support System

MCDMM – Multi Criteria Decision Making Method

WSM – Weighted Sum Model

WPM – Weighted Product Model

AHP – Analytical Hierarchy Process

ABSTRACT

Author: Fosu, Richelle. PhD

Institution: Purdue University

Degree Received: December 2017

Title: Decision Making Processes for BIM Software Selection in the U.S. AEC Industry:
Developing a Unified, Streamlined Framework and Tool.

Committee Chair: Patrick Connolly

The use of Building Information Modeling (BIM) techniques and tools continues to gain popularity in the Architecture, Engineering and Construction (AEC) industry as more companies in the various sectors are utilizing it in one form or another. In this research, the decision-making process of construction firms with respect to the selection of BIM software for use is investigated. Through one on one interviews and gathered survey responses, a framework mapping out the various paths that exist in the decision-making process are explored. This data is then used to form a framework for BIM software selection in the construction sector of the AEC industry in the United States.

CHAPTER 1. INTRODUCTION

This chapter establishes the major research questions which pertain to the overall motivation and objectives of this study. The overarching significance is presented and explained, as the overview of the scope covered is introduced. Assumptions, limitations and delimitations as they relate to the goals of this research are also outlined in this chapter.

1.1. Statement of Purpose

The main goal and focus of this research was to uncover a pattern within the software selection decision-making process, that can be used to establish a general framework for Building Information Modeling (BIM) software selection in the Mechanical/ Electrical/ Plumbing (MEP) sector of the Architecture Engineering and Construction (AEC) industry.

The steps followed for the BIM software selection process in the AEC industry was investigated. Figure 1.1 depicts a simplified representation of the basic components for the framework explored as a result of this research study. The different criteria considered for BIM software selection within this sector of the AEC industry are also identified and presented at the end of this study.

Processes involved in each step were explored, and a select group of Multi Criteria Decision Making Methods (MCDMM) were examined in order to determine the most appropriate methodology for the quantitative BIM software selection evaluation in the decision-making process.

Finally, the resulting framework, in addition to the identified criteria and MCDMM, was implemented in the form of a proof of concept, complementary Web Based Decision Support System (WBDSS) aimed at assisting with the BIM software selection process.

It is intended for this theoretical framework, together with its implemented web based decision support system, to serve as a guide which other firms in the MEP sector can use during the selection and adoption of Building Information Modeling (BIM) software.

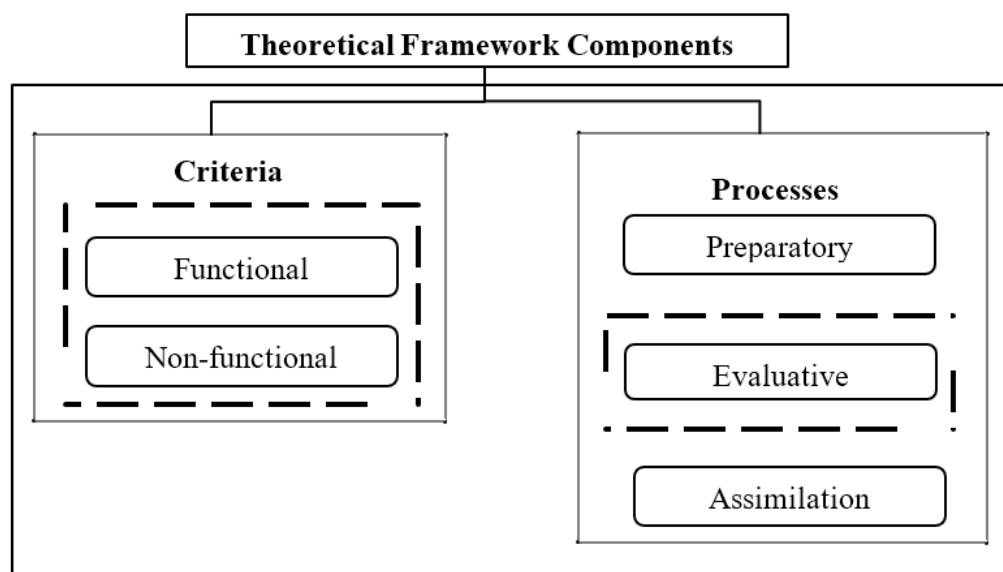


Figure 1.1 Proposed theoretical framework components. The components surrounded by ‘- - -’ represent the parts of the framework that will be implemented in the WBDSS

1.2. Research Question

This research sought to find a detailed answer to the question of “How does a company in the Mechanical/Electrical/Plumbing sector of the Architecture Engineering and Construction industry select the appropriate Building Information Model software for their use?”

Additional sub-questions addressed during this research were:

- What is the framework/methodology that MEP firms follow in order to select their BIM software?
- What is the most appropriate Multi-criteria Decision-making method that can be applied to aid in the BIM software selection process for the MEP sector?
- What are the rankings, by importance, of the software selection criteria identified as per the specialty sub sectors of the industry?

1.3. Scope

As this research aimed at identifying a general framework for BIM software selection within the MEP sector of the AEC industry, Mechanical/Electrical/Plumbing firms of the AEC industry were the target population. Specifically, MEP firms that were identified as being current BIM adopters were sought out for data collection – as they would have already gone through the decision-making process for BIM software selection at least once. Only companies within the U.S. were considered in this study. The stages of the software selection decision making process focused on were those concerned with the steps of the selection, as well as the criteria involved. Other stages such as the adoption and implementation were out of the scope of this research.

In their research, Hanna, Boodai and El Asmar (2013) established that there was a correlation between company size and BIM use, indicating that the larger sized companies – determined through billings per year - were more involved with BIM adoption. A similar categorization was followed in this research when distinguishing the larger from the medium sized and smaller firms - e.g. larger firms were expected to have above \$100 million in billings per year (Boktor, Hanna & Menassa, 2014; Hanna, Boodai & El Asmar, 2013). Firms fitting the aforementioned criteria were specifically targeted as potential participants in the first phase of

data collection, as they would have had the most exposure and experience with the BIM software selection process.

Additionally, participants from these firms fulfilled the criteria of either having been directly involved in the decision-making process for BIM software selection and/or had experience with at least 2 of the BIM software used in that sector for a minimum of 1 year.

1.3.1. MEP related BIM software

According to previous research conducted by Kent (2014); Boktor, Hanna and Menassa, 2014; Hanna, Boodai and El Asmar, 2013); and the Smart market report (2009), the top uses of BIM software in the MEP sector were for clash detection, visualization and shop drawings. These were then followed by quantity take off and cost estimation, as well as project scheduling (Eastman, Teicholz, Sacks, & Liston, 2011; Gilligan & Kunz, 2007; Ruiz, 2009). Based on these findings, the scope of software considered in this research was limited to the identified categories of use, outlined in table 1.1.

1.3.2. Categorization of criteria

An important factor when creating this framework was to identify all the viable criteria for BIM software selection considered within the MEP sector of the AEC industry. All identified criteria were categorized under the broad definitions of functional and non-functional criteria.

In addition to this, the criteria were further categorized into objective or subjective criteria. For the purpose of this study, objective criteria refer to those that do not illicit biased judgement in order to determine their applicability from one software to another. The subjective criteria on the other hand, are those that cannot be rated fairly or unambiguously by any one

person or group without prior prejudice – since they would be relying solely on their own personal experience, and this differs greatly from person to person.

Table 1.1

Broad List of BIM software used in the MEP sector and their vendors

Software	Vendor	Software	Vendor
3D MEP/PREFAB		4D BIM	
Autodesk REVIT MEP	<i>Autodesk</i>	Synchro	<i>Synchro Ltd</i>
Bentley Hevacomp Mechanical Designer	<i>Bentley</i>	Vico Software	<i>Trimble</i>
AECOSim Building Designer	<i>Bentley</i>	Navisworks	<i>Autodesk</i>
4Ms Finehvac + Fineelec + Finesani	<i>Ghery Technologies</i>	Bentley Project Wise	<i>Bentley</i>
Digital Project MEP Systems Routing	<i>Ghery Technologies</i>	Innovaya	<i>Innovaya</i>
Auto CADMEP	<i>Autodesk</i>	Primavera	<i>Oracle</i>
Graphisoft MEP Modeler	<i>Graphisoft</i>	5D BIM	
Cadpipe HVAC	<i>AEC Design Group</i>	Innovaya	<i>Innovaya</i>
CAD MEP Planca Nova	<i>Trimble</i>	Vico Software	<i>Trimble</i>
Trimble Pipe Designer			<i>Beck Technology</i>
3d/Quickpen Piping Designer 3d	<i>Trimble</i>	Dprofiler	
MagiCAD	<i>MagiCAD</i>	QTO	<i>Autodesk</i>
DDS-CAD MEP	<i>Nemetschek</i>	Coordination/Clash Detection	
CADMEP+	<i>MAP</i>	Navisworks	<i>Autodesk</i>
Plant 3d	<i>Autodesk</i>	Solibri	<i>Solibri</i>
Sketchup	<i>Trimble</i>	Vico	<i>Trimble</i>
Archicad	<i>Graphisoft</i>	Tekla BIMsight	<i>Tekla</i>
Mep Designer	<i>Trimble</i>	Smartplant Review	<i>Intergraph</i>
CADMEP	<i>Autodesk</i>	Bentley Project Wise	<i>Bentley</i>
EST MEP	<i>Autodesk</i>	Digital Project Designer	<i>Ghery Technologies</i>
CAM Duct	<i>Autodesk</i>	Rendering/Animation	
CAD MEP (Cadduct / Cadmech)	<i>MAP</i>	Navisworks	<i>Autodesk</i>
CAD Pipe Commercial Pipe	<i>AEC Design Group</i>	3d Max	<i>Autodesk</i>
Fabrication for ACAD MEP	<i>East Coast CAD/CAM</i>	Lumion 3d	<i>Lumion</i>

The labels of functional vs. non-functional; and objective vs. subjective were used to categorize and group the identified criteria together. These groupings were performed for clarity, as different criteria serve different purposes during the course of this study. The specific groupings are further discussed in chapter 3. Table 1.2 shows the preliminary list of BIM software selection criteria obtained from literature, and their categorizations using the aforementioned labels described. More detail on the sources for each of the criterion can be found in Appendix A and Appendix B.

This preliminary list of criteria was used as a starting point during the first phase of this research, and was altered as needed, based on feedback from the participants. The initial questions used in the first phase of the research can be found in Appendix C and Appendix D.

Table 1.2

List of preliminary criteria and their categorizations

CRITERIA		OBJECTIVE	SUBJECTIVE	FUNCTIONAL	NON FUNCTIONAL
1	Flexible conceptual design modeling / design freedom				
2	Co-ordination/interference checking	y	y		
3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	y	y		
4	Ease of editing and adding custom components /object libraries		y		
5	Use of software application required by contract/company's business strategy	y		y	
6	In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents	y	y		
7	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members	y	y		
8	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dfx etc]	y	y		
9	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application		y	y	

Table 1.2 continued

CRITERIA		OBJECTIVE	SUBJECTIVE	FUNCTIONAL	NON FUNCTIONAL
10	Initial investment costs for hard & software, implementation and training; expected ROI	y			y
11	History tracking, change management, data management and automated updating		y	y	
12	Improved link from design to fabrication; support for rapid prototyping and 3d printing		y	y	
13	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources		y		y
14	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].	y		y	
15	Ability to efficiently work on large projects without resulting in cumbersome file sizes		y	y	
16	Security and access controls, with recovery mechanisms to ensure data integrity	y		y	
17	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]		y	y	
18	Known successful BIM cases by major subcontractors/business partners	y			y
19	Number of third-party developers with add-on applications for the tool	y			y
20	Market share leadership position of the vendor offering the BIM solution	y			y
21	How well it can be adopted, without conflict, into the company's traditional work process		y		y
22	Built-in ability to generate highly-photorealistic renderings and animations	y		y	
23	Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)	y		y	
24	Availability of extensive out-of-the-box content/object libraries		y	y	
25	Ability to capture local building codes and standards/ support for LEED	y		y	

1.4. Significance

Although it is pertinent for companies to have guidance when trying to determine which of the numerous, viable BIM software will best suit their needs, there is no widely accepted and publicly available decision making framework, and evaluation criteria for the MEP contractors to follow when selecting BIM software. The knowledge generated from this research will be

beneficial to most – if not all – companies within the MEP sector of the AEC industry, that are going through the selection of BIM software. It will be especially useful to companies that are going through the process for the first time, as this will be an appropriate and helpful guide that can be adapted to suit the needs of the company.

The main benefit of the results from this research will be the inevitable reduction of time and resources spent during the decision-making process, thereby facilitating an easier and smoother transition to BIM software in a firm.

The immediate goals and contributions of this research are:

- Describe a software selection decision-making framework for the MEP firms.
- Identify a list of user needs and evaluation criteria when seeking out various software
- Identify a list of user rating/ranking for each identified criterion.
- Determine an appropriate modeling technique that can aid in the decision-making process.
- Create an online web based decision support system that can be used to facilitate a firm's decision making process for BIM software selection.

1.5. Assumptions

The assumptions for this research include the following:

- It is assumed that at the end of the first phase, the initial set of questions used will be refined and suitably adjusted based on feedback, for use in the second phase.
- It is assumed that the initial set of criteria identified will be refined based on the feedback provided during the course of this research, in order to appropriately represent the needs of each of the specialized facets of the AEC industry.

- It is assumed that the majority of the larger MEP companies would have a higher level of BIM experience and maturity as compared to smaller companies.

1.6. Limitations

The limitations for this research include:

- Only companies willing to participate in the study will be included in the samples.
- Only companies that have in-house BIM departments will be used in this research – those that employ third parties will not be included.
- Third party modelers will not be included in the scope of this research.
- Only the following uses of BIM software will be considered for the software evaluations:
3D modeling/ shop drawing/ prefabrication; 4D and 5D BIM; clash and collision detection; as well as visualization.

1.7. Delimitations

The delimitations for this research include:

- Only companies within the US will be included in this research.
- Only BIM software used by sampled companies that fall within the constraints of this research will be considered.
- BIM software for the following will not be considered: civil and infrastructure, site logistics, fire protection, Building Performance Simulation, Facility Management, air flow analysis, acoustical analysis, and environmental analysis.

1.8. Chapter Summary

In this chapter, the motivation behind this study has been explored. The main research question on which the study is based was also introduced, along with the subsequent minor research questions for which answers will be uncovered during the course of this research. Next, a background and literature review will be presented.

CHAPTER 2. LITERATURE REVIEW

In this chapter, the relevant literature pertaining to the major topics playing a role in this research will be explored. These major topics include Building Information Modeling, Software selection frameworks, Multicriteria Decision making methods and Decision support systems. These will be reviewed in order to provide a broader understanding of the principles and methods in the subject area which will be applied later on in the methodology of this dissertation.

2.1 Building Information Modeling

Building Information Modeling (BIM) as a technology and a concept, is firmly making a lasting impression in the Architecture Engineering and Construction (AEC) industry. BIM is rapidly replacing its 2D Computer Aided Design (CAD) predecessors as a more efficient means of communicating designs (Arayici, Khosrowshahi, Ponting, & Mihindu, 2009). For certain AEC professionals, BIM represents a process; for some, it is interpreted as a product; and for others, BIM is considered as a tool (Zuppa, Issa, & Suermann, 2009).

As a process, the National Building Information Model Standard project committee (NBIMS) describes Building Information Modelling (BIM) as representing “...an interoperable process for project delivery—defining how individual teams work and how many teams work together to conceive, design, build & operate a facility.” (NBIMS, 2015, para. 7).

As a technology/tool, Eastman et al., (2011) refer to BIM as being a disruptive technology, that will reshape the AEC industry, while Zuppa, Issa and Suermann (2009) refer to it as a “...tool for visualizing and coordinating AEC work and avoiding errors and omissions.” (p. 150).

As a Product, BIM is described as, “an intelligent 3D virtual building model that can be constructed digitally by containing all aspects of building information — into an intelligent format that can be used to develop optimized building solutions with reduced risk and increase value before committing to a design proposal,” (Woo, Wilsmann & Kang, 2010, p. 538).

For the purpose of this research, the concept of the use of BIM as a technology/tool was adopted. This research subsequently investigated the factors involved in the selection of BIM tools, within the MEP sector of the AEC industry.

2.2 BIM Software Selection Considerations

Although literature supports the notion of the need for software evaluation criteria and a selection framework for BIM in the AEC industry (Omar, Nawi & Nursal, 2014), there is currently very limited research into the documentation of a framework for the decision-making process in the AEC industry. A study by Khemlani (2007) focused mainly on identifying the criteria related to Revit and Bentley BIM software, while the work of Won and Lee (2010) had only a slight emphasis on the general software selection criteria.

For most companies, seeing BIM being successfully implemented by others is enough to nudge them in that direction as well. However, since the inception of BIM, great strides have been taken to improve upon BIM software capabilities, catapulting the software from 3D to nD (Eastman, Teicholz, Sacks, & Liston, 2011). As a result, the AEC industry has experienced a burgeoning of varied BIM software in the market, making it more difficult for companies now breaking into BIM to discern and select the most appropriate software for use.

According to Hartmann, Fisher and Haymaker (2009), projects within the AEC industry differ greatly and require a variety of tools and skillsets in order to accomplish. It is therefore

important for companies to keep up with the various technologies available which offer the required tools to accomplish projects. Developing these tools in-house is a tedious and specialized task that many AEC companies are not equipped for. It is therefore much simpler to purchase a packaged, off-the-counter application which possess the functionality they require (Hartmann, Fischer & Haymaker, 2009).

2.2.1 Software Selection

As stated by Smith and Tardif (2009), selected software should enable companies to “...do more with less...” (p. 16). The identification of a suitable software during the decision-making process is a small part of a larger, problem solving process that involves a lot of effort, careful thought and time. Several factors come into play and need to be considered thoroughly in order to ensure the right choice is made. Amongst these factors are user needs, cost, desired functionalities and current company workflow and practices.

2.2.1.1 People concerns and its impact on the selection procedure

A major aspect of software selection which is commonly overlooked is the human factor - an oversight that could easily lead to delays or unsuccessful adoption process (Othman, Mazen, & Ezzat, 2010). To facilitate the process of accepting impending change, people's attitudes and preconceptions need to be altered (Davis & Songer, 2008). The human factor should thus be considered through inquiry by the selection of a representative team. All individuals involved with the use of the software at all company levels need to be represented on the project team that deals with the planning and decision-making process (Kent, 2014). This should include not only those at the executive and managerial levels, but also the office and field users of the software.

Lack of competency was listed as the third highest risk item in the MEP trades (Boktor, Hanna, & Menassa, 2014). Ensuring the needs of the end users are met, and not only the needs of upper management, encourages the adoption process. For this reason, training is identified as a major BIM investment (Hanna, Boodai, & El Asmar, 2013) underscoring the importance of developing user competency. Workshops, demonstrations and training sessions are thus highly recommended as they ease the transition and allow the employees to feel in control, making them less likely to resist the change (Intelera, 2010).

2.2.2 BIM USE in MEP

Literature suggests that AEC companies seem to rely primarily on case studies from other companies and their own opinions to decide which BIM software to adopt (Won & Lee, 2010). However, the variety of BIM capable software available has increased tremendously, providing even more options to sift through. BIM software now can be broadly categorized into several domains by use, as shown in the table 2.1.

According to previous research conducted by Kent (2014); Boktor, Hanna and Menassa (2014); Hanna, Boodai and El Asmar (2013); and the Smart market report (2009), the top uses of BIM software in the MEP sector were for clash detection, visualization and shop drawings. These were then followed by quantity take off and cost estimation, as well as project scheduling (Eastman et al, 2011; Gilligan & Kunz, 2007; Ruiz, 2009).

Table 2.1

Categories of BIM software Use

List Of categories of BIM software use
Conceptual Design tools
BIM authoring tools -
Architecture/Structure/MEP
BIM Structural Analysis tools
BIM Energy Analysis tools
BIM Simulation tools
BIM Fabrication tools
BIM Management tools
Quantity take off and estimation tools
Scheduling tools
Rendering/Visualization tools

However, even with this narrowed down categorization of BIM uses in the MEP sector, there would still be quite a number of options to choose from, requiring further detailed guidance amongst the many software choices available on the market. The average manager may be unable to carefully scrutinize the many choices - due to lack of sufficient time, knowledge or data. Some companies go by the most popular software which may not be entirely appropriate to fit their needs (Smith & Tardif, 2009). This results in a company paying for extra software capabilities that they may never use. An efficient and informative software selection decision making procedure is thus an important and necessary tool.

The need for BIM is most evident when considering the potential it offers to avoid rework due to the ability for coordination and clash detection in the construction sector'. According to Hanna, Boodai, and El Asmar (2013) "Rework is typically caused by poor coordination and conflicts of systems, which is why these problems are most visible in labor intensive trades such as mechanical, electrical, and plumbing (MEP) construction" (p. 1).

A report by Hanna (2010) showed that close to 40-60% of a construction project's overall cost stems from the MEP components of the project. Boktor et al., (2014) also noted that the MEP trade was a follow-up trade, meaning that the role of the MEP contractors on a project was dependent on others for completion of complex building systems. BIM proves itself as a versatile tool in the MEP industry that offers improved accuracy, detail and efficiency, and minimizes rework to ultimately save on those associated costs.

Due to the reliant nature of the MEP trade, it is important to be able to exchange information with the other specialty trades. However, the different trades may not all use the same software for their work. This brings up the issue of interoperability, which deals with the ability to transfer file information from one format to another, between various software platforms. Interoperability is crucial as the exchange of information is a necessity.

The data richness of a building information model allows for spatial co-ordination, which is one of the primary and most important uses of BIM software in the industry. Being able to work together brings up the issue of worksharing and the inherent dependence on the reliability of the software being used to ensure data integrity, through change management of the shared central file.

Visualization is an aspect of BIM software that was found to be the third most significant reason for the investment in BIM by MEP contractors (Boktor et al., 2014). Project visualization that aids in communication of design intent, and is thus useful in the AEC industry for marketing concepts and projects to clients and prospective clients.

2.2.3 BIM Maturity

BIM maturity can be defined as the extent of defining, and integrating a highly-developed BIM standard on a project or within a firm (NIBS, 2007; Chen, Dib & Cox, 2012). BIM maturity models and indexes have been proposed by Richards (2010), Succar (2010), and the National Institute of Building Sciences (NIBS, 2007) amongst others.

The AGCA (2006) presents general guidelines contractors can follow for implementing BIM in their firms. Dib, Chen & Cox (2012) and Chen, Dib & Cox (2012) also present frameworks to test out the BIM maturity in firms. The purpose of the maturity index/model is to present a scale that can be used to determine the level of BIM expertise across projects and firms. Thus, a project that has a high score on the NIBS Capability Model, for example, can be said to have a more sophisticated level of BIM applied to it.

The factors used to rate this level of maturity can also be useful in determining the capabilities that a firm might look out for when assessing a software for use, depending on their need. These factors include, change management, interoperability, and work sharing processes. The factors for BIM maturity models were also considered when compiling the criteria from literature. This was in addition to various literature sources from which general criteria (Won and Lee, 2010; Gu and London, 2010), as well as software specific criteria (Khemlani, 2007) were found and gathered from.

2.2.4 Benchmarking and its role in the selection procedure

As stated by (Bhutta & Huq, 1999) “The essence of benchmarking is the process of identifying the highest standards of excellence for products, services, or processes, and then making the improvements necessary to reach those standards” (p. 254). There are several types

and functions of benchmarking, such as: product, process, generic and functional benchmarking (Bhutta & Huq, 1999). For the purpose of the BIM software selection procedure, only product and process benchmarking will be discussed here.

2.2.4.1 Product/software benchmarking

At the core of a selection procedure is the actual process of choosing the right fit, after all preliminary requirements are identified. When applied to software packages, benchmarking is a methodology that results in a comparative performance measure of multiple software operating under the same conditions (Stair & Reynolds, 2010).

Once the necessary criteria and list of potentially capable software have been identified in the initial decision-making process, benchmark testing can be used as a final determiner of which software package would be most appropriate for the company's needs. According to Haifang et al., (2010), the evaluation model and benchmark method are vital to the software selection process as they will reduce impreciseness if selected appropriately.

Software benchmarking tests are carried out by performing comparisons of one software package to another, and are weighted based on user input and expectations (Correia & Visser, 2008). If conducted successfully, benchmarking will result in an objective and more precise result. This is accomplished by taking into consideration all pertinent technical functionalities as well as the more ambiguous non-functional aspects of the software, and by weighing them together, present the optimal recommendation (Haifang et al., 2010).

2.2.4.2 Process/best practice benchmarking

When applied to companies, benchmarking can be described as referring to the process of comparing one's business processes to industry or to other companies (Bhutta & Huq, 1999). Through this comparison, improper and inefficient practices are highlighted and can be improved upon by analyzing the paths taken by more successful firms. This can be especially useful when a company is about to adopt a new software they do not know that much about. Guidelines from such benchmarking can be invaluable to a company's internal selection and decision-making process.

According to Tatum and Korman (1999), the current work process in the MEP sector is for the MEP design consultants or design-build contractors to create their systems independently. Systems such as the HVAC and piping are sized during this initial design, however other trades such as electrical are not. This implies that at the end of the design stage, some systems are drawn to scale, while others are not, and some may be drawn in great detail, while others are only depicted with lines and references for sizing. Coordination responsibility is then assigned to one firm, typically the general contractor (Tatum & Korman, 1999). The advent of BIM tools with enhanced clash detection, and worksharing, has encouraged more open communication between disciplines, in a work process known as the Integrated Process Delivery. This not only encourages communication but also enables concurrent work to be done on a central file, thus resolving clashes in real time (Smith & Tardif, 2009).

A general benchmarking methodology to improve a company's process flow would involve steps such as problem identification; needs and practices identification; identification of similar organizations; comparison of practices; formulation of improvement plan; implementation of improvement plan (Andersen & Pettersen, 1995). The best strategies

identified through this process can then be incorporated into the software benchmarking process and the systems implementation plan to ensure the smooth selection and execution of the software.

Currently, a BIM protocol was deemed as being the most highly important risk factor according to the study by Hanna, Boodai, and El Asmar (2013). A well-defined BIM protocol is needed, in order to define standards and ensure that quality control procedures are followed during the entire BIM process through all the phases of design. This aids in the monitoring of the access rights to the model, and liability involved with collaboration on a shared file (AGCA, 2006). A detailed BIM protocol would also include streamlined processes to follow, as well as the delegation of responsibilities and duties to the team members - enabling efficient communication and risk management (AGCA, 2006).

2.2.5 Cost

A survey conducted by Hanna et al., (2013) yielded responses that suggested that about 2% of the overall cost of a construction project was typically applied towards the implementation of BIM for the project workflow. The cost of implementing BIM can generally be credited to the following factors: Hardware costs - although most companies would most likely have the hardware to support most of the software, there may still need to be minor upgrades and enhancements in order to get the most out of the software; Software costs - which is usually per seat or license per year (Boktor et al., 2014). On average, software costs accounted for about 55 percent of total implementation costs (Olatunji, 2011). Although, companies are typically given a discount once they subscribe to a particular vendor and its product line.

In addition to the hardware and software costs, further basic criteria that go on to impact the overall cost of software adoption and implementation are: Training, Maintenance, Software Services (backup, storage hosting), Contingencies (insurance, initial consulting) and Recruitment (Boktor et al., 2014; Hanna et al., 2013; Olatunji, 2011).

Training of employees - As the software keeps getting updated year after year, with changes in interface and functionalities, the employees need to be constantly kept up to date in order to make the most of the new additions to the tools; Maintenance - this could be hardware or software maintenance and troubleshooting issues that may arise during the course of use of the software; Recruitment - in the event that a company does not have the required skilled personnel, they may deem it fit to hire on new employees to fill the roles that having BIM software requires. (Boktor et al., 2014; Hanna et al., 2013; Olatunji, 2011).

Undoubtedly, cost plays an important role in most decisions made in any organization. Business leaders tend to evaluate technology on the basis of acquisition cost rather than full revenue generating potential as well as the implementation cost. This results in the underutilization of most software due to poor matching or under exploitation of the acquired software (Smith & Tardif, 2009). Thus, although companies need to select carefully keeping in mind all the aforementioned factors, the cost of the implementation typically tends to have a major impact as well on the final decision made. A well-defined cost benefit analysis would be the best way to ensure a good match is selected – one that suits the needs of all those involved.

2.3 Software Selection Frameworks

According to Comella-Dorda, Dean, Morris, and Oberndorf (2002), a Commercial-Off-The-Shelf (COTS) software “is a product that is sold, leased, or licensed to the general public; offered by a vendor trying to profit from it; supported and evolved by the vendor, who retains the intellectual property rights; available in multiple, identical copies; and used without modification of the internals.” (p. 1). This is a description that certainly fits the majority, if not all, of the BIM software in the market today.

Thus, although there are no documented frameworks for decision making involving BIM software selection in the MEP industry, by considering BIM software as also being a COTS software, a number of frameworks for the evaluation and selection of COTS software can be considered and used as a starting reference point. Although primarily aimed at firms in the industry of software development and software engineering for various fields - these frameworks will be useful in serving as a structural guide when consolidating the collected data to form the ideal framework that will be most suitable for the MEP sector.

2.3.1 COTS based on Requirements Engineering

COTS based on Requirements Engineering (CRE), is an iterative goal oriented framework for software selection that utilizes the method of rejection to eventually choose a suitable software (Alves, & Castro, 2001). It focuses on using non- functional requirements in order to evaluate and select COTS products. The CRE framework considers factors such as the overall time needed, domain coverage, vendor input, and cost into consideration through the

evaluation process, and uses the AHP method when determining the ranking of alternatives and their benefits as per the identified criteria (Baharom, Yahaya, & Tarawneh, 2011).

2.3.2 Procurement-Oriented Requirements Engineering

Procurement-Oriented Requirements Engineering (PORE) is an iterative template based strategy of COTS product selection (Ncube & Maiden, 1999). PORE follows a template strategy that it uses for the acquisition and evaluation of COTS alternatives, but only provides a superficial view of steps to follow for a systematic evaluation (Tarawneh, Baharom, Yahaya & Ahmad, 2011). The PORE framework also uses the AHP method, as well as the out-ranking method, to aid in the evaluation of alternatives.

2.3.3 Off-The-Shelf Option

Off-The-Shelf Option (OTSO), is one of the initial methods for evaluating and selecting COTS software based on a cost and benefit analysis (Kontio, 1995). It was created as a customizable generic process model that could support many techniques. The OTSO could thus be used for which are used for deciding on appropriate criteria for evaluation; for the cost and benefits analysis of alternatives, and to support decision making methods such as the Analytical Hierarchy Process technique (AHP) (Baharom, Yahaya, & Tarawneh, 2011; Tarawneh, Baharom, Yahaya & Ahmad, 2011; Alves & Castro, 2001)

2.3.4 Social-Technical Approach to COTS Evaluation

The Social-Technical Approach to COTS software Evaluation (STACE) focuses on social issues and organizational issues involved in the COTS Product selection process, such as the incorporation of customer requirements and vendor capabilities (Kunda & Brooks, 1999; Tarawneh, Baharom, Yahaya, & Ahmad, 2011). STACE however, does not provide a definitive evaluative analysis of products with a decision-making technique, but merely recommends the AHP as a preferred method (Alves & Castro, 2001).

2.3.5 Generic Frameworks

The frameworks above can be seen to be attempting to compensate for deficiencies that exists in those before them. Work by Tarawneh, Baharom, Yahaya and Ahmad (2011) also contributes to this by providing a scrutiny and theoretical study of the aforementioned frameworks. By categorizing the similar processes and strategies into one overarching theoretical framework Tarawneh et al., (2011) created an amalgamated framework which successfully combines portions from the CRE, PORE, OTSO and STACE frameworks.

Comella-Dorda, Deam, Morris and Oberndorf (2002), also presented a description of the steps that could be followed in a selection and evaluation process. Their description dealt with assessing the appropriateness of specific COTS products for use in a system. Their paper is a theoretical discussion and description of the process. Table 2.2 provides a tabular summary of the simplified major steps in each of the frameworks discussed above.

As previously mentioned, there is currently no documented and in-depth description of the selection process or a declared framework to specifically guide in the selection of BIM software for MEP companies. Thus, none of these discussed frameworks for COTS can yet be

singled out as being an adequate representation of what goes on during the software selection process in the MEP sector.

Table 2.2

Summary of framework phases for COTS components selection

Alves & Castro (2001)	Kontio (1995)	Ncube & Maiden (1999)
<i>COTS-based Requirements Engineering (CRE)</i>	<i>Off The Shelf Option (OTSO)</i>	<i>Procurement Oriented Requirements Engineering (PORE)</i>
<ul style="list-style-type: none"> • Identification • Description • Evaluation • Acceptance 	<ul style="list-style-type: none"> • Search • Screening • Evaluation • Analysis • Deployment • Assessment 	<ul style="list-style-type: none"> • Requirement acquisition, definition & validation • Supplier selection • Software selection • Contract production • Package acceptance
Kunda & Brooks (1999)	Tarawneh, Baharom, Yahaya & Ahmad (2011)	Comella-Dorda, Deam, Morris & Oberndorf (2002)
<i>Social-Technical Approach for COTS selection (STACE)</i>	<i>Evaluation and Selection COTS Software Process</i>	<i>P.E.C.A.</i>
<ul style="list-style-type: none"> • Requirement elicitation • Social technical criteria definition • Alternatives identification • Evaluation/assessment 	<ul style="list-style-type: none"> • Planning • Preparation • Evaluation • Selection 	<ul style="list-style-type: none"> • Plan evaluation • Establish criteria • Collect data • Analyze data

The discussed frameworks showed a pattern of similarities within their stages. As such, for use in this research, the major commonalities present in the frameworks discussed were consolidated into: Criteria and Processes - the criteria being functional or nonfunctional; while the processes were summarized into preparatory, evaluative, and assimilation. These two major

pieces were simplified in order to depict a representation of the very basic structure of the framework as a starting point. This is visually displayed in figure 2.1.

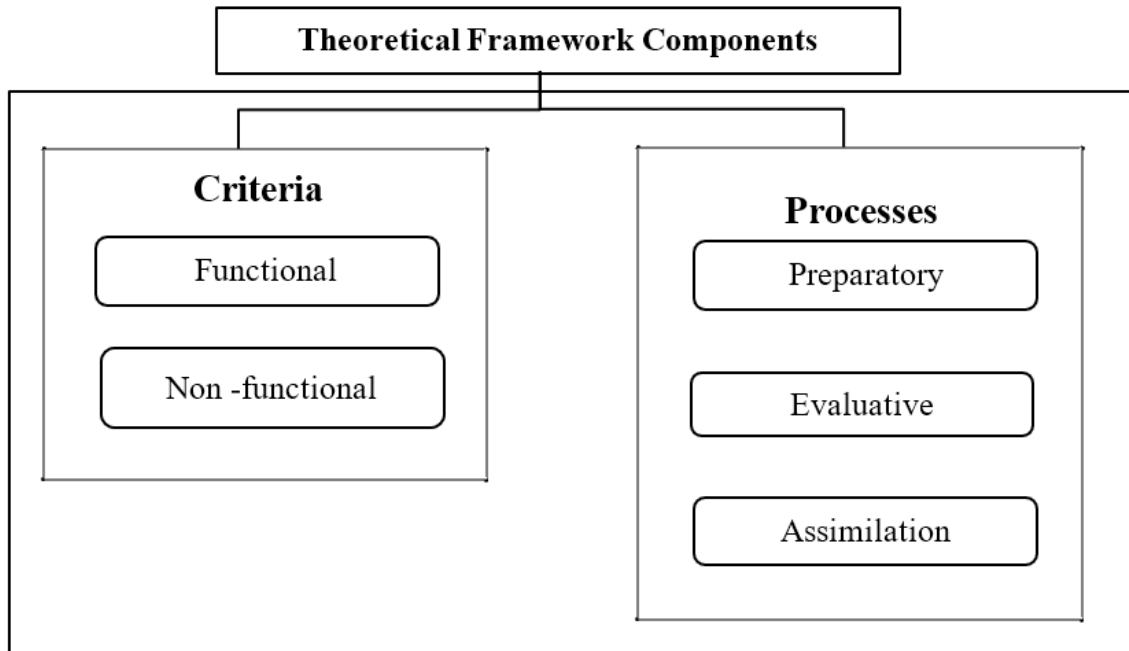


Figure 2.1 Proposed theoretical framework components

In the subsequent chapters of this research, the processes in figure 2.1 are verified and elaborated on. The current processes of software selection as it takes place in the MEP sector were documented. In addition, using data collected, and with findings from the industry professional's experience and practices, a tailored framework for the construction sector was developed.

2.4 Multi Criteria Decision Making Methods

There exists a myriad of multi criteria decision making methodologies (MCDMM) for decision making support in a variety of situations and scenarios (Toloie-Eshlaghy & Homayonfar, 2011). They range from simple and intuitive methods, such as the Weighted Sum Model (WSM); to the intermediate level – Analytic Hierarchy Process (AHP); to the rather complex level – MCDMM using Fuzzy logic. The increasing complexity of these methodologies evolved as a response to attempts to ensure more accuracy in the outcomes of the decision-making processes.

The frameworks being considered as a reference made mention of MCDMM such as the WSM and AHP, as possible alternatives for the decision-making methods implemented for the frameworks. As such, in order to determine which MCDMM would be the most appropriate for the BIM software selection process in the MEP sector, the methodologies of WSM, and the AHP will be examined. It is interesting to note that, according to Triantaphyllou and Lin (1996), the formula used for AHP is the same as that used for WSM, with the difference being that AHP uses relative values instead of actual values, making it a more suitable option for multi-decision making involving varying units. The WPM – being similar in nature to the WSM - will also be included in the simulation analysis.

2.4.1 Weighted Sum Method and Weighted Product Method

The weighted sum method (WSM) is one of the most well-known decision-making methodologies which involves assigning each alternative and criteria with a score and weight (Triantaphyllou & Mann, 1989). These are then multiplied and added together, with the

alternative receiving the highest score being the selected and preferred option (see figure 2.2). It is represented mathematically as follows:

$$A_i^{WSM} = \sum w_j a_{ij}, \text{ for } i = 1, 2, 3, \dots, m. \quad (1)$$

Where A_i^{WSM} is the score of the alternative being considered, a_{ij} is the score of alternative i and w_j is the weight of the importance of the criterion. A weakness of this method as pointed out by Triantaphyllou and Lin (1996), is that the WSM can only be used with attributes that are of the same units – due to the additive utility being applied.

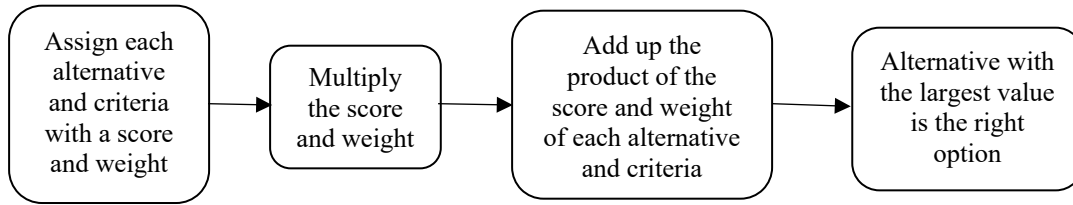


Figure 2.2 Weighted Sum Method steps

The weighted product method (WPM), similar to WSM, takes into consideration the same alternatives, and criteria, as well as their respective scores and weights (see figure 2.3). However, it uses the product of the ratio of scores of alternatives raised to the power of their weights, to determine which alternative out of a pair is ‘better’ than the other, depending on whether the ratio between the two is greater than 1 or not (Triantaphyllou & Mann, 1989). It is represented mathematically as follows:

$$B(A_p/A_q) = \prod (a_{pj}/a_{qj})^{w_j}, \text{ for } i = 1, 2, 3, \dots, m. \quad (2)$$

Where A_p and A_q are the alternatives being considered, a_{pj} and a_{qj} represent the score of alternative and w_j is the weight of the importance of the criterion.

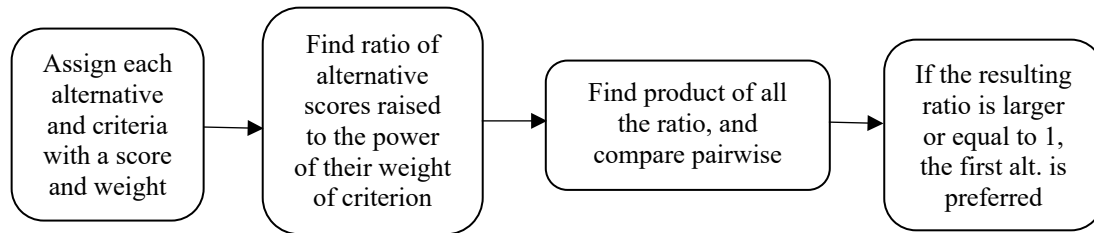


Figure 2.3 Weighted Product Method steps

2.4.2 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a methodology for decision analysis that “...allows a set of complex issues with impact on an overall objective, to be compared with the importance of each issue relative to its impact on the solution of the problem.” (Meade & Presley, 2002, p. 60).

The frameworks discussed in the section before all implemented or recommended the use of the AHP. The major steps for the AHP are summarized in the figure below (see figure 2.4):

- Decompose problem into hierarchy – goal, (sub)criteria, alternatives
- Perform pairwise comparison of alternatives per criteria
- Create decision matrix
- Calculate eigenvector for relative weights
- Check consistency of results
- Aggregate ratings and weights of each alternative per criteria

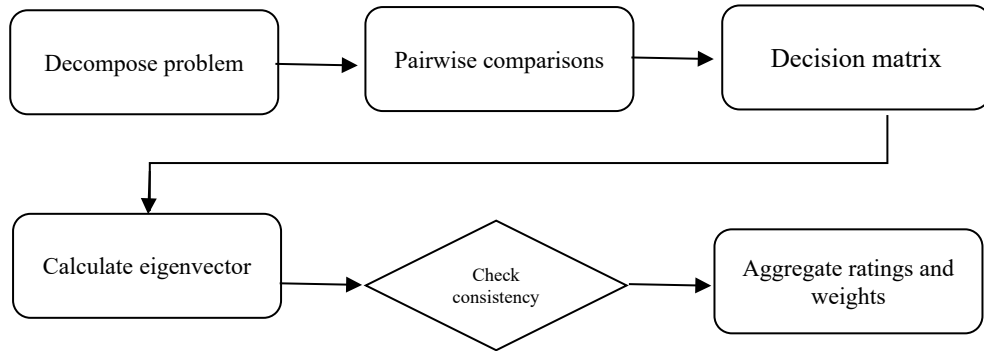


Figure 2.4 Analytic Hierarchy Process steps

Although widely accepted, the AHP has a weakness of priority reversal when an additional and identical alternative to one of the non-optimal alternatives is introduced (Belton and Gear, 1983). This is solved in the Revised-AHP by dividing the relative value of each alternative by the maximum value instead of having the relative values of the alternatives adding up to one (Belton and Gear, 1983).

2.4.3 Selection of MCDMM

As mentioned in the previous section, several factors such as dependencies, criteria type, number of criteria, number of alternatives, all affect the performance and complexity of the decision-making process. Thus, in order to select the appropriate MCDMM, it is important to understand the behavior of the criteria being used in the evaluative process. Table 2.3 summarizes the strengths and weaknesses of the MCDMM options described in this section.

Triantaphyllou and Sánchez (1997) demonstrated a sensitivity analysis methodology on the WSM, AHP and WPM decision making methods in order to demonstrate how robust each of

these methods were. The sensitivity analysis of a decision-making method indicates its tendency to produce a different outcome with varying values as input. The measure of sensitivity is an important due to the subjectivity of the user input and identification of importance of weights (Pamučar, Božanić, & Randelović, 2017; Triantaphyllou, & Sánchez, 1997).

Conclusions from past research indicated that neither the type of MCDMM, nor the number of alternatives being considered had much of an effect on the sensitivity analysis. Thus, the major factor that impacted the sensitivity analysis was the criteria and the relative weight or importance assigned to the criteria used for evaluation. Triantaphyllou and Sánchez (1997) determined that if the criteria were measured in relative terms, the criteria with the largest weight affected the sensitivity analysis the most. This effect was reversed if the criteria were measured in absolute terms.

Table 2.3

Strengths and weaknesses of the MCDMM under consideration

	Strengths	Weaknesses
AHP	Handles inconsistent data. Can handle both qualitative and quantitative data.	Cannot handle interdependent criteria.
WSM	Simple and intuitive.	Additive, not appropriate for multi-dimensional decision making problems
WPM	Eliminates units of measure, can handle multi-dimensional decision making	Cannot handle 0 values

2.5 Decision Support Systems

MCDMM are widely used alongside Decision Support Systems (DSS) by decision makers in various fields. DSS are interactive systems designed to support decision-making problems by utilizing “...data, models, visualizations and user interface to solve semi-structured or unstructured problems.” (Poletto, de Carvalho, & Costa, 2015, p. 14).

A DSS typically has a set of basic components: a database to store information that can be accessed; a model base which is the core of the system and handles the computational aspects of the process, as well as an interface the user interacts with (Poletto, de Carvalho & Costa, 2015). Although the final choice is made by the decision makers, the DSS is intended to provide an easy to use and intuitive interface that guides the user through the process, allowing them to create and review reports and visualizations of the data in order to support their final decision.

2.5.1 Web Based Decision Support Systems

The Web Based DSS (WBDSS) is typically hosted and made accessible to users via the internet. The trait of accessibility via the world wide web makes the web based DSS an ideal platform for reaching large numbers of people through the use of web sites and web pages (Palmer, 2002).

This global access also aids in facilitating the WBDSS function for group decision making as well. Ozer and Lane (2010) used this concept to create a WBDSS to support in solving decisions with relation to fish farming; while Hämäläinen and Mustajoki (1998) created the Web-Hierarchical Preference analysis - a Java-applet run decision making tool - on the World-Wide WEB. It is also known as the first WBDSS.

2.5.2 WBDSS Architecture

For the structure of the WBDSS, the Model-View-Control (MVC) paradigm as proposed by (Cruz-Reyes, Medina, & López, 2013) is a commonly adopted model. The MVC paradigm allows the separation of control, operational and presentational logic in a DSS. These sections of the WBDSS are explained below:

Model: In the model aspect of this paradigm consists of, the protocols, database and libraries associated with the DSS (Cruz-Reyes, Medina, & López, 2013). The MYSQL database - an open source relational database management system – is an example of such a database that could be used in order to store the relevant data and login information of the clients (Ozer & Lane, 2010).

View: in the view layer, the user interface of the DSS, with which the client interacts, is developed (Cruz-Reyes, Medina, & López, 2013). Most people tend to appreciate well-formed visual representations of ideas and concepts. This is especially true in an era when we are being constantly bombarded by information. Research suggests that several elements contribute to the usability of a site, which in turn determines the consumer response and experience, as well as the influence the medium has on the consumer and the overall success of the site (Palmer, 2002).

To enhance usability of the developed model web application will be designed to follow the Jakobs Nielsen's definition thereof, as described in the paper by Tripathi, Pandey and Bharti (2010):

- The interface appeals to the user to enhance its memorability;
- The utility provided will be efficient and easy to navigate,
- The system has few errors in order to ensure user satisfaction

Thus, the end result will be a simplistic and straightforward interface, set up to allow for maximum interaction between the user and the selection tool, while guiding the user through a step-wise approach that will provide useful detailed reports for final judgement.

Controller: In the controller layer, the issue of decision making is solved, using the identified MCDMM and the user rankings and data input (Cruz-Reyes, Medina, & López, 2013).

DSS hosted on the web are typically created with HTML, CSS, PHP and/or JavaScript. These are the most common languages used for developing and coding online and are determined to be the most suitable due to their versatility. These languages can also be used for creating interfaces for translating inquiries and information from an SQL database to the DSS interface and vice versa (Ozer and Lane, 2010).

2.6 Chapter Summary

In sum, this chapter presented the various subject areas connected with the MEP sector, BIM use, framework creation, decision making methods and criteria selection. It also explained the design of the WBDSS and rationale for the selection of the MCDMM. The following chapter will delve into the procedure and data collection strategies involved in this research.

CHAPTER 3. METHODOLOGY

In this chapter, the methodology for the research will be discussed. Specific strategies and procedures of collecting the data necessary for the successful completion of this research will be explained and justified. The phases of the research, the steps for analysis and validation will be elaborated on as well.

3.1 Overview and Data Collection Strategies

The main research question and sub questions as stated in chapter 1 were:

- How does a company in the Mechanical/Electrical/Plumbing sector of the Architecture Engineering and Construction industry select the appropriate Building Information Model software for their use?
 - What methodology do MEP firms follow in order to select their BIM software?
 - What is the most appropriate Multi-criteria decision-making method that can be applied to aid in the BIM software selection process for the MEP sector?
 - What are the rankings, by importance, of the software selection criteria identified as per the specialty sub sectors of the industry?

In order to answer these questions, an understanding of the rationale and methodology behind the decision-making processes taking place within the MEP sector of the AEC industry was required. To do this, a pragmatic paradigm was adopted.

The pragmatic paradigm assumes multiple realities that are relative to the individuals and to the context in which they are created. In other words, the world is experienced and interpreted

through the lens of each individual's subjective assessment and understanding. Thus, pragmatism looks to realize an answer which is practical and useful to individuals in their own defined context - rather than being solely defined by the researcher's objectivity (Creswell, 2013).

Pragmatism acknowledges the existence of multiple realities but does not pose a restriction on how that research can be determined. It is thus typically attributed to mixed methods research (Johnson & Onwuegbuzie, 2004). To that end, a mixed methods approach was selected for data collection and analysis.

The main data collection was conducted in 2 phases. The first phase relied on interviews in order to gather information, while the second phase relied on the use of a mixed method surveys to gather the necessary qualitative and quantitative data. Figure 3.1 depicts the outline of steps in this research within its major phases.

Each of the depicted steps and phases in the figure are discussed in the sections to follow. Section 3.1.1 - 3.1.2 delves into the data collection strategies employed in this research; while section 3.2 outlines the sampling strategies taken for each phase. Section 3.3 presents a detailed breakdown of the procedures to be followed in each phase; while section 3.4 explains the steps taken for data analysis. Section 3.5 concludes by outlining all the considerations and measures taken to endure the reliability and validity of this research and its instruments.

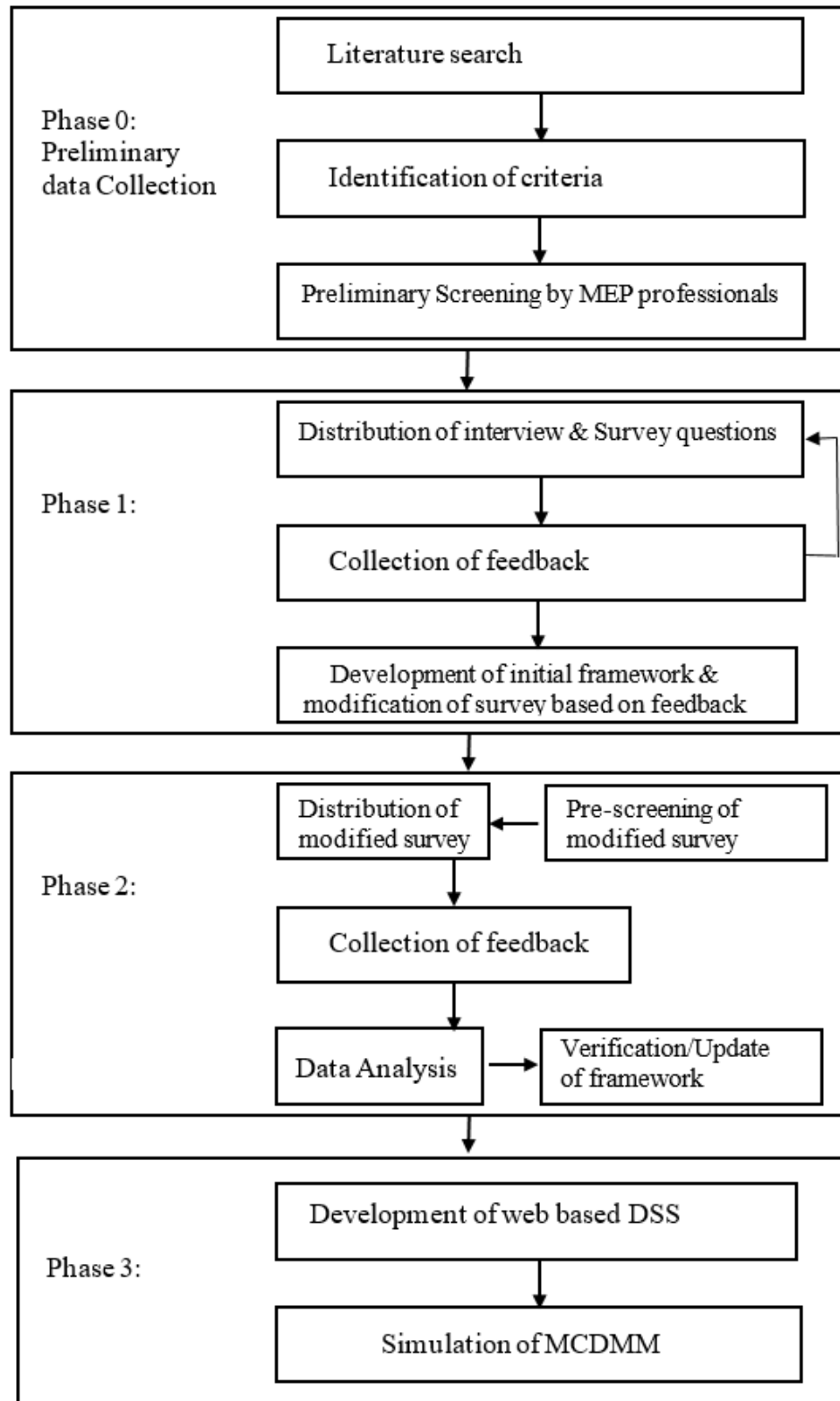


Fig 3.1 Summary of Research Phases

3.1.1 Collection Strategy 1 - Interviews

One on one phone interviews with professionals from the MEP sector of the were conducted during the first phase of the research. The interviews were structured and participants were provided with the interview questions beforehand.

Participants in the first phase of data collection were also sent the preliminary version of the data collection survey. They were asked to review the survey and identify any suggestions for improvement on the questions. Their responses were collected and analyzed before the one on one phone interviews were conducted. During the phone interview session, their opinions, suggestions and feedback on the survey were further discussed. They were also asked to describe the process of BIM software selection in their firm. Details of the analysis and procedures can be found in the sections to follow.

The interview protocol for phase 1 can be found in appendix D. This protocol was constructed keeping in mind the objective of the research. The questions related directly to the subject matter of interest and were intended to guide the conversation into the inquiry of details about the pilot survey as well as the decision-making process in a structured manner (Seidman, 2013).

3.1.2 Collection Strategy 2- Surveys

Surveys were deployed in both phases of the research – although they were aimed at gathering data for different purposes. The survey instrument stemmed from one initial survey, and was modified based on the expert opinions and feedback received in the first phase, giving rise to 2 distinct versions of the surveys.

Survey version 1: The first survey – and preliminary version of the survey - was sent out during phase 1 of the research as a pilot run. This survey was sent out with the aim of gathering feedback on the content and presentation of the survey questions. Based off the feedback from the responses and follow up interviews, it was then modified for the second phase of the research. The survey questions were adopted from previously conducted and validated studies into BIM maturity done by Chen, Dib and Cox (2012). The Cronbach's alpha coefficient was found to be 0.83, indicating that the survey was a valid instrument of measure (Chen, Dib and Cox, 2012).

Due to the overlapping nature of the data being collected, the questions were only slightly modified. The modified survey used in this research can be found in Appendix C, and has 3 parts.

- The first part inquired on general company information such as firm type, size, length of BIM adoption, and software being used.
- The second part inquired on personal information such as experience with BIM, participation in previous BIM software selection processes and position in the company.
- The third part of the survey required participants to rank the importance of a list of presented selection criteria they took into account for the evaluation and adoption of the software.

Survey version 2: This survey was an improved version of survey 1. It was first sent out in the latter stage of the first phase, in an attempt to assess the face validity of the improved questions from phase 1. The face validation step provided an additional layer of vetting by industry professionals to determine the clarity of questions. More feedback on potential improvements

was also gathered at this step. Once the vetting was complete, the survey was distributed during the second phase to various user groups and associations. This version of the survey also had an image depicting the draft of the preliminary framework included, for verification and validation by the industry experts taking the survey.

The version of the survey sent out in phase 2 was designed with a cut off in the second part. Participants who indicated that they had not previously taken part in the software selection process were redirected past the portion of the survey that had questions pertaining to the framework. Participants who indicated that they did previously take part in the decision-making process were allowed to continue onto to the additional section that covered the decision-making process framework details. The flow of the survey logic is depicted in figure 3.2.

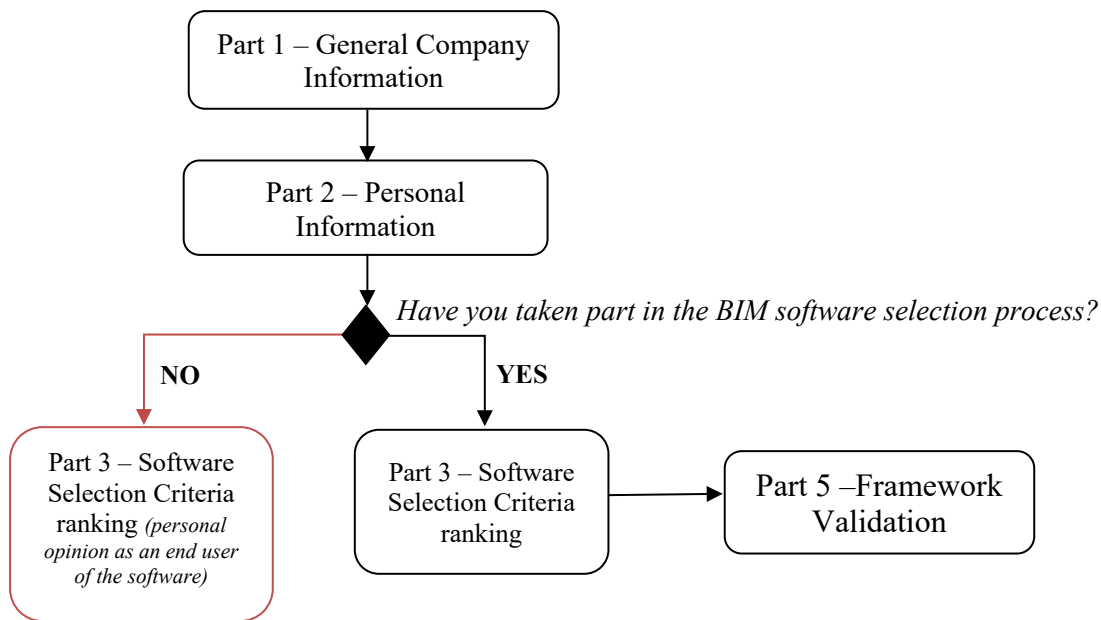


Figure 3.2 Survey logic flow chart

3.2 Sampling Strategy

The sampling design used was that of a stratified one-stage cluster design. The primary sampling units were the MEP firms in various locations in the US, and the participants were the professionals within each firms BIM department. Participation in this research was voluntary, however firms and participants contacted had to meet certain requirements as discussed below.

3.2.1 Criteria for companies

Research by Hanna et al., (2013) and Boktor et al., (2014) showed that MEP firms were still relatively new to the use and adoption of BIM, with approximately 40% of MEP firms having 4 years or more of BIM experience, and approximately 60% having 3 years or less of experience with BIM software. They thus concluded that MEP contractors' expertise or maturity with BIM could be categorized based on the number of years of BIM usage: those with more than 3 years were advanced or experts; while those with less than 3 years were considered beginners or not as efficient with BIM. Moreover, Hanna et al., (2013) and Boktor et al., (2014) also stated that the larger MEP firms were higher adopters of BIM tools. Thus, companies considered for this research had to fulfil the following requirements:

- Had been using BIM for a minimum of 3 years.
- Company size determined by billings as suggested by Hanna et al (2013) and Boktor et al., (2014) should be a minimum of \$10 million per year.

3.2.2 Criteria for individuals

Participants in the interviews and survey were employees from the BIM department of the aforementioned firm types. Specifically, the BIM managers, BIM directors, BIM engineers and /or coordinators. Participants also had to fulfil the criteria of either having been directly involved in the decision-making process for BIM software selection and/or had experience with at least 1 of the BIM software used in that sector for a minimum of 1 year.

3.2.3 Sampling – Phase 1 & 2

For the first phase - involved interviews – it companies sought had to fulfil the aforementioned criteria in section 3.1.2. These companies were identified using listings from the Engineering News Record (ENR) 2015 top 600 specialty contractors (ENR, 2015). Companies were contacted from this list until participation from at least 12 companies that fit the requirements described earlier was secured. For the latter part of the first phase, participants that took part in the preliminary screening of criteria were contacted in order to perform a face validity check on the edited surveys before they are widely distributed.

The vetted survey was then disseminated to participants, sought out from associations linked with the aforementioned sub sectors of the AEC industry, as listed below:

- Mechanical Contractors Association of America (MCAA)
- National Electrical Contractors Association of America (NECAA)

Furthermore, specific software used in this sector were identified by the interviewed professionals during the first phase. User groups for those trade specific software, such as the LinkedIn MEP BIM user group, were identified as an additional source of potential participants, for further distribution of the survey.

3.3 Procedure breakdown

Before the beginning of this research, a preliminary list of criteria was compiled from literature. Table 1.1 shows this list of the 25 criteria, the sources for which were obtained from past research, which covered general criteria (AGCA, 2006; Gu & London, 2010; Ruiz, 2009; Won & Lee, 2010); software specific criteria (Arayici et al., 2011; Khemlani, 2007); as well as criteria covering issues of policy and BIM maturity (Chen, Dib & Cox, 2012; Dib, Chen & Cox, 2012; NIBS, 2007; Succar, 2010).

A total of approximately 120 criteria were initially listed from each of the sources. Coding of this extensive list was performed, in order to group redundancies together and consolidate similarly themed criteria. Coding is described as a process of analysis in which researchers subdivide and assign data to categories, in order to deduce meaning from the information (Basit, 2003; Seidman, 2013). The criteria were thus arranged into categories based off similar wording or themes. Those that were found to be very similar or themed on the same concept were grouped together as one.

For example, the following criteria from Khemlani (2007)

- *“Direct integration with structural analysis applications*
- *Direct integration with energy analysis applications*
- *Integration with facilities management*
- *Integration with space programming and planning tools” (pg. 3 ,*

were consolidated to

- *Direct integration with external applications (energy, structural project management, FM, space programming tools, etc.).*

This process of coding was first done manually on paper, and then transferred and rescreened on a word processor, as recommended by Seidman (2013). This was the first pass, which resulted in 44 criteria, and are listed in Appendix A.

The entire process was repeated, which further consolidated the criteria to 25. These 25 criteria were then distributed to 6 randomly selected MEP professionals using BIM, for screening. This was done in order to ensure clarity and make any necessary corrections to the preliminary list before the first phase of the research began.

During this review the professionals were asked to indicate which criteria they considered when selecting BIM software for their own company. They were also asked to indicate any further criteria that may not have been included in the initial list. The results of which are shown in table 3.1.

Table 3.1

Preliminary votes obtained on criteria list from literature

	CRITERIA	VOTES
1	Flexible conceptual design modeling / design freedom	6
2	Co-ordination/interference checking	5
3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	5
4	Ease of editing and adding custom components /object libraries	5
5	Use of software application required by contract/company's business strategy	5
6	In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents	4
7	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members	4
8	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dxf etc]	4
9	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application	4

Table 3.1 *continued*

CRITERIA		VOTES
10	Initial investment costs for hard & software, implementation and training; expected ROI	4
11	History tracking, change management, data management and automated updating	3
12	Improved link from design to fabrication; support for rapid prototyping and 3d printing	3
13	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources	3
14	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].	3
15	Ability to efficiently work on large projects without resulting in cumbersome file sizes	2
16	Security and access controls, with recovery mechanisms to ensure data integrity	2
17	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]	2
18	Known successful BIM cases by major subcontractors/business partners	2
19	Number of third-party developers with add-on applications for the tool	1
20	Market share leadership position of the vendor offering the BIM solution	1
21	How well it can be adopted, without conflict, into the company's traditional work process	1
22	Built-in ability to generate highly-photorealistic renderings and animations	0
23	Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)	0
24	Availability of extensive out-of-the-box content/object libraries	0
25	Ability to capture local building codes and standards / support for LEED	0

During this preliminary screening, it was seen that the last 4 criteria were listed as having no importance. However, they were still retained in the list sent out during phase 1, in order to ensure that they were represented and to verify whether or not they truly had no impact on the selection of BIM software.

The participants in the preliminary screening also did not indicate the need for further addition of criteria. However, this option was still presented in the interview questions of phase 1, to ensure that no potential criterion was missed.

Based on the categorization mentioned in chapter 1 of functional and non-functional vs objective and subjective, the identified criteria were separated into the following categories:

- A - Objective functional;
- B - Objective non-functional;
- C - Subjective non-functional;
- D - Subjective functional,

as shown in tables 3.2 and 3.3.

Table 3.2

Subgroup of objective and functional and non-functional attribute criteria

OBJECTIVE FUNCTIONAL CRITERIA	
A1	Co-ordination/interference checking
A2	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling
A3	In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents
A4	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members
A5	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, etc]
A6	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].
A7	Security and access controls, with recovery mechanisms to ensure data integrity
A8	Built-in ability to generate highly-photorealistic renderings and animations
A9	Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)
OBJECTIVE NON-FUNCTIONAL CRITERIA	
B1	Use of software application required by contract/company's business strategy
B2	Initial investment costs for hard & software, implementation and training; expected ROI
B3	Known successful BIM cases by major subcontractors/business partners
B4	Number of third-party developers with add-on applications for the tool
B5	Market share leadership position of the vendor offering the BIM solution

Those that fall under objective functional will be used for the first iteration of the web based decision support system/framework.

Table 3.3

Subgroup of subjective functional and non-functional attribute criteria

SUBJECTIVE NON-FUNCTIONAL CRITERIA	
C1	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources
C2	How well it can be adopted, without conflict, into the company's traditional work process
SUBJECTIVE AND FUNCTIONAL CRITERIA	
D1	Flexible conceptual design modeling / design freedom
D2	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application
D3	History tracking, change management, data management and automated updating
D4	Improved link from design to fabrication; support for rapid prototyping and 3d printing
D5	Ability to efficiently work on large projects without resulting in cumbersome file sizes
D6	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]
D7	Availability of extensive out-of-the-box content/object libraries
D8	Ability to capture local building codes and standards / support for LEED
D9	Ease of editing and adding custom components /object libraries

Those that were objective nonfunctional were expected to vary via firm, and were identified as criteria of which an importance ranking would vary greatly within each individual firm during their decision-making process.

The two latter subgroups, of subjective functional and subjective nonfunctional were proposed for use as the second level needs during the software selection process. The rest of this section will further describe the subsequent phases of the research.

3.3.1 Phase 1 Procedure Description

During the first phase, a minimum of 10 BIM professionals with knowledge of the software selection process were sought out from each of the identified sub sectors (M/E) in the AEC industry. There were 3 main steps in this phase.

Step 1: The professionals were provided with initial survey questions, to which were asked for responses on the clarity of the questions and content. Their responses were collated and analyzed. The analysis was done in order to identify any ambiguities in responses and were factored into the next phase in order to improve the flow of the survey questions. The BIM professionals were then provided with the interview questions before hand.

Step 2: The pre-survey was followed up by a recorded, structured phone interview for approximately 10 minutes. During this interview session, the professionals were asked for clarification on feedback on the survey questions (if needed), and the BIM software selection process as it took place in their experience. A similar process of sending out surveys before conducting interviews, was followed by CIFE in their study of VDC use in 2007 (CIFE, 2007).

- *Step 3:* The participants will be sent the transcribed phone interview for member checking, in addition to the preliminary framework, for review. The updated survey was then sent out to more professionals for face validation.

The goals of this phase are twofold:

- As a first step to ensure there was no ambiguity in the interpretation of questions, and gather professional feedback which was then used to modify and restructure the questions as needed for the subsequent data collection phase.
- To gather qualitative data for the creation of the preliminary decision-making framework.

3.3.2 Phase 2 Procedure Description

The feedback from phase 1 aided in the modification of the questionnaire used in the survey for data collection in this phase. The updated survey was then sent out to selected experts for a final review, before being disseminated to participants of associations mentioned in section 3.2.3 and user groups specific to their subsectors.

The survey also contained a visual representation of the framework for review by those knowledgeable in the selection process, and followed the survey logic described in section 3.1.2. The desired end result of this phase was:

- Establishing the rankings of the software criteria
- Validating the framework structure(s) obtained from phase 1.

3.3.3 Phase 3 Procedure Description

In the final phase of this research, the collected information was incorporated into a proof of concept design of the web based decision support system (WBDSS). The web tool was built on the 3-tiered model of website design. This model is composed of a Web server which communicates and collects input from the users using HTTP (Hypertext Transfer Protocol); an application server; and a back-end database server which stores all the necessary data collected.

For this proof of concept interface, Apache Tomcat was used as the web and application server environment for compiling and testing the code, while JavaScript Object Notation (JSON) was used as a temporary storage in place of a more sophisticated database management system such as MySQL. JSON is a lightweight web data exchange format with a high parsing efficiency that allows easy generation and translation by computers (Wang, 2011).

In addition to the WBDSS, a simulation of the MCDMM, using the MATLAB software package, was performed in this phase in order to assess the consistency of the selected methods when compared with one another. The output from these tests and simulations were then examined to determine the performance of the 3 methodologies being considered.

The MCDMM tested during this simulation were the Weighted Sum Method (WSM), the Weighed Product Method (WPM), and the Analytic Hierarchy Process (AHP). The methods for the AHP, WSM and WPM methods were programmed and simulated within MATLAB, following the steps in the flow chart shown in figure 3.3, in order to replicate the function of the methodologies being considered. Two random matrices were generated: one was used for the eigen vector that served as the weights assigned to the criteria; while the other was used as user input for all 3 methods.

The desired end result of this phase was:

- Set up the proof of concept version of the WBDSS
- Compare the consistencies of the MCDMM

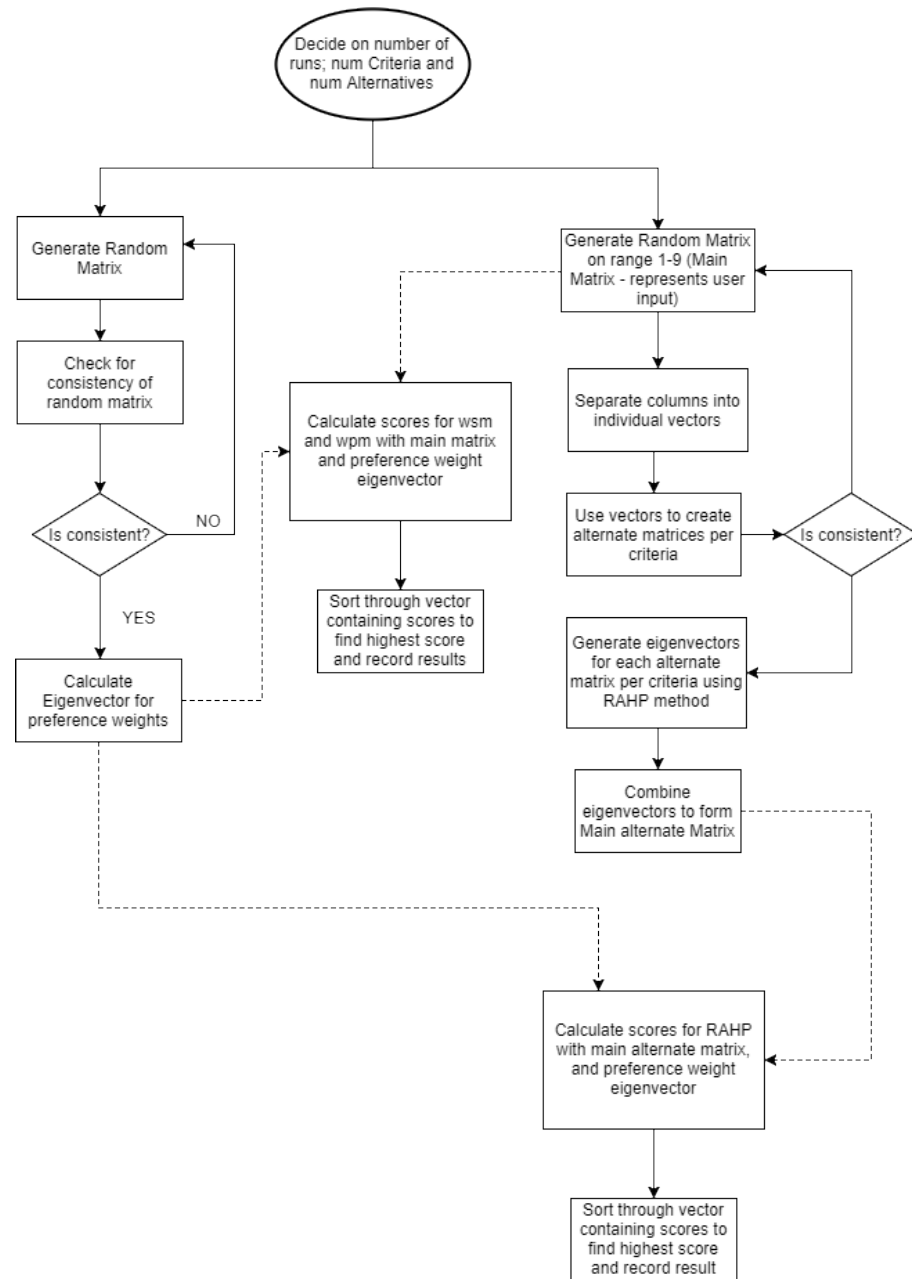


Figure 3.3 Flow chart of steps to implement the MCDMM in MATLAB

3.4 Data Analysis

Since a mixed methods approach was used for the data collection, the resulting information gathered was analyzed with both qualitative and quantitative strategies. Just as the collection of the data, the data analysis was also performed sequentially.

3.4.1 Interview Analysis

The recorded phone interviews from the first phase were transcribed and studied. Member checking is described as sharing of the written transcript report with participants, and is performed in order to ensure that the conclusions drawn from their input reflect the intent of their responses (Fereday & Muir-Cochrane, 2008). Once the framework was initially set up and the survey was fully edited, the interviewees were presented with the framework, as well as their interview transcript for member checking to ensure that their input was not wrongly interpreted by the researcher.

The process of coding was used to analyze and interpret the transcript, in order to extract pertinent information for building the software selection decision framework. Manual coding by the researcher, as well as electronic coding with the NVivo software was conducted, in order to enhance efficiency and accuracy when analyzing the interview transcripts. As described in the paper by Welsh (2002), the memo and search tools within NVivo may increase the rigor and validity of results, however, with varying synonyms of search terms some information may still be missed. Thus, in order to avoid this manual coding was conducted before, and in tandem with the electronic coding to further reduce the chance of missing data.

The two main purposes of the qualitative data collected was to modify the given survey questionnaire, as well as build the preliminary framework. The transcripts were subdivided according to the category of questions followed in the interview protocol. The following steps, loosely adopted from the description given by Basit (2003), were followed for coding each of the divided categories:

- Identifying the commonalities of feedback presented in the form of phrases or words.
- Form the emergent concept by analyzing their differences and patterns.
- Incorporate them into a final whole.

In addition to coding, memos and diagrams will be used to aid in visualizing and further understanding the data analysis procedure (Martin & Turner, 1986), and help in the development of the framework.

A grounded approach was taken while performing the coding process. The grounded theory approach is one that studies a process of action in order to develop a unified ‘explanation’ based on data collected from participants who have experienced said process or action (Creswell, 2013). Thus, for this research, there was no pre-coding, but rather by inductively exploring the collected data and seeing “...how it functions or nests in its context.” (Basit, 2003. pg. 5), the framework was generated, grounded in the collected data.

This coding of information gathered was anticipated to result in one of two differing outcomes:

- Several completely differing strategies for software selection could be found to be occurring across the various companies. This would suggest that there was no general underlying structure or framework commonly being followed. In this case, the identified strategies would thus be grouped, based on similarities and categorized based off any unique identifiers that are uncovered during the analysis.

- A relatively common framework could be found to be generally followed in industry. This would be generalized to fit any user.

3.4.2 Survey Analysis

In the final version of the survey used in phase 2, participants were asked to rank various criteria by importance on a likert scale of 1 – 7. Lissitz and Green (1975), suggested in their research, that the reliability of the likert scale does not significantly increase after 5 points on the scale. However, the 7-point scale was adopted for the ranking of importance in the surveys used for this research - with 1 representing “Not at all important”, and 7 representing “Very Important”. This type of likert scale was used in order to add additional flexibility and granularity to the variation of responses from the participants about their perceived importance of the criteria (Bertram, 2007).

The rating of criteria importance on the likert scale from the participants in phase 2 will be consolidated and used to produce the importance rankings of the criteria per group based on contractor type. In order to determine an appropriate expected sample size, an a-priori power analysis was conducted using the G-power package.

According to Leon, Davis and Kraemer (2011), power analyses are “...used to determine the sample size that is needed to provide adequate statistical power (typically 80% or 90%) to detect a clinically meaningful difference with the specified inferential statistical test.” (p. 627). Cohen (1988) described power as the “...probability that a test will result in the conclusion that the phenomenon exists.” (p. 4). Power is closely related to effect size. Cohen (1988) noted, the effect size of 0.5 is considered large – meaning that the effect being measured is consistent and substantial.

Since this research is dealing with subjective rankings of criteria, it is expected that there will be wide variations in the individual rankings of the criteria importance. Thus, by paying attention only to the larger measured effects, being overly sensitive to the smaller variances that are caused by human subjectivity can be avoided.

The a priori power test was conducted assuming an effect size of 0.5, alpha of 0.05 and a power of 80%. The output indicated that the required sample size of each group would be 64 participants.

The quantitative responses on the results from the survey were also presented using descriptive statistics – i.e., via the mean, variance, frequency and percentages - to get an overview of the data obtained from the sample. Inferential statistics were used to determine significance in responses between the various possible groupings of the participant responses.

3.5 Data Validation – Validity & Reliability

It is pertinent to ensure that the interview protocol and survey instrument are both valid and consistent, in order to ensure successful end results. To this end, a number of measures were taken during the course of this research, in order to ensure the validity and reliability of the instruments and findings.

3.5.1 Reliability

According to Merriam (1995) “...the more times the findings of a study can be replicated, the more stable or reliable the phenomenon is thought to be...” (p. 55). The reliability

of the findings in this research were measured using data triangulation on the data collected from the two methods – namely surveys and interview (Merriam, 1995).

This offered a chance to examine and verify the consistency of responses, adding onto the robustness of the concluded outcomes. The survey responses obtained were also checked for reliability using the kendall's coefficient (W) of concordance test. This test was run on the quantitative aspects of the survey instrument responses. Kendall's W is used to determine the measure of agreement when we have two or more judges rating items on a likert scale (Daniel, 1980; Marascuilo & McSweeney, 1977).

According to Ary, Jacobs, Sorenson and Walker (2013), results from an instrument can be reliable without being valid but cannot be valid unless first regarded as being reliable. Thus, a number of additional measures will also be taken to ensure the validity of the research - and by extension, further enhance the reliability of the results.

3.5.2 Construct and Content Validity

Construct Validity can be defined as the determination of the extent to which a predefined measure is actually assessing that which it was intended to assess or measure, instead of other variables (Bagozzi, Yi & Phillips, 1991). It is thus aimed towards the connection of abstract ideas and labels to concrete facts and characteristics.

According to Adcock and Collier (2001) *Content validity*, "... assesses the degree to which an indicator represents the universe of content entailed in the systematized concept being measured." (p. 537). This implies that the interpretation of results based in one context of understanding may not apply to a similar interpretation in another.

To ensure that there was no confusion of the construct or content validity of the instruments to be used, it was ascertained that the research was being conducted in the proper context (Abowitz, & Toole, 2009). It was therefore important to firmly establish the definitions, scope and terminologies that will be used during the course of this research so as to determine what “label” refers to which “concept”. This was done in the preliminary and first phase of the research, in order to avoid the event of discovering during data analysis, that an element had been misinterpreted by participants - an event that could jeopardize the validity and reliability of the entire research study (Abowitz, & Toole, 2009).

One method of dealing with these two forms of validity - which was employed during the first phase of this research - was by relying a panel of “experts” to provide an informed assessment of the clarity of the content and the constructs being measured by the instruments used in this research (Shadish, Cook, & Campbell, 2002).

This means there was a need for all concepts and terms to be unambiguously and operationally defined in the context of the AEC industry and its practices concerning BIM, as well as ensuring that the use of terminology and criteria throughout the research matches those that are currently in use in industry as well.

To that end, the industry professionals taking part in the first phase aided in shaping the questions to be used in the data collection phase of the research; as well as verifying their validity before being distributed in the second phase.

Definitions were further refined as necessary during the member checking section of the in-depth interview stage in the main data collection phase. By doing this, the reliability of the questions as well as the responses in the second phase were reinforced.

Explanations of terms were provided to all participants in the main data collection phase, to ensure a uniform awareness and understanding of terminologies being used.

3.5.3 Internal and External Validity

To ensure the validity of the data collected from the research, a few strategies were employed to bolster the internal validity of the tools being used for the data collection, as well as the methods being applied for data analysis.

- Triangulation - Since the questions in the survey and pilot interviews were similar, the outcome of both analysis was compared for data triangulation - by making comparisons between the collected data across the methods. Corroborating emergent themes from all sources would be a good indicator of reliable and thus valid results (Creswell, 2013).
- Member checks - After completing the interviews with participants, member checks were conducted by the respondents to ensure that the interpretations derived from their input in the interviews ‘rang true’ as put by Merriam (1995). If more than one potential meaning was associated with the definition of a particular concept on the use of BIM, then, as suggested by Adcock and Collier (2001), a “matrix of potential meanings with the background concept” (p. 532) would be created, to accommodate all the possible definition variations.
- Surveys sent out were anonymous, and sent via email. Each email contained a unique link, which could only be completed once – this avoided several entries from the same participant.

While the previously discussed methods contributed to the internal validity and reliability of the data, in order to ensure the external validity and generalizability of the study results, a

thick detailed description providing interconnecting details of the participants, setting, events and actions was provided. This enabled readers to determine the transferability and generalizability of the research findings (Creswell, 2013).

3.5.4 Face Validity

According to Ary, Jacobs, Sorensen, & Walker, (2013), face validity is "... the extent to which examinees believe the instrument is measuring what it is supposed to measure" (p. 245). Face validity takes into account the perceptions and intuitive judgment about the relevance, reasonableness and clarity of the items within a questionnaire, and relates to feasibility and acceptability (Lu, Yu & Lu, 2001).

Face validity of the survey instruments used - as well as of the framework - was tested during the first phase of this research; and subsequently throughout the course of the study through constant verification by industry professionals.

3.6 Chapter Summary

This chapter covered the methodology employed to conduct the research; the justification for selection of the chosen methods; description of the data collection; instrument and data collection processes development and validation. The next chapter delves into the presentation and analysis of the results obtained from the implementation of the methods described here.

CHAPTER 4. RESULTS AND ANALYSIS

In this chapter, the results of data collected throughout the course of the research will be chronologically presented and reviewed. Analysis of the qualitative and quantitative data will also be performed in order to further interpret and understand the findings of collected information.

4.1 Phase 1 Results and Analysis

In first phase of the research, a preliminary survey was sent out to industry professionals in the Mechanical and Electrical contracting fields of the AEC industry. Ten mechanical contractors and nine Electrical contractors were contacted for this phase. Tables 4.1 and 4.2 below present a summary of the details of the companies interviewed for this phase.

Table 4.1

Details of electrical contractors interviewed

E	BIM use (years)	Size (millions)	Interviewee BIM experience	Main BIM software choices	Other bim related software choices
1	>6	>100	>8years	Revit MEP/Cad MEP	Navisworks
2	3 to 6	>100	>8years	Revit MEP/Cad MEP	Navisworks/3dmax/Primavera
3	>6	>100	5-8 years	Revit MEP	Navisworks
4	>6	>100	3-5 years	Revit MEP/Cad MEP	Navisworks
5	3 to 6	>100	5-8 years	Revit MEP	Navisworks
6	3 to 6	>100	>8 years	Revit MEP/Cad MEP/Sketchup/Inventor	Navisworks/Primavera/Teklabim Sight/3dmax
7	>6	>100	5-8 years	Cad MEP	Navisworks
8	>6	>100	>8years	Revit MEP/ Gtp Revit	Navisworks
9	3 to 6	>100	>8years	Cad MEP	Navisworks

Table 4.2

Details of mechanical contractors interviewed

M	Use of BIM (years)	Comp Size (millions)	Direct BIM experience	Main BIM software choices	Other bim related software choices
1	>6	>100	>8years	Revit MEP/CadMEP/EstMEP/ Fabrication for Acad MEP	Navisworks/Tekla Bimsight
2	>6	40 - 100	5-8 years	Cad MEP/Camduct/Fabrication For Acad MEP/ Revit MEP	Navisworks
3	>6	>100	5-8 years	Revit MEP/ Fabrication for Acad MEP	Navisworks/3dmax
4	>6	40 - 100	5-8 years	Revit MEP	Navisworks/Primavera
5	3 to 6	>100	3-5 years	Revit MEP/Intergraph Cadworx	Navisworks/Teklabimsight
6	>6	>100	3-5 years	Revit MEP/EstMEP -4d	Navisworks
7	>6	>100	>8 years	Revit/Sketchup/Cam Duct/CadMEP. Fabrication for Cad MEP/Cad MEP	Navisworks/Synchro
8	>6	>100	5-8 years	Revit MEP/Fab for Acad MEP	Navisworks/Innovaya
9	>6	>100	5-8 years	Revit MEP	Navisworks/Sketchup
10	>6	>100	5-8 years	Revit MEP/Fab for Acad MEP/Cad MEP	Navisworks/Assemble/ Costx/Lumion

The interviewees identified their firms as being were primarily large companies with annual billings greater than \$40 million; and with BIM departments that had at least 3 years of experience implementing BIM. They also indicated the software currently being used in their department BIM workflow for their projects.

4.1.1 Updating the Preliminary Survey

Following the receipt of their written comments, a time was scheduled for a follow up phone interview. The main purpose of the phone interview was to clear up any ambiguity in their comments for revisions on the survey questions; as well as to gather information that would then be used to create the preliminary frame work.

For example, as can be seen in figure 4.1, following recommendation from the industry professionals reviewing the survey, the first two questions were consolidated into one simplified entry – on account of it being too cumbersome in its initial format.

Please identify the BIM software applications used in your company for modeling/prefab (select all that apply):

- ☐ Autodesk REVIT MEP
- ☐ Bentley Revcomp Mechanical Designer
- ☐ AECOsim Building Designer
- ☐ 4Mx Finelvac + Finelvac + Finelvac
- ☐ Digital Project MEP Systems Routing
- ☐ Auto CADMEP
- ☐ Graphisoft MEP Modeler
- ☐ Cadpipe HVAC
- ☐ CAD MEP Plancal Nova
- ☐ Trimble Pipe Designer 3d/Quickpen Piping Designer
- ☐ MagiCAD
- ☐ DDS-CAD MEP
- ☐ CADMEP+
- ☐ Plant 3d
- ☐ Sketchup
- ☐ Archicad

Please identify the BIM software applications used in your company for the following:

	USE			
	4D	5D	Animation/Rendering	Collision detection, Coordination
Synchro	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Vico Software	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Navisworks	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bentley Project Wise	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Innovaya	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Primavera	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dynaflo	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
QTO	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Buildx	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Tekla BIMbaht	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Smartplant Review	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Digital Project Designer	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3d Max	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Lumion 3d	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Please identify how BIM software applications are used in your company by indicating the BIM tools used for each purpose:

Modeling/Prefab

4D scheduling

5D Cost estimation

Animation/Rendering

Collision Detection/Coordination

Figure 4.1 Example change to preliminary survey

4.1.2 Creating the Preliminary Framework

Information gathered from the phone interviews and comments was also used to produce an initial framework. The data collected from the phone interviews was analyzed inductively, in order to identify common themes or patterns in the various accounts of the software selection process.

This process was performed in the NVIVO software package, and was completed in two iterative cycles. In the first cycle, answers to the responses were grouped by question accordingly, and assigned to nodes. This was done for each of the company types. The questions asked during the phone interview encompassed various aspects of the software selection process. This included the total time taken, the various steps followed the number of individuals that took part in the process, as well as the number of software options and criteria considered at a time.

Within each node, every line of text transcribed from audio or from written memos and notes, was carefully read and openly coded. i.e., any phrase or word from the various perspectives given that seemed to be relevant or important was coded. The coded data for each contractor type was then grouped visually as word cluster concept maps. This is illustrated in figure 4.2.

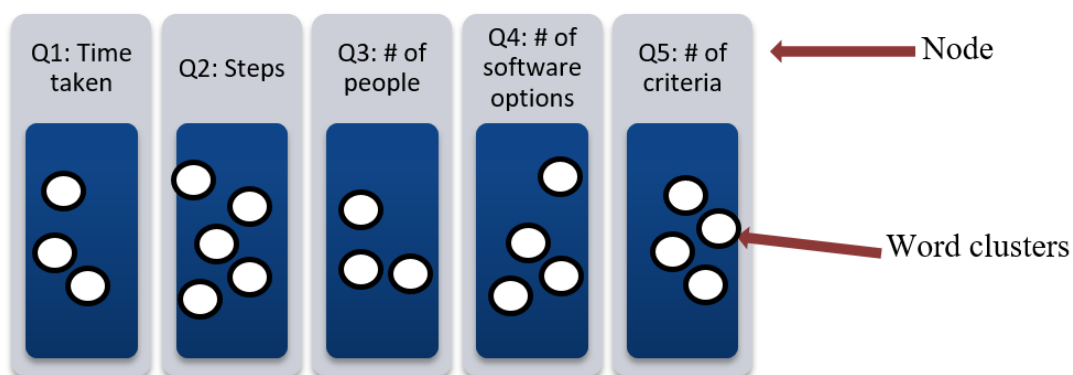


Figure 4.2 Representation of word clusters

During the second cycle, similar overlapping codes within the word clusters of each node were extracted from the grouped phrases further reducing the data into a more concise description of the processes. Any un-coded text that had been missed during the first cycle was also captured. The second cycle was repeated until no unique codes or themes were discovered in

the collected data. This was done separately for the data collected from the electrical contractors, and mechanical contractors. Once the cluster analysis was completed, they were compared between the mechanical and electrical contractors.

From the data gathered in the remaining questions, the following general information was surmised about the BIM software selection process:

- During the software selection process, there are typically 2-5 individuals that participate in the evaluation and decision making process within a company. This can differ due to varying BIM department sizes and BIM usage within a company.
- During the software selection process 2-5 criteria are typically considered when evaluating options. These are typically determined by various factors, including client needs, price, and learning curve.
- During the software selection process 1-3 software options are taken into consideration at a time and evaluated simultaneously. In the situation where only one software is being considered this is usually an evaluation of software that has been recommended or is required by contract according to a current job.
- The software selection process takes anywhere from less than a month to three or more months at a time, with the hands-on evaluation period taking the longest period of time. This depends on factors such as the type of software, and whether or not the users have had prior knowledge of the software or something similar.

The major question that provided data from which the framework was put together was that of the steps involved in the selection process. From this node – and subsequently the compiled word clusters within – it was noted that, there existed two major paths of the software selection processes.

- The first path was one that indicated very little freedom in the selection process;
- The second path described the actual steps of the selection process.

These two paths were present in both the electrical and mechanical contractors interviewed, however it was noted that the first path was more dominant among the electrical contractors than it was among the mechanical contractors. Although both the electrical and mechanical contractors interviewed contributed to the description of detailed selection process steps, the majority of the electrical contractors indicated that they had very little say in the matter of software selection. Their comments were dominated by indications that their selections were dictated by the requirements of clients and contract agreements, as is evident from the comment snippets below:

“...we just follow what is specked out for us to use.”

“...there was no process, we were at the mercy of the architects, since we are more in the construction side of things.”

In order to construct the framework for the selection process, only the second path was considered. This was because the major assumption of this research was that the company would have to be able to freely choose their options in order to make use of the framework. Without the freedom to choose, they would not have to use the framework or have the need to go through a formal selection process, as pointed out by an interviewee:

“...we often times receive some model files from the engineers/owner/vendors in a specific format. This means, that while we may not own license for that specific software or even if we prefer a different software package, we become locked into using something simply because it is what we were provided. In these cases, the whole selection process gets thrown out the window if we want to utilize the provided models - unless it can be converted into a more preferable format.”

The image shown in figure 4.3 is an example of the word cluster within the node of ‘steps followed’, for the mechanical contractors. After a final review of the categories in the second path of clusters, the extracted steps were as follows:

- Past experience
- Group discussions
- Testing platform through trial
- Testing platform by vendor presentation
- Evaluating specific capability
- Solution search



Figure 4.3 Sample word cluster concept map for mechanical contractors selection steps

The transcripts were re-read in order to ensure the correct placement and ordering of the steps extracted. Finally, the initial BIM software selection process framework was constructed from the extracted data, following the logical progression of main steps as described by the interviewed professionals.

The construction of the framework began with the following theoretical skeletal configuration shown in figure 4.4. In constructing the theoretical framework, the process of the BIM software selection coupled with the criteria used to evaluate and ultimately decide on the final selection were both taken into consideration.

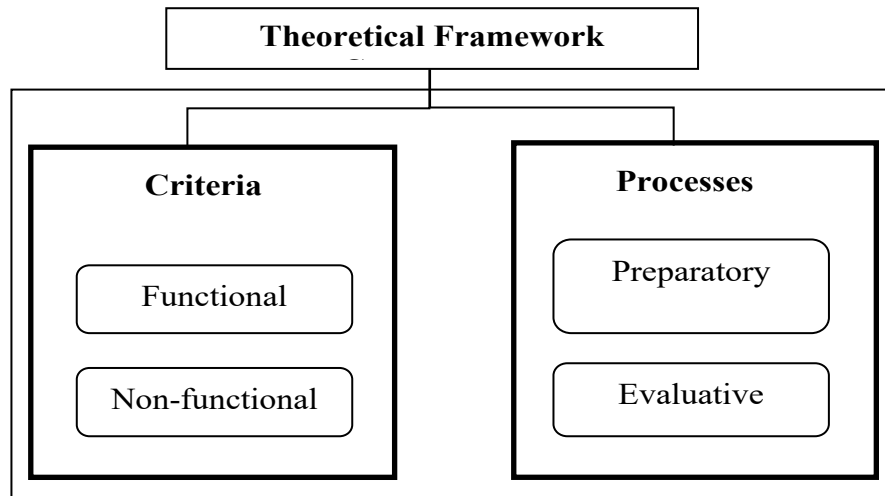


Figure 4.4 Theoretical framework for software selection

4.1.2.1 Selection Criteria

As a first step, before the evaluation of software options can begin, it is necessary to know beforehand which specific qualities should be considered for decision making by the evaluators during the hands-on trial period. In the preliminary period of this research a comprehensive list of possible criteria was collated from literature and separated into 4 major groups. These groups were namely:

- Objective functional criteria – basic capabilities of the software that does not require biased judgement to determine
- Subjective functional criteria - basic capabilities of the software, that cannot be rated fairly or unambiguously by any one person or group without prior prejudice
- Objective non-functional criteria – properties of the software application not linked to the behavior or capability of the software, and that does not require biased judgement to determine

- Subjective non-functional criteria - properties of the software application not linked to the behavior or capability of the software, that cannot be rated fairly or unambiguously by any one person or group without prior prejudice

Together, the various types of criteria described above form the two major groups of objective and subjective software selection criteria as shown at the bottom of figure 4.5. These criteria groups are used at different stages of the software selection process, when appropriate.

Typically, once the software selection process is embarked upon, the users collectively identify which criteria are most important for that particular software solution search or evaluation. As mentioned before, this will differ and depend on the current needs and job demands.

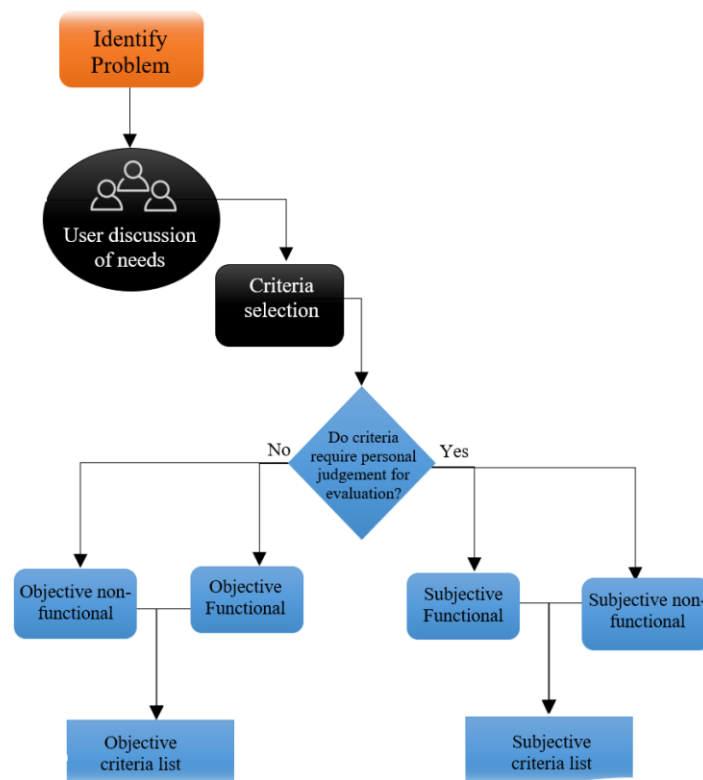


Figure 4.5 Filtering the selection criteria groupings in the software selection process

4.1.2.2 Process: Preparatory

The second step of the process deals with preparing and deciding on the software options to be taken into consideration. This can be either a simple or slightly more involved task depending on the current situation within the company. The simpler route is when a company has one or two software to choose from as a result of client or job demands. In this case, a preliminary search for possible solutions is not necessary, and the next step would be the evaluation stage in the process.

In the event that there are more options to choose from, this stage would then require the added step of sorting through the possible options in order to come up with a workable shortlist of less than 4 possible software options as depicted in figure 4.6.

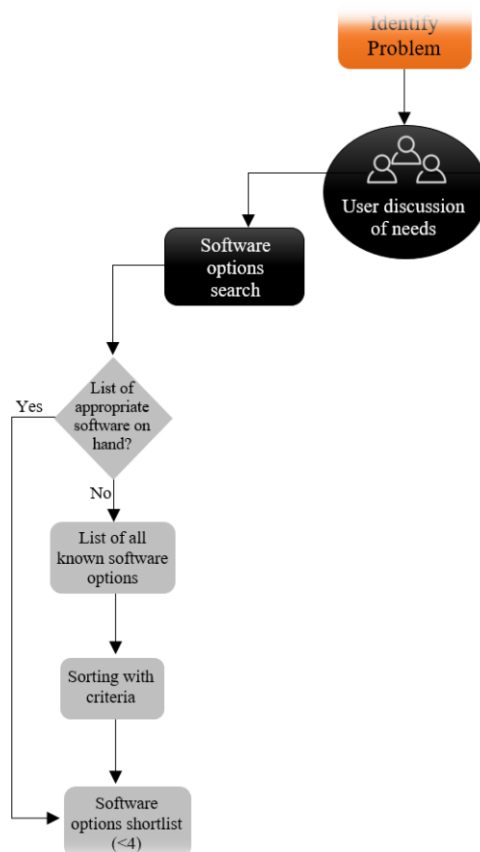


Figure 4.6 Preparatory steps in the software selection process

4.1.2.3 Process: Evaluative

Once the shortlist of possible software options has been obtained, the next step is the evaluation process. This process typically begins with access to a trial version of the software in question. Team members are then able to personally test out the capabilities of the software briefly and then decide whether to obtain further information directly from the vendors in the form of virtual or in-person demonstrations. However, depending on whether or not there is an individual on the team that has prior knowledge or past experience with the software, the team as a whole may or may not seek vendor input.

Following this initial stage of inquiry, a formal trial run or testing of the software is conducted within the team to determine how well the software meets their criteria. During this stage the software is evaluated especially to determine how well it can fit into the current workflow of the company as well as how efficiently and quickly the software can be picked up by the team members.

A final team discussion then leads the to the selection of the preferred option by the team (if more than one is being considered at a time). At this stage, it moves on to the approval process within the higher management and IT department. If the selected option is able to make it through all approval routes, it is then able to move on to the adoption stage of the selection process as shown in figure 4.7.

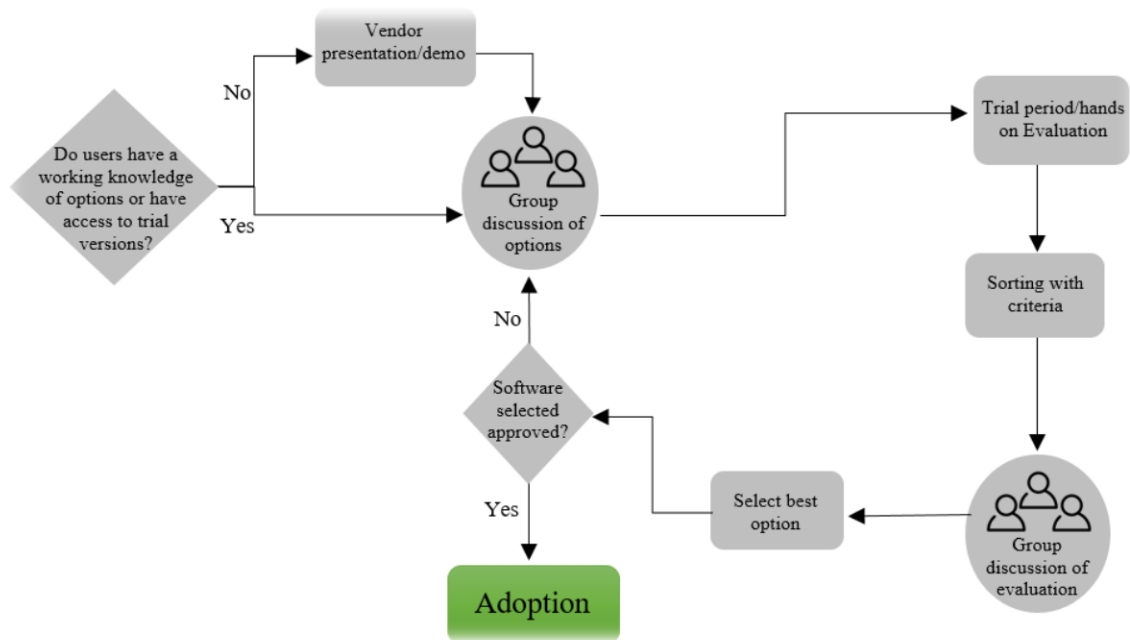


Figure 4.7 Evaluation steps of the software selection process

If the selected option is unable to make it through the approval stage the team members go back to the discussion table to determine their next best options.

The preliminary framework is displayed in figure 4.8. This framework is a combination of the various pieces discussed earlier: criteria selection; preparatory steps and evaluative steps.

The connection and purpose of the objective and subjective criteria groupings are as follows: in the event of many initial options in the early stages of the preparatory steps, the objective criteria can be used to sort the initial list of viable options. From there the subject criteria come into play once the shortlisted software being considered seriously are undergoing the hands-on evaluation and sorting stage.

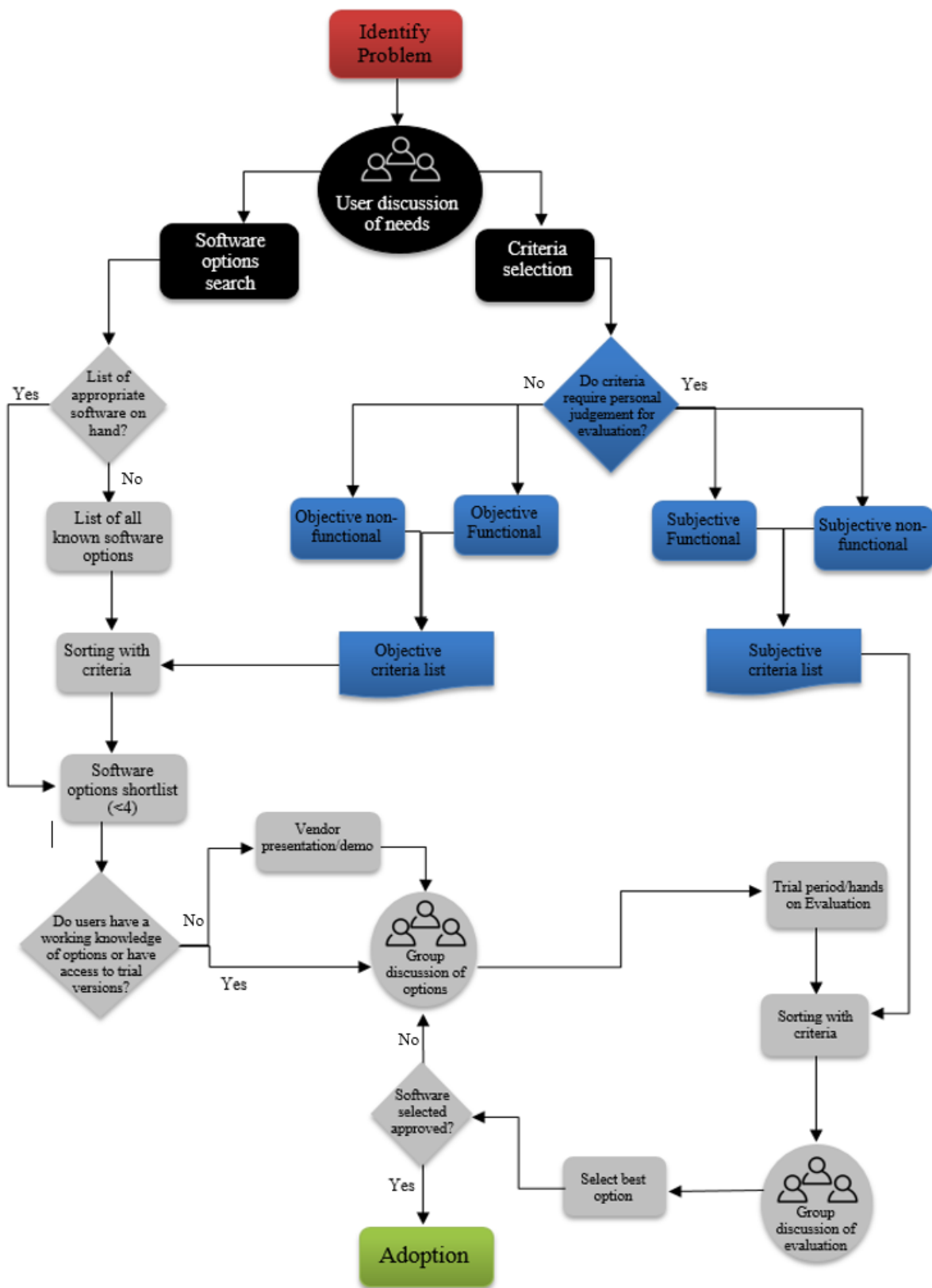


Figure 4.8 Preliminary framework for software selection

4.1.3 Face Validation of updated survey and initial framework

As a final step for the first phase of this research, the updated survey and framework were sent to an additional nine mechanical contractors were sent the updated survey and framework for face validation. The feedback from these professionals indicated that the survey questions were unambiguous in their nature and there were no further consolidations or alterations of the question content or format needed. Their comments on the frame work were also along the lines of the comments received from the interviewees, and will be further discussed in the next section.

4.1.4 Final Notes

In the course of the first phase of this research, the concept of software plugins and add-ons was brought up by the industry professionals interviewed. This was noted during the interviews as well as through the comments of the face validators. Their comments revealed that they had more flexibility with the selection and use of these software extensions as opposed to the major BIM platforms. A sampling of their feedback is listed below:

“There was no process, we were at the mercy of the architects, since we are more in the construction side of things but we do have some flexibility with the choice of Bolt on/add ons”

“We discover an issue and try to find a solution with a software add-on or stand-alone product.”

“...do your research on software and further the add on software required.”

“The list available software for a specific industry is already a shortlist. However, there is Autodesk and then there are various "plug-in" solutions that build on to the Autodesk platform.”

As this study was designed on the grounded research theory, it was decided at this point to conduct further interviews during the second phase of the research in order to explore the newly discovered theme. The inclusion of the interviews was in addition to the surveys scheduled for distribution during the second phase.

The focus of this research was thus shifted slightly at the end of the first phase. This shift was a slight deviation from the original plan of having only surveys in the second phase. The intent of creating the framework for the selection of BIM authoring software, was thus also changed to also focus on the applicability of the framework to the selection of BIM addins/plugins/addons and other third party software that enhanced the overall BIM workflow in a company. To that effect, interviews of mechanical and general contractors were added onto the methodology for data collection in phase 2 of this research, in addition to the originally planned mixed methods surveys for that phase.

4.2 Phase 2 Results and Analysis

The data collected in phase 2 consisted of two components:

- The quantitative survey responses
- The qualitative responses;

Analysis from the qualitative and quantitative responses were used to continue the construction of the software selection framework. The gathered data from these sections will be described and analyzed in the subsequent sections.

4.2.1 Quantitative survey results

To begin the second phase, a mixed methods survey was sent out for this phase of research. The survey incorporated the preliminary framework as an embedded image as shown in figure 4.8. It also allowed for participants to rank the criteria list presented in table 3.1 of chapter 3, on a scale of 1 – 7 by order of importance. The importance of the criteria rated was determined according to a 7-point Likert scale from 1 (least important) to 7 (most important).

The survey was sent out to members of the NECA, MCAA as well as mailing lists of attendees at the Purdue University School of Construction management career fair. In total 156 responses were obtained. Out of the 156 however, only 114 responses had enough information to be considered for further analysis. Of the 114, 54 identified themselves as general contractors while 60 identified themselves as subcontractors (Electrical or mechanical).

(a) Normality test

Out of the 114 respondents, 82 responses were complete for the ranking of the 25 listed software selection criteria (40 general contractors; 42 sub-contractors). A test for normality of data was conducted on the 82 responses, using the Shapiro Wilk test. The full list of criteria descriptions as well as their associated labels to be used throughout the tables of statistical analysis can be found in table 4.4.

Results from the Shapiro Wilk test indicated that the assumption of normality had been violated, with significance levels less than 0.05 (i.e., $p < .05$) reported for all criteria. The full output of which can be found in appendix H.

(b) Power Analysis

In order to achieve the standard power of 80% and an effect size of 0.5, the desired sample size should have been 64 for each group according to the a-priori test – as mentioned in section 3.4.2 of chapter 3. However, after the data collection phase was closed, the actual useable sample sizes of the collected data were 40 responses from the general contractors and 42 responses from the sub-contractors instead. Thus, using the G-power software package, a post hoc power analysis was conducted in order to determine the actual obtained power from the collected data.

The post hoc power analysis test showed that the achieved power was 60.87%, with an assumed effect size of 0.5; alpha of 0.05 and sample sizes of 40 and 42. This indicated that that there was about a 60% chance of identifying a statistically significant difference in the analysis of the collected data.

(c) Inter rater reliability test

Before any further statistical analyses were conducted, an inter-rater reliability test was performed in order to ensure that the data would yield valid results. The Kendall's coefficient of concordance test (Kendall's W) was used for the inter-rater reliability test of the responses.

The Kendall's W test measures the level of agreement between individual judges by determining the amount of variability present between average rankings of a data set as compared to the maximum possible (Hollowell, 2010; Marascuilo & McSweeney, 1977).

Kendall's W is used under the following assumptions:

- There are three or more judges rating items on an ordinal scale
(e.g. A likert scale)

- The judges are rating the same list of items
- The judges are independent of one another (Laerd Statistics 2016)

Since this research study design fulfilled all three of the required assumptions for the use of Kendall's W , the test was deemed appropriate. The Kendall's W test was run separately for the subcontractors group, as well as for the general contractors group, to determine if there was agreement between the individual rankings of criteria importance within each group.

The test was conducted in the SPSS statistical package, the results of which are displayed in table 4.3.

Table 4.3

Results from the Kendall's coefficient of concordance test

General Contractors		Subcontractors	
Total N	40	Total N	42
Kendalls W	0.194	Kendalls W	0.178
Test Statistic	185.938	Test Statistic	179.103
Degrees of Freedom	24	Degrees of Freedom	24
Significance (2-sided test)	P<0.005	Significance (2-sided test)	P<0.005

The results indicated that there was a statistically significant agreement between the assessment of criteria importance levels within the group of 40 general contractors, with a value of Kendalls $W = 0.194$, and p value of $p < .005$. The results from the test also indicated that there was a statistically significant agreement between the assessment of criteria importance levels within the group of the 42 subcontractors, with a value of Kendalls $W = 0.178$, and a p value of $p < .005$.

The obtained kendalls W statistic of 0.194 and 0.178 indicate that the observed differences in average ranks of the 40 general contractors and 42 sub-contractors are 19.4% and 17.8 % of the maximum variability possible respectively.

4.2.1.1 Statistical significance in of criteria rankings between groups

Following the test for inter-rater reliability of the responses, the remaining statistical test of significance between groups were conducted. Due to the violation of normality, the independent t test could not be used for further statistical significance difference testing. Instead, the Mann-Whitney U test (or the Wilcoxon-Mann-Whitney test) was used to test for statistical significance.

The Mann-Whitney U test is a rank-based nonparametric statistical test (Laerd Statistics, 2016). It is commonly used to determine differences between two groups on an ordinal dependent variable - such as items ranked on a likert scale.

The Mann-Whitney U test follows the following assumptions:

- One dependent variable, measured at the ordinal level.
- One independent variable that consists of two categorical, independent groups
- Independence of observations
- Similar or different shape of the distribution of scores for both groups of the independent variable. (Laerd Statistics, 2016)

The Mann Whitney U test was used to check for significant differences between the following groupings of data: company type groupings; company size groupings and company BIM usage groupings. In order to support robustness of the analysis, a stricter and more conservative alpha value of 0.01 was adopted while running the Mann Whitney U test for the aforementioned groupings of responses. The full tables for all the above comparisons can be found in appendix

G. Within the company type groupings, the tests were conducted on criteria ranking responses of general contractors versus sub-contractors; as well as on the criteria ranking responses of electrical and mechanical subcontractors.

Table 4.4

Criteria descriptions and labels

Label	Criteria details
criteria1	Flexible conceptual design modeling / design freedom
criteria2	Co-ordination/interference checking
criteria3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling
criteria4	Ease of editing and adding custom components /object libraries
criteria5	Use of software application required by contract/company's business strategy
criteria6	In built multi –disciplinary ability [architecture, structural, MEP etc.] for producing complete construction/as-built documents
criteria7	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members
criteria8	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dxf etc.]
criteria9	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees can use software application
criteria10	Initial investment costs for hard & software, implementation and training; expected ROI
criteria11	History tracking, change management, data management and automated updating
criteria12	Improved link from design to fabrication; support for rapid prototyping and 3d printing
criteria13	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources
criteria14	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].
criteria15	Ability to efficiently work on large projects without resulting in cumbersome file sizes
criteria16	Security and access controls, with recovery mechanisms to ensure data integrity
criteria17	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc.]
criteria18	Known successful BIM cases by major subcontractors/business partners
criteria19	Number of third-party developers with add-on applications for the tool
criteria20	Market share leadership position of the vendor offering the BIM solution
criteria21	How well it can be adopted, without conflict, into the company's traditional work process
criteria22	Built-in ability to generate highly-photorealistic renderings and animations
criteria23	Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)
criteria24	Availability of extensive out-of-the-box content/object libraries
criteria25	Ability to capture local building codes and standards / support for LEED

The first Mann Whitney U test within the groupings by company type, indicated no significant differences between the electrical and mechanical subcontractor's rankings of criteria importance. However, when the criteria rankings of the subcontractors as a group was compared to the criteria ranking of the general contractors as a group, significant differences between the rankings of five distinct criteria were observed as shown in table 4.5.

The results of the U test showed that the importance ranking of criteria 4, 12, 17, 19 and 24 were statistically significant, with p-values less than 0.01 for each of the aforementioned criteria rankings.

Upon visual inspection, it was assessed that the distributions of those criteria importance rankings between the general contractors and sub-contractors were not similar. The Mann-Whitney U test is used to determine the differences in the mean rank distributions between two groups with differently shaped distributions (Laerd Statistics, 2016). The distributions of the statistically significant criteria are displayed in figures 4.9 – 4.13.

The results thus indicated that the mean rank for the sub-contractors' criteria rankings were consistently significantly higher than that of the general contractors for these criteria 4, 12, 17, 19 and 24.

Table 4.5

Mann Whitney U test for significant differences between ranking of criteria by contractors and subcontractors

	GC		SubC		
	Mean	Std. Deviation	Mean	Std. Deviation	Sig
criteria1	4.2250	2.01898	5.2143	1.68979	0.0240
criteria2	6.2500	1.29595	6.4286	1.03930	0.4730
criteria3	5.4500	1.60048	5.4048	1.72584	0.9200
criteria4	4.9750	1.65618	6.1905	.99359	0.0000
criteria5	4.7250	1.75393	5.1667	1.59139	0.1950
criteria6	4.6250	1.74954	4.8571	1.93266	0.4260
criteria7	4.9000	1.62985	5.2143	1.67530	0.2630
criteria8	4.9250	1.70049	5.6190	1.76625	0.0320
criteria9	5.2750	1.55229	5.9762	1.11504	0.0280
criteria10	5.3000	1.58842	5.2857	1.64221	0.9730
criteria11	4.4500	1.85293	5.2381	1.49486	0.0430
criteria12	3.3250	1.95314	5.2143	1.82844	0.0000
criteria13	4.5000	1.64862	5.2619	1.62390	0.0240
criteria14	5.0500	1.93417	5.4286	2.02596	0.2060
criteria15	5.3500	1.61006	5.5714	1.96485	0.2000
criteria16	4.7500	1.77951	5.5000	1.51818	0.0390
criteria17	4.0250	1.67160	5.3571	1.37613	0.0000
criteria18	4.4750	1.66391	4.9762	1.64522	0.1400
criteria19	3.7500	1.48064	4.6905	1.27811	0.0030
criteria20	3.9250	1.81712	4.6905	1.52200	0.0330
criteria21	5.2250	1.51043	5.5476	1.34713	0.3060
criteria22	4.1500	1.52836	3.5714	1.69853	0.0740
criteria23	4.0000	1.53590	4.1429	1.90726	0.6290
criteria24	4.2250	1.68686	5.3810	1.48081	0.0010
criteria25	3.8250	1.97273	4.5952	1.79511	0.0690

Note: test was conducted at significance level of 0.01

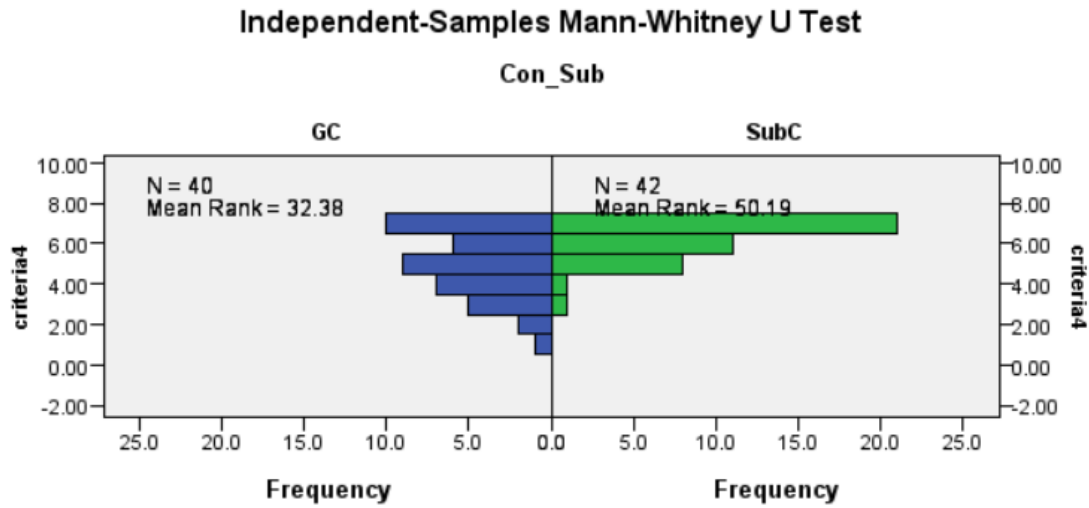


Fig 4.9 Ranking distribution for criteria number 4

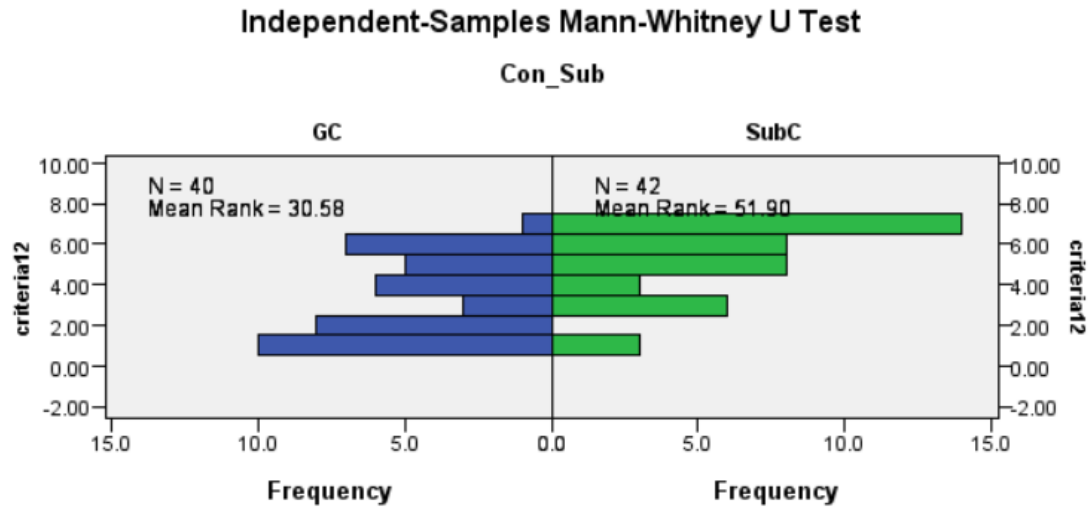


Fig 4.10 Ranking distribution for criteria number 12

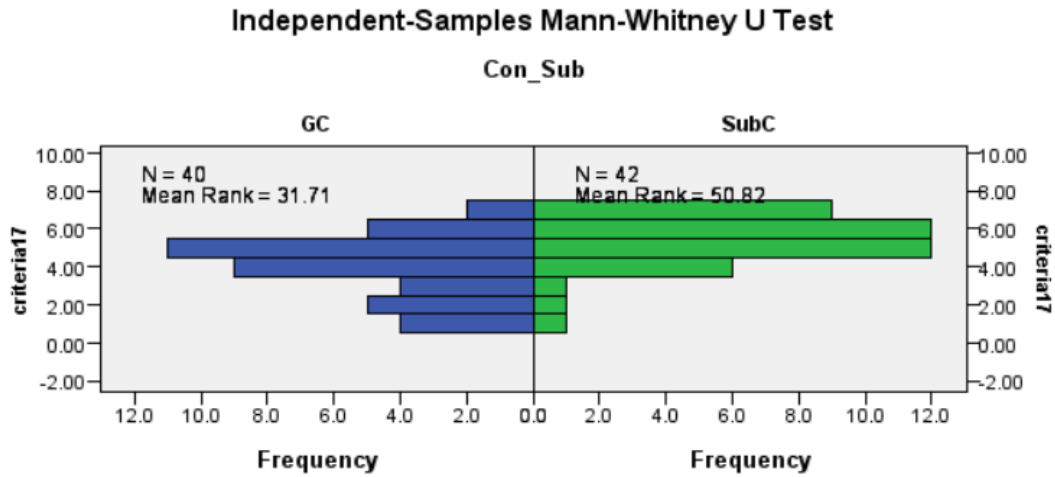


Fig 4.11 Ranking distribution for criteria number 17

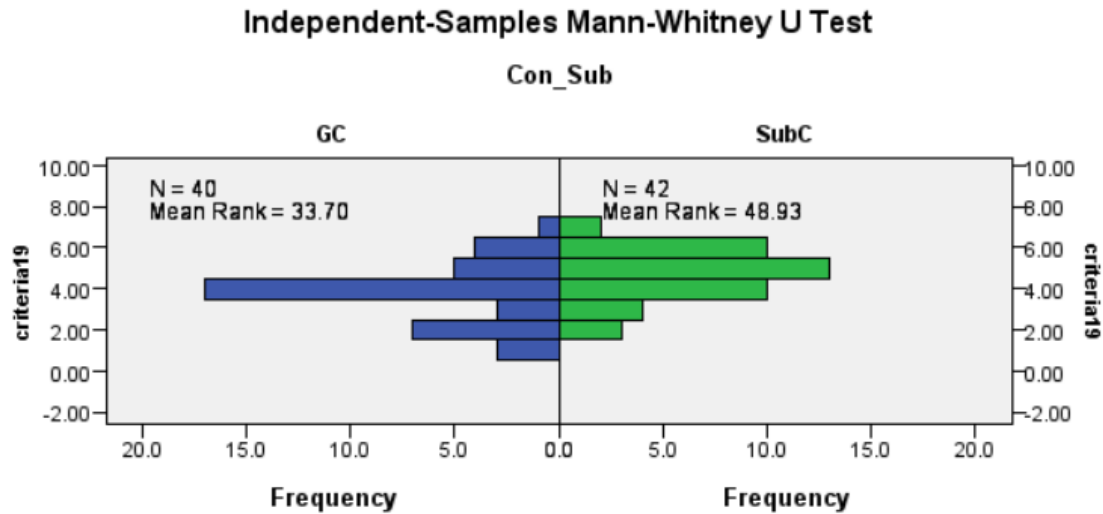


Fig 4.12 Ranking distribution for criteria number 19

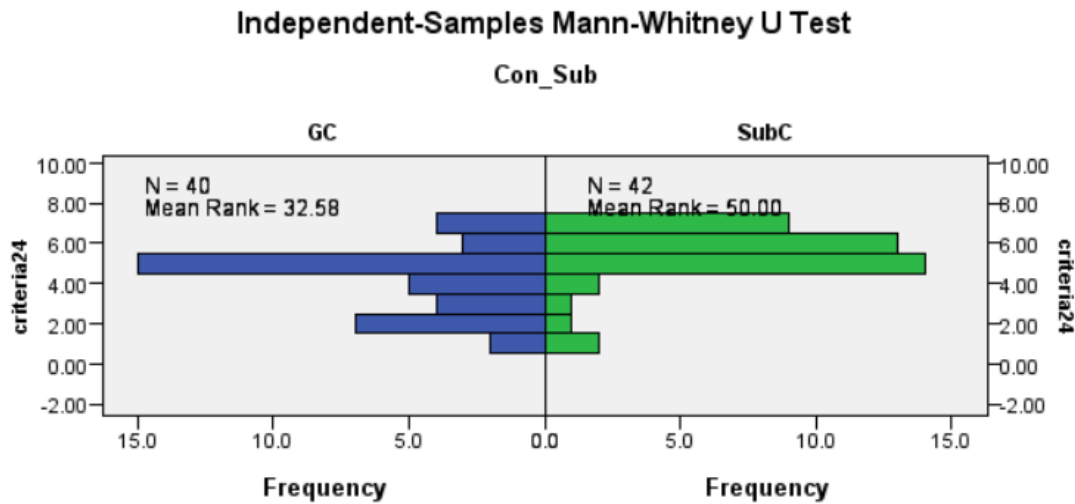


Fig 4.13 Ranking distribution for criteria number 24

Within the company size groupings, the responses were categorized as either small to medium companies or as medium to large companies. This grouping was based on their indicated annual billings. Companies with annual billings beneath 100 million were labeled as ‘small to medium’, while companies that indicated annual billings above 100 million were labeled as ‘medium to large’. Following the same procedure as was conducted for the comparison between the general and sub-contractors, the Mann Whitney U test yielded no statistically significant differences in the importance ranking of criteria based on company size, at a significance level of 0.01.

Within the company BIM usage groupings, the responses were categorized based on the indicated number of years of BIM usage in the company. The groupings were based on BIM usage that was either less than 6 years, or more than 6 years of indicated BIM usage. The final test Mann Whitney U procedure conducted on these groupings also yielded no significant differences in the criteria importance ranking by the general or sub-contractors.

4.2.1.2 Criteria Rankings

After obtaining the statistical significance based on the mean ranks distributions of the criteria importance rankings, the median values of the criteria rankings were calculated and compared between the contractors and sub-contractors. Medians typically represent the middle value of central tendency in data set. While the mean and median can be almost equal at times, they are significantly different if there are a few outlier values. The presence of extreme or clustered data values can significantly influence the mean values, making the average unrepresentative rendering, the median as a better alternative representation of central tendency (Dixon, 1953).

To further ease the analysis of the median value comparisons, the criteria were separated into their various categorizations as described in section 1.1.2.1 of this chapter. This breakdown is illustrated in table 4.6.

Table 4.6

Median rank values of criteria between contractors and subcontractors

OBJECTIVE FUNCTIONAL CRITERIA		GC , N = 40	SC, N = 42
criteria2	Co-ordination/interference checking	7	7
criteria3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	6	6
criteria6	In built multi –disciplinary ability [architecture, structural, MEP etc.] for producing complete construction/as-built documents	5	6
criteria7	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members	5	5.5
criteria8	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, etc]	5	6
criteria14	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].	5.5	6.5
criteria16	Security and access controls, with recovery mechanisms to ensure data integrity	5	5.5
criteria22	Built-in ability to generate highly-photorealistic renderings and animations	4	4

Table 4.6 continued

	OBJECTIVE FUNCTIONAL CRITERIA	GC , N = 40	SC, N = 42
criteria23	Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)	4	5
OBJECTIVE NON-FUNCTIONAL CRITERIA			
criteria5	Use of software application required by contract/company's business strategy	5	5
criteria10	Initial investment costs for hard & software, implementation and training; expected ROI	6	6
criteria18	Known successful BIM cases by major subcontractors/business partners	4	5
criteria19	Number of third-party developers with add-on applications for the tool	4	5
criteria20	Market share leadership position of the vendor offering the BIM solution	4	5
SUBJECTIVE NON-FUNCTIONAL CRITERIA			
criteria13	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources	5	6
criteria21	How well it can be adopted, without conflict, into the company's traditional work process	5	6
SUBJECTIVE AND FUNCTIONAL CRITERIA			
criteria1	Flexible conceptual design modeling / design freedom	4	5
criteria9	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application	6	6
criteria11	History tracking, change management, data management and automated updating	5	5.5
criteria12	Improved link from design to fabrication; support for rapid prototyping and 3d printing	3	6
criteria15	Ability to efficiently work on large projects without resulting in cumbersome file sizes	6	6.5
criteria17	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc.]	4	5.5
criteria24	Availability of extensive out-of-the-box content/object libraries	5	6
criteria25	Ability to capture local building codes and standards / support for LEED	4	5
criteria4	Ease of editing and adding custom components /object libraries	5	6.5

4.2.1.3 Survey Results - Image Rankings

As part of the mixed methods survey sent out during phase 2, the image of the initial framework (as seen in figure 4.8 in the prior section 4.1.2) was included. In response to the image of the framework displayed, participants were asked to rank their level of agreement with the image on a likert scale. The likert scale had 7 options to choose from. These options ranged from strongly disagree; disagree; somewhat disagree; not sure; somewhat agree; agree and strongly agree.

The question posed to participants pertaining to the displayed image of the framework was: “In your opinion, is the framework an accurate representation of the BIM software selection process in industry?”. The descriptive charts used to display the information obtained are shown in figures 4.14 and 4.15.

Out of the 114 respondents with viable responses, only 49 participants answered this part of the survey. These responses came from 22 general contractors and 27 subcontractors. Their responses and distributions of opinions are represented table 4.7.

Table 4.7

Level of agreement with framework by contractors and subs.

Contractors (n = 22)	
Agree	6
Somewhat Agree	10
Not sure	1
Somewhat Disagree	4
Disagree	1
Sub-Contractors (n = 27)	
Agree	11
Somewhat Agree	9
Not sure	5
Disagree	2

Amongst the general contractors that responded, 27% and 45% of the responses were of the selection options 'Agree' and 'Somewhat Agree' to the flow of the framework respectively. The remaining 28% were divided between 'not sure' (5%), 'Somewhat disagree' (18%) and 'Disagree' (5%).

Among the sub-contractors that responded, 41% and 33% of the responses were of the selection options 'Agree' and 'Somewhat Agree' to the flow of the framework respectively. The remaining 28% were divided between 'not sure' (19%), and 'Disagree' (7%).

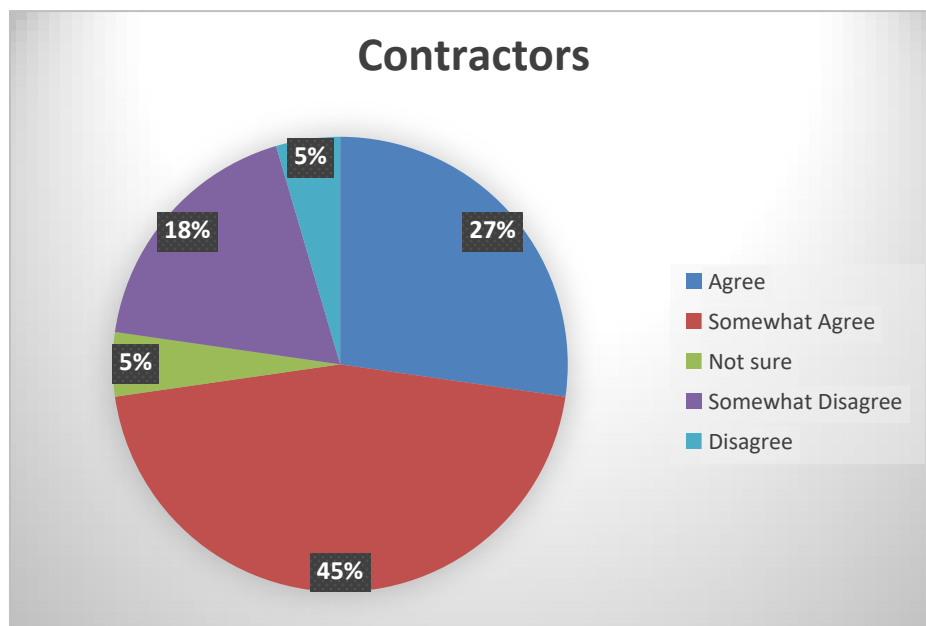


Figure 4.14 Contractors agreement with preliminary framework

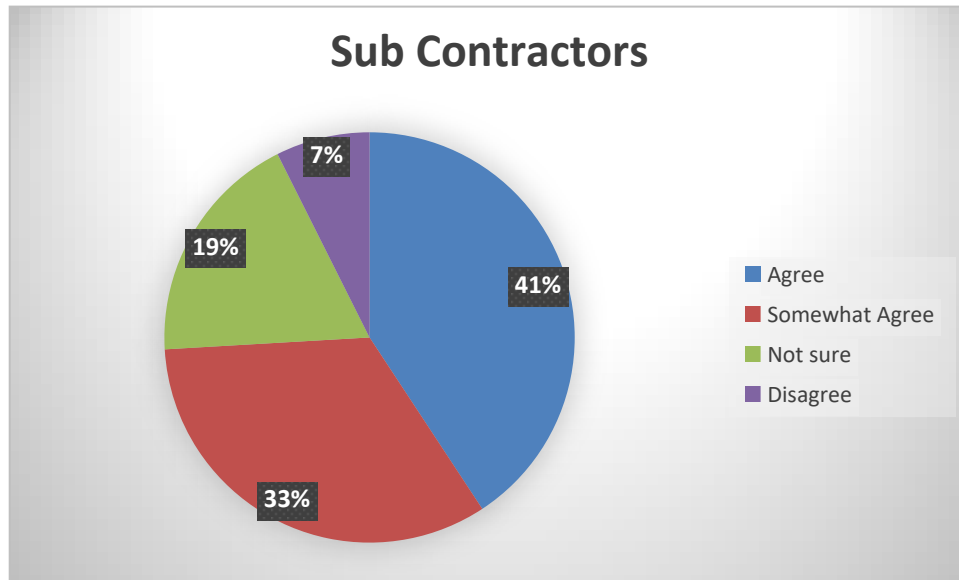


Figure 4.15 Subcontractors agreement with preliminary framework

In addition to the likert scale ranking of their opinions on the preliminary framework, participants were able to include written comments to further elaborate their agreement or disagreement with the framework. 30 individual comments were gathered through the survey in this manner. These comments explained further the opinions that had been indicated – and which are displayed in the figures 4.14 and 4.15 before.

These comments were collated and included as part of the qualitative data analysis at the end of phase two, together with data collected from the phone interviews.

4.2.2 Qualitative Analysis - Interview 2

As mentioned before in section 4.1.2 of this chapter, the findings from the qualitative results and analysis of the first phase indicated that sub-contractors did not have much leeway to select software platforms for use other than those required by contract for interoperability

reasons, or requested by clients. However, the responses given – such as those displayed below - did indicate an important role that software plugins and add-ons played.

“All major contracting companies who have a business model that incorporates being a leader in technology would most likely be incorporating add-ins/plugins/addons to their already existing authoring software.”

“Some Add-ins aid new functionality by allowing cross platform integration. Sometimes this is the only way we can provide the client with exactly what they want”

When it came to the selection of third party tools that enhanced their workflow, there existed some freedom for the BIM team to exercise their discretion in selecting the best option. These third-party tools were referred to as add-ons or plugins by the professionals interviewed. Although commonly used interchangeably, the terms add-ons and plugins do have certain slight differentiators.

Add-ons are designed to act as a supplement to existing software by extending the functionality of that software. As stated by Oreizy and Taylor (2003), they can provide “...alternative implementations for behaviors anticipated by the original developers.” (p. 3). Add-ons are thus typically meant to work with one software and are usually created by the same software vendor.

A plugin, or add-in, is a third-party tool that can be used together with an existing software to communicate and be compatible with other software (Dewan, & Freimer, 2003). Plugins also have the ability to add specific features to a software, however a plugin can work with various software, and is usually created by a third party – i.e., one other than the original software vendor. For simplicity, the plug-ins and add-ons will be referred to as software extensions for the remainder of this dissertation.

In order to explore the applicability of the framework shown in figure 4.8 to the selection process of these software extensions, the phone interviews conducted for this phase were directed specifically at assessing the completeness of the current framework. The interview questions for the second phase can be found in appendix F. These phone interviews also provided additional face validation the framework created from both mechanical and general contractors.

In total, 14 Mechanical contractors and 12 General contractors were interviewed for this phase of the research. These interviews were conducted in a similar manner as in the first phase of the research. Following the data collection, the qualitative data analysis also followed the same procedure as previously described in section 4.1.2 for the first phase of the research.

4.2.2.1 Completing the Framework

The responses of the interviewed general contractors and mechanical sub-contractors mirrored those found in phase one - with respect to the application of the framework to the selection of the major BIM platforms. The interviewees voiced that the major platforms were primarily selected based on interoperability needs, needs of the client, as well as the needs of their partnered firms, as mentioned in the sample comments below:

“For most sub-contractors the basic platform is decided by the general contractor or by the owner - for interoperability issues.”

“This industry is very competitive and companies are forced to adapt based on the customers. Subcontractors basically adopt industry trends whenever the owner or GC, or VE determines that that’s what we need to deliver in order to receive that job.”

With the increase in use of Integrated project delivery methods, communication between stakeholders has become of paramount importance in the industry, requiring file sharing amongst

disciplines and trades. To this end, most contractors tend to adopt the same software whenever possible in order to avoid such interoperability issues.

When asked about the applicability of the framework to the selection of plugins, the interviewees responses indicated and that the framework did indeed represent their selection process closely, however a few additional steps were brought up by the interviewed industry professionals.

The additional steps suggested dealt with (a) the process of custom development and evolution of software solutions; and (b) the process of actively seeking solutions, even in the absence of specific needs.

(a) Custom development and evolution of software solutions

During the initial phase of data collection, interviewed professionals pointed towards the use of extra software extensions and third party software in order to achieve their client requests and work seamlessly with other stakeholders during the construction process. In this stage of data collection, the development and evolution of software solutions – although rare in the construction industry – was an interesting factor in the selection process that was highlighted.

From the data collected, the findings uncovered the creation and development of these tailored software extension tools in 2 ways: as a collaborative effort with the software vendors directly; and as an in-house development endeavor.

For the first route, the professionals pointed out the fact that the functionality provided by current software is not yet able to fully satisfy all the requirements of the companies or client demands. This thus leads to the pathway pointing towards the creation or development

of tailored solutions in conjunction with software vendors, to create extensions that can provide the desired results functionality and results.

“The current ‘out of the box’ software packages do not incorporate all the functionality required to stay competitive. Therefore, if a company is not using a process to assess new tools to improve their efficiency, they will most likely fall behind during this technological revolution the construction industry is now experiencing.”

The second route mentioned was the development of the tailored extensions through in-house development of custom solutions. This was done either from scratch, or was implemented as in-house development using existing or older software Application Programming Interfaces (API) available - in conjunction with a clear development plan. A software API acts as a gateway that enables the development of certain changes to an existing software application. API's thus provide access to functions necessary to establish communication between two applications. (Oreizy & Taylor, 2003). According to Oreizy and Taylor (2003), “APIs are commonly used as tool integration mechanisms since they enable other applications to invoke the services of the host application without user involvement. APIs provide a limited subset of the operations necessary to support evolution.” (p. 3)

“A lot of times, we share information internally between groups. And we find out that the company already invested in a certain, piece of software or tool. We don't want to re-invest in something that's similar to it so we try to tailor it to meet our needs instead of re-investing in a brand-new product.”

These development/evolution options are incorporated in the partial framework addition depicted in figure 4.16.

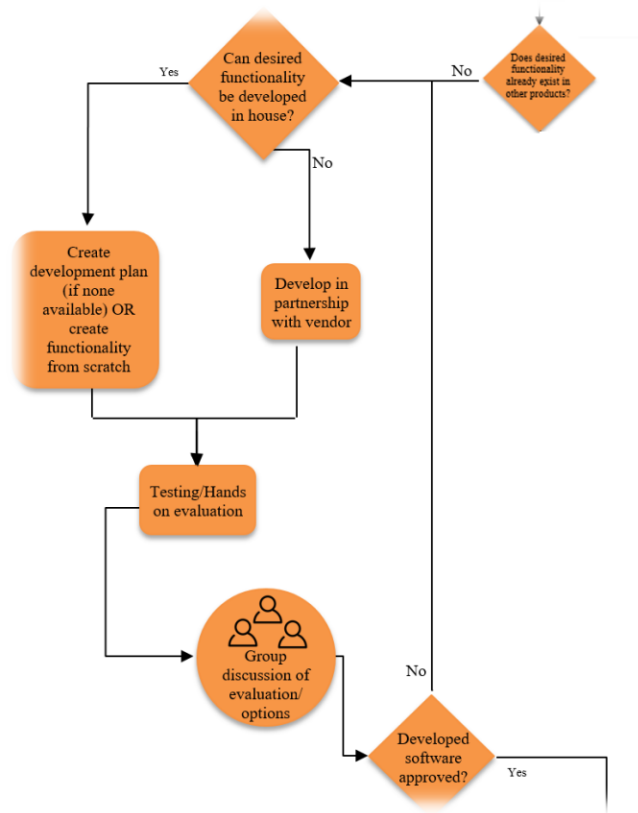


Figure 4.16 Development branch of software selection framework

(b) Actively seeking solutions even in the absence of specific needs

An additional pathway towards the discovery and exploration of potential solutions was also discussed for inclusion in the framework. During the first stage of data collection in this research, the interviewed professionals described how they went through the selection process in order to find a solution to meet a specific need. The professionals interviewed during the second phase agreed with this concept but pointed out that that was not always necessarily the case.

According to the interviewed professionals in this stage, most contractors are constantly on the lookout for something new that could potentially improve their current workflow efficiency.

“We pretty much go out there, hear from other companies, see what other people are doing. We tend to you know, attend seminars or conferences to see what’s out there or have people come in and teach us.”

“We don’t always start out with a formal and clear cut problem and then go search for a solution rather, we’re always looking and trying to keep up with whats out there, whats coming and what new features are being developed an what new players are coming to the market and what they can bring and that’s kind of. That’s definitely more frequent in the approach.”

Thus, as opposed to seeking a solution to meet an existing and pressing need – which was already incorporated in the preliminary framework – these group of interviewees pointed out that actively seeking solutions even when there was no apparent need was also fairly common, and somewhat necessary in order to stay informed and successfully keep up with new practices and advances in the industry.

In order to achieve this, contractors – mechanical and general contractors alike – routinely attend industry seminars, conferences and trade shows, so as to interact with others in the field and gain exposure to the various methods of performing tasks. Thus, be it via word of mouth through discussions with other contractors, or gaining knowledge from conference or seminar presentations, contractors make conscious efforts to stay in tune with advancements in their field. In this way, companies are proactive in their anticipation of areas in which new and emerging technology and techniques could enhance their processes and increase their efficiency. This introduced an alternate mode of beginning the selection process as can be seen in the framework presented in figure 4.17.

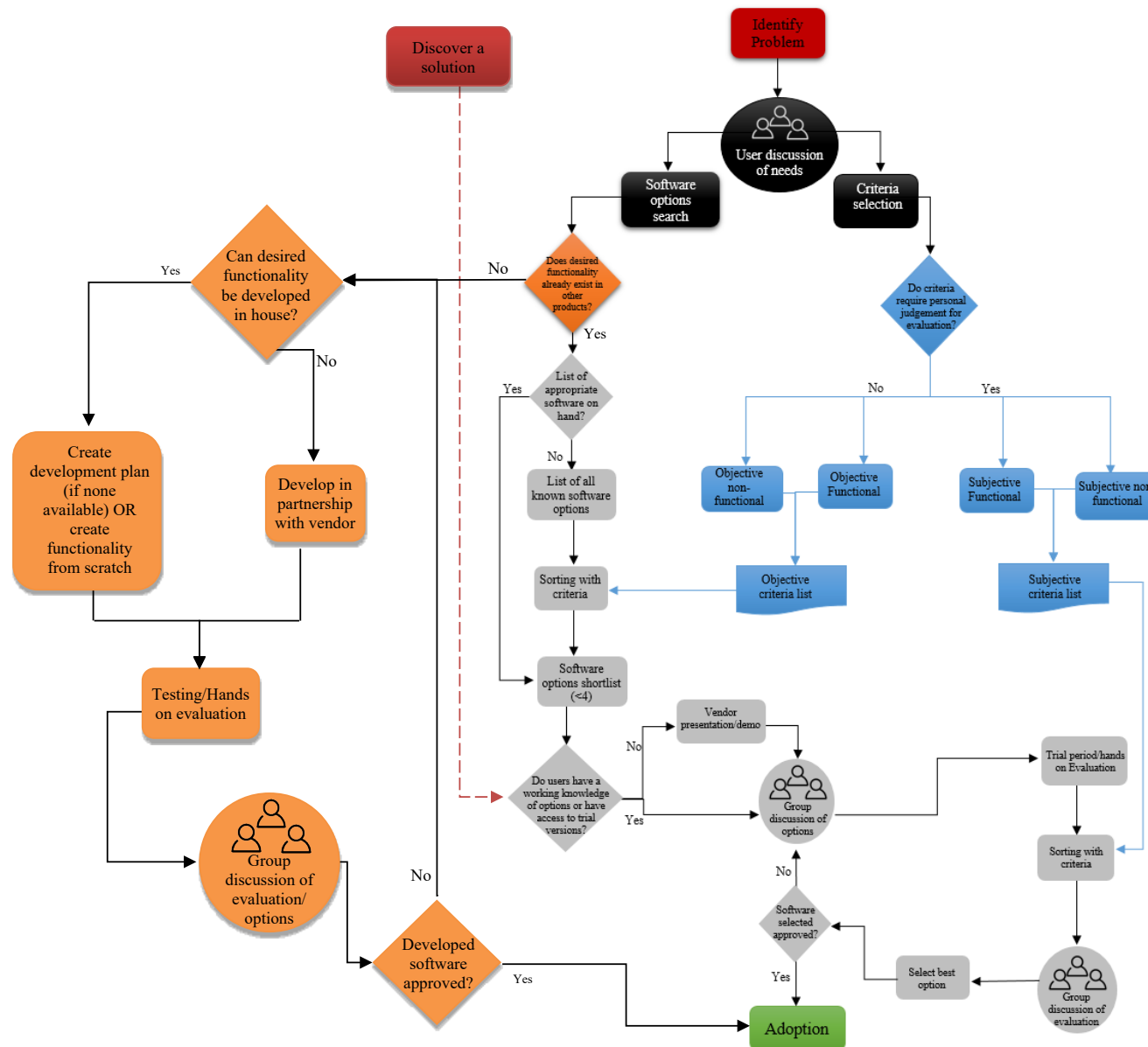


Figure 4.17 BIM software selection framework at the end of phase 2

4.3 Phase 3

Phase 3 consisted of the analysis of the MCDMM as well as the design of the proof of concept web tool aimed at complementing the framework constructed in the first 2 phases. The outcomes of both undertakings will be presented in the following final sections of this chapter.

4.3.1 Decision Making Method Simulations

The main purpose of this section of the research was to compare the consistency rate - or the rate at which the methods came to the same results - of the AHP WSM and WPM methods when compared to one another. Thus, to begin the third phase of this research, the MCDMM were coded in MATLAB. The number of alternatives and criteria used in the simulation ran from 2-7 criteria and 2-5 alternatives. All combinations of the number of alternatives and criteria were tested, resulting in 24 unique combinations of criteria and alternatives in all.

The simulation was run 1000 times, through each of the 24 scenarios. During each run of the simulation, the output values of each of the MCDMM was recorded. The final results were collated and the consistency percentages were calculated for all the methods in order to examine their general consistency performance with respect to one another.

Figures 4.18 and 4.19 show graphs for the consistency rates with increasing alternatives and increasing criteria respectively for the 3 pairs of the MCDMM. Vertical lines grouping the sections of constant criteria numbers with increasing alternative numbers in figure 4.18 were added to the graph to enhance interpretation.

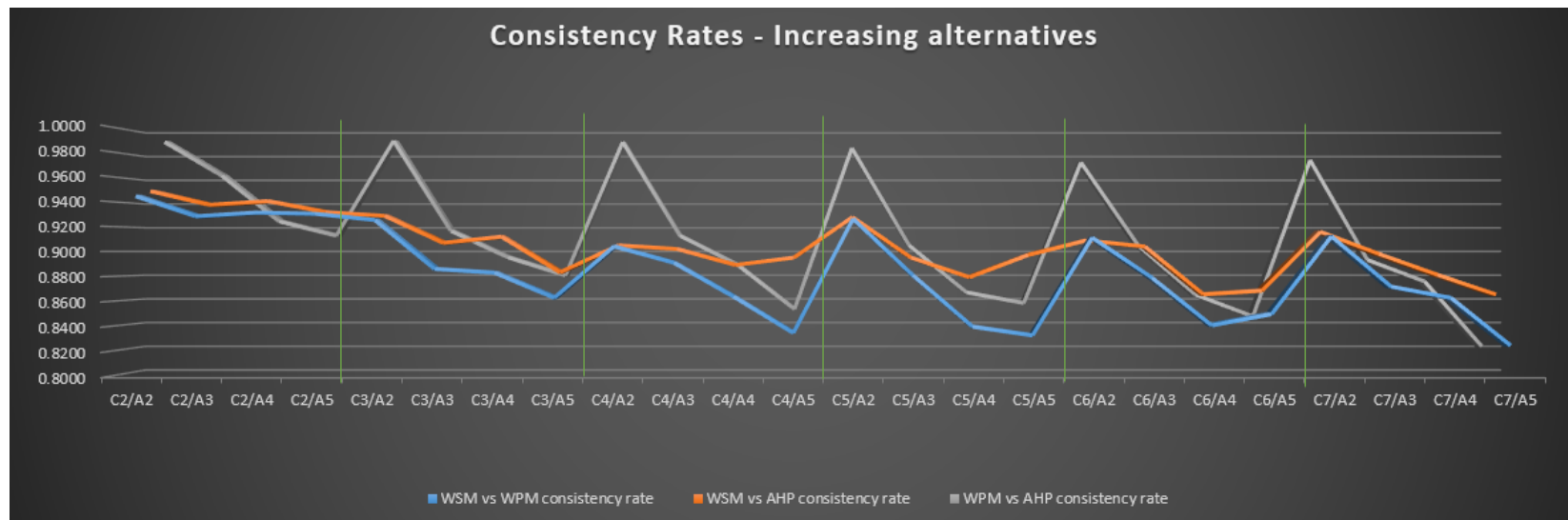


Fig 4.18 Consistency rates of MCDMM pairs with increasing number of alternatives

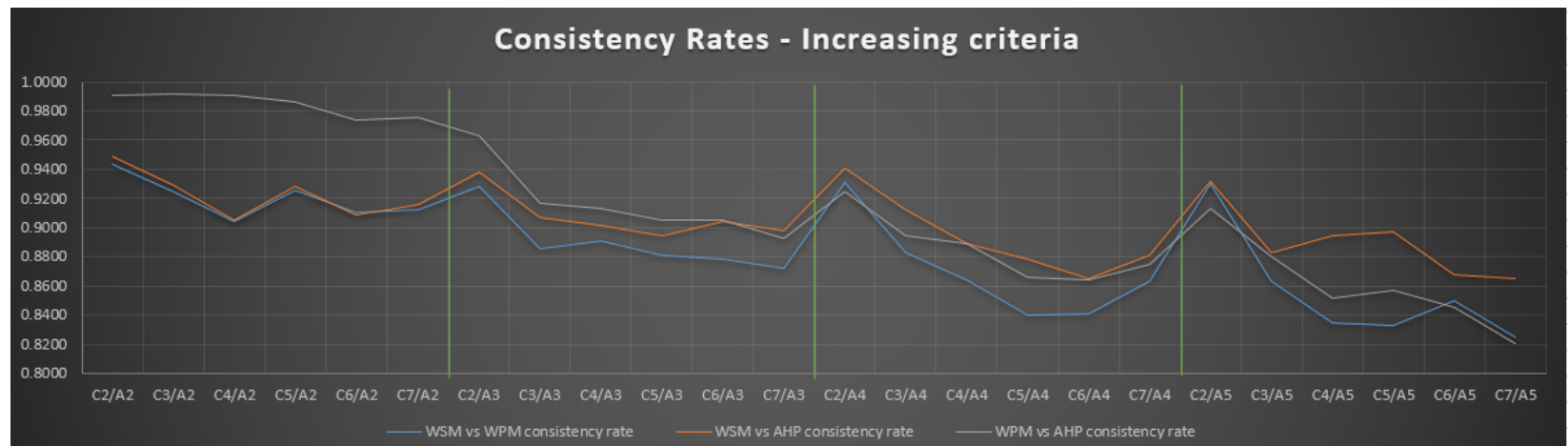


Fig 4.19 Consistency rates of MCDMM pairs with increasing number of criteria

Similarly, vertical lines grouping section of constant alternative numbers with increasing criteria numbers were added to figure 4.19. overall, the two graphs show similar pattern of slight peaks at the beginning of each set of grouping and dips at the end.

The consistency rates indicate the number of times the paired methods produced the same output during the simulation for each specific scenario, when run 1000 times – as a percentage. This graph can thus be used to determine which pair of MCDMM would be the most suitable for any given scenario. Once the MCDMM pair has been identified, it the use of either method would be up to the discretion of the user.

4.3.2 Web Based Decision Support System

The final step of the research was the creation of a proof of concept design of the web interface for the decision-making tool. This web decision-making system is envisioned to act as an assistive tool that works complimentarily with the software selection process mapped out in the resulting framework of this research. The intended application of this tool is in the sections of the framework that require testing and evaluation. The web tool will act as a platform for the qualitative and quantitative evaluation of the performance of software options being considered.

The web interface was created using the Eclipse software development kit (SDK), and coded with HTML5 and CSS. The calculations for the AHP methodology were implemented in the JavaScript scripting language. Input data collected from the users temporarily stored in JSON containers, which were then called and utilized within the JavaScript as needed.

As this was merely a proof of concept, the web tool was designed to cater to the specific scenario of having 2 software alternatives being considered, and 3 criteria being used for the

evaluation. The steps in the implemented process are shown in figure 4.20. Each of the steps of the web tool are further elaborated in the subsequent sections.

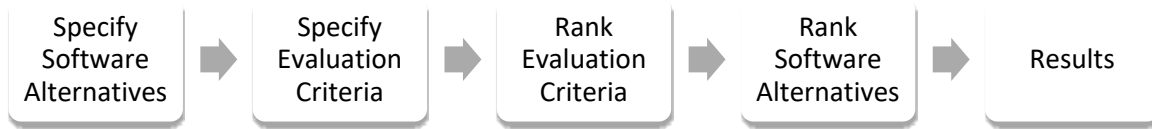


Fig 4.20 Sections of the WBDSS proof of concept design

(a) Step 1: Specify Software Alternatives

In the first step of the web tool, users are given 2 options: i) they are able to use a basic list of objective criteria to sort through all viable software options for a short list, or ii) they are able to directly type in the name of which ever software alternative they would like to go through the evaluation with. This allows flexibility of the tool and enables it to be used in the evaluation of all kinds of software tools.

(b) Step 2: Specify Evaluation Criteria

In the second step of the web tool, users are again given two options similar to those mentioned above. They are able to: i) select their desired criteria from a predefined list of software selection criteria, or ii) they are able to directly type in their own custom criteria as they see fit. The criteria options displayed at this point would be from the subjective criteria options list and will be used for the evaluation of the alternatives specified in the prior step.

Figure 4.21 Interface of steps 1 and 2 of the proof of concept WBDSS

(c) Step 3: Rank Evaluation Criteria

The third step marks the beginning of the evaluation process. Since this web tool was modeled using the AHP method as a basis of its quantitative analysis, the first step in the evaluation process would be for the users to indicate the importance of the criteria they specified in the prior step. The scale used for the ranking of importance will be a 9-point scale as shown in the figure 4.21. Users have the option to rank the criteria they feel more strongly about. As can be seen in the figure the criteria are ranked in pairs against one another. Only one criteria in each pair may be ranked at a time. The second in the pair will be automatically given the inverse of the ranking input of the first.

(d) Step 4: Rank Software Alternatives

Once the criteria have been ranked, the following step in the web tool calls for the users to perform a similar ranking process of their specified software alternatives. Again, this is done in pairs per each criterion indicated, as can be seen in figure 4.22. At this stage, users are also able to input their own notes pertaining to the software alternatives and their performance per criteria.

Step 3: Specify importance of the individual Criteria

Consider each evaluation criteria against the other. Which is more important?

Equal Performance 1	Slightly Better Performance 3	Strong Performance 5	Very Strong Performance 7	Extreme Performance 9
Criteria 1				
Click here if you prefer this		Criteria 2		
		Click here if you prefer this		
		criteria 2 rank 3		
Criteria 1				
Click here if you prefer this		Criteria 3		
		Click here if you prefer this		
		criteria 1 rank 7		
Criteria 2				
Click here if you prefer this		Criteria 3		
		Click here if you prefer this		
		criteria 1 rank 1		

Step 4: Evaluation

Rank the alternatives in pairs, for each evaluation criteria on a scale from 1-9, using the ranking system below:

Which software alternative is more important?

Equal Performance 1	Slightly Better Performance 3	Strong Performance 5	Very Strong Performance 7	Extreme Performance 9
Click to evaluate software X and Y against Criteria 1				
Criteria 1				
Alt 1		Alt 2		
Click here if you prefer this		Click here if you prefer this		
		criteria 3 rank 2		
Notes: Enter any notes about your choice in here				
Click to evaluate software X and Y against Criteria 2				

Figure 4.22 Interface of steps 3 and 4 of the proof of concept WBDSS

(e) Step 5: Results

The qualitative data imputed thus far will be collected and used in the AHP calculations in order to present the final results to the user. These results will be displayed in the form of a recommendation, indicating to the users the overall score each software alternative achieved based on their own subjective input.

4.4 Chapter Summary

This chapter described the progress made in each of the phases described in chapter 3. This chapter also outlined and presented the analysis of the results obtained in the various phases of this research. The next chapter will provide further discussion and will present the final conclusions.

CHAPTER 5. DISCUSSION AND CONCLUSION

In this chapter, a more detailed discussion of the results analyzed from the two main phases detailed in the previous chapter is presented. Final conclusions, and deductions made are examined as well, culminating in the exploration of recommendations for future directions.

5.1 Overview Summary

The main research question of this study was: “How does a company in the Mechanical/Electrical/Plumbing sector of the Architecture Engineering and Construction industry select the appropriate Building Information Model software for their use?”

To further elaborate on the answer to the main research question in full, the following sub-questions were also necessary:

- What methodology do MEP firms follow in order to select their BIM software?
- What is the most appropriate Multi-criteria decision-making method that can be applied to aid in the BIM software selection process for the MEP sector?
- What are the rankings, by importance, of the software selection criteria identified as per the specialty sub sectors of the industry?

The steps taken from the beginning until the end of this research - in order to answer the research question and sub-questions listed above - as well as the outcomes of each step taken, are summarized in figure 5.1. The 3 phases of this research were preceded by an extensive review of literature concerning BIM related software selection criteria in the industry; which then culminated in a consolidated list of 25 identified software selection criteria.

This list of 25 criteria played an integral part of the subsequent phases of the research. The list was used to produce the objective and subjective criteria lists that played a role in the framework, and was also used in the surveys sent out, to gather quantitative data on their importance rankings in the industry.

The answers to the posed research questions and conclusions garnered from each of the unique phases will be further discussed in the subsequent sections.

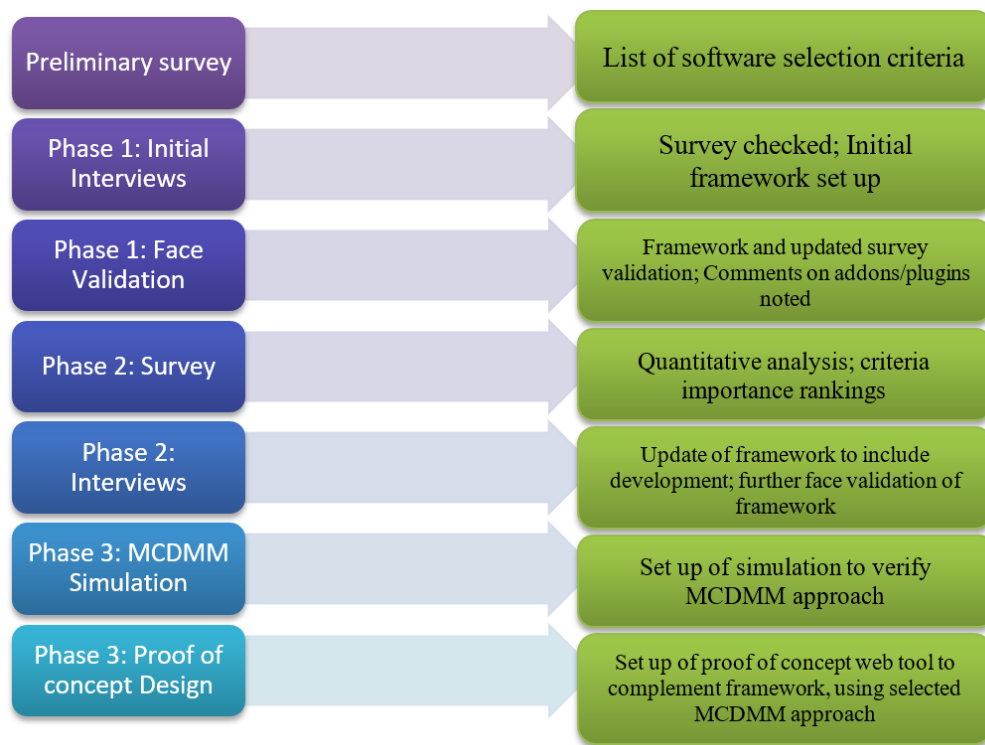


Fig 5.1 Overview summary

5.2 Discussion of Results

5.2.1 Phase 1

Findings from this research indicated that when it came to the major BIM authoring software, the specializations within the industry were mostly pre-defined and tailored towards the specific needs of the trades. Each software package has been adjusted to service a particular area of the AEC industry. For example, micro station is well suited for civil projects, while Revit is well suited for commercial building projects and AutoCAD and, its variants, is well suited for the trade specialties – just to name a few. Companies are thus obliged to select their basic platforms based on contract or client requirements. Moreover, the need for interoperability is a strong driver that steers most companies to adopting the most commonly used platform in their sector in order to easily share documents and data.

These software adaptations, coupled with the need for interoperability amongst stakeholders, leaves little room for companies to wander far from the more popular and well-known brands of BIM authoring platforms available. Another observation from the first phase was that the main software platform of use in the AEC MEP industry was predominantly Autodesk based software.

As a result, when considering options for the selection of a major BIM platform for use, the proposed framework would have little effect since the options for BIM authoring software are limited per specialty area.

5.2.2 Phase 2

5.2.2.1 Survey results discussion

With regards to the importance ranking; the extracted median rankings were comparable between the contractor types. Both general and mechanical contractors indicated similar ranges of criteria importance, with criteria 2: ‘Co-ordination/interference checking’ being the only one to be labeled a 7 on the 7-point likert scale by both groups. This is to be expected as one of the most important tasks necessary in construction is the performance of collision detection (Boktor, Hanna & Menassa, 2014; Hanna, Boodai & El Asmar, 2013).

The software selection criteria importance rankings obtained indicated that there was not much of a difference between the mechanical and general contractors when it came to their priorities. The criteria that showed the most differentiation in importance between the two groups were subjective and functional group as shown in table 5.1.

These were identified as being subjective functional criteria that dealt with fabrication, customizability and ease of editing components. All three of the criteria showed a point difference of more than 1, and upon observation, all three of the criteria dealt with tasks that could be seen as primarily performed by subcontractors. This follows in line with findings from research by Kent (2014); Boktor, Hanna and Menassa (2014); Hanna, Boodai and El Asmar (2013) that indicated the top use of BIM software in the MEP sector were for clash detection and shop drawings.

Table 5.1

Criteria with large differences in importance ranking

SUBJECTIVE AND FUNCTIONAL CRITERIA		GC	SC
criteria12	Improved link from design to fabrication; support for rapid prototyping and 3d printing	3	6
criteria17	Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc.]	4	5.5
criteria4	Ease of editing and adding custom components /object libraries	5	6.5

5.2.2.2 Interview results discussion

A major conclusion drawn from the interviews was that contracting firms in the AEC industry do not have a set method for selecting the various types of software they use. While some companies did seem to display structured approaches to the issue of software selection, others took proactive measures and kept themselves constantly updated with the latest technology and emerging trends and tools from conferences, discussions with colleagues or educational seminars.

Findings from the interviews conducted in the second phase of the interviews pointed towards the increasing influence of software extensions and third-party applications in the industry. When considering addons that could potentially aid in enhancing the overall BIM workflow of a company, there existed more flexibility and freedom of choice for mechanical and general contractors alike.

Moreover, a handful of companies attested to tailoring solutions to their specific needs. This signaled the emergence of an increasing effort towards the development of specialized software extensions either in-house or in partnership with vendors. Although admittedly rare in

the contracting industry, this nonetheless goes to show how the advancement of technology in construction is slowly reshaping the face of what was known as a typical construction company. Add-ins – in house or via third parties - are a way of decentralizing the BIM software evolution.

Although developing these tools in-house is a tedious and specialized task that many AEC companies are not necessarily equipped for, some industry professionals interviewed indicated that their firm had been involved in such a process in order to achieve their desired results. The complexity of the developed software extensions could range from simple scripts that serve to automate repetitive and frequently performed tasks, to complete applications that perform specific, customized tasks.

5.2.3 Phase 3

5.2.3.1 Simulation of MCDMM

The observed trend in the graphs produced from the MATLAB simulation was that overall, the WPM and AHP pair started off with high consistency rates, but ended at the end of the graph with the lowest consistency; while the WSM and AHP pair showed a more stable trend. This was true in both graphs.

The observed consistency rates from the simulation results provided a rough guide to the selection of a preferred method. However, it should be noted that there is no right or wrong answer in the output of an MCDMM since the user criteria weights – which are highly subjective - go a long way to affect the outcomes of these methods (Triantaphyllou & Sanchez, 1997: Pamučar, Božanić, & Randelović, 2017).

Triantaphyllou and Mann (1989), also conducted studies to investigate the accuracy and contradiction rate of various decision-making methodologies – namely, WSM, WPM, AHP.

Their study yielded the conclusion that the number of criteria being dealt with played the most important role in deciding which method is more appropriate (Triantaphyllou & Lin, 1989).

Due to the AHP's ability to handle multidimensional decision making it was the selected choice for implementation in the proof of concept design of the WBDSS web tool. It should be noted that all of these MDCMM could be implemented in the WBDSS, leaving it as a matter of user preference as to which method to use.

5.2.3.2 Proof of concept WBDSS

Although testing of the proof of the concept web tool fell out of the scope of the study, its design showed that the implementation of a quantitative aspect of the evaluation and decision-making process was possible.

For future improvements of the WBDSS, features that allow for users to create a company account, with an overseeing account manager(s) could also be incorporated. The account manager would have the ability to allow for the creation of further user accounts for the remaining individuals to take part in the decision making. The WBDSS would then be linked with a database containing all the information gathered during the course of this research, to be used in its functions and recommendations.



Fig 5.2 Summary of features

Overview description of the WBDSS functions

The function of the WBDSS is envisioned to be structured in the following way (see figure 5.3): the first step after the creation of accounts is the preselection stage. During this stage, a progressive filtering strategy as described by Baharom, Yahaya, and Tarawneh (2011), will be implemented. To do this, the account manager will have to select his desired category of need from the BIM use category. This will eliminate the software that do not meet that requirement. Next, the account manager will be asked to specify user needs from the list of identified basic functional criteria. This will be used to sort through the list of software and pull up those that possess the indicated functionalities.

From this point, the account manager specifies the second level of needs that are being considered along with associated user weights, and then invites vendors for company

presentations and trial demonstrations. During this stage, the individual users can put in their rankings of the software according to their experiences.

Once complete, the WBDSS runs the computations using the selected MCDMM, and produces a summary report outlining the comparison of the software.

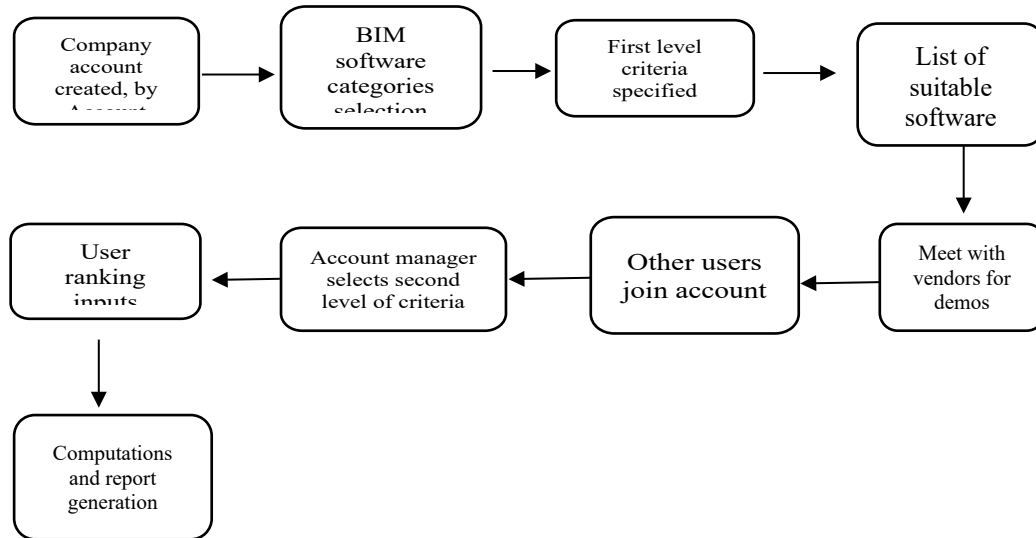


Fig 5.3 Flow chart of the WBDSS

5.3 Conclusion

This research set out to understand the decision-making process for BIM software selection contracting firms go through in the AEC industry. In answering the set research question and sub-questions, the following goals were also accomplished:

- ✓ Identify a list of user needs and evaluation criteria when seeking out various software
- ✓ Identify a list of user rating/ranking for each identified criterion.
- ✓ Determine an appropriate modeling technique that can aid in the decision-making process.

- ✓ Create an online web based decision support system (proof of concept) that can be used to facilitate a firm's decision-making process for BIM software selection.

Ultimately, the final and most important goal of the research cumulated in the creation of the BIM software selection framework shown in figure 5.4.

Validation of framework

The final framework was completed using data collected from the first interview phase through to the surveys of the second phase, until the final interviews of the second phase. At each of the aforementioned stages, the framework was continuously vetted by industry professionals as illustrated in figure 5.4. Face validation sent the preliminary framework through its first stage of vetting. Additional data and validation was further performed via the survey in phase two as well as the interviews in the second phase. The framework thus includes the consolidated major points obtained from the analyzed data collected from the interviews, qualitative survey data, and feedback collected from the face validation steps throughout the research phases.

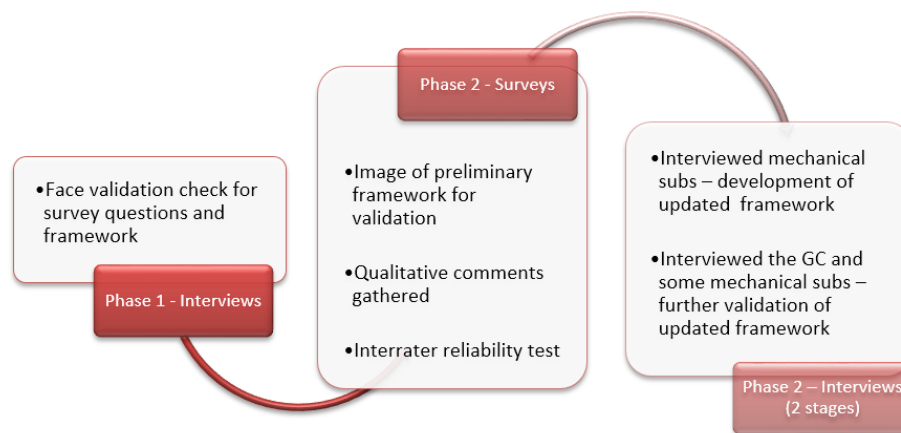


Fig 5.4 Stages of framework validation

All possible pathways described and identified through the data collected were incorporated into the framework in a logical and sequential manner, effectively summarizing the various means contractors were able to achieve their results of software selection in the industry.

The framework itself is thus the embodiment of the various possible paths that take place in the construction sector of the AEC industry: development; discovery of something specific; and deciding between various options. It also depicts the areas in which the proposed WBDSS could be effectively utilized during the process – shown with a green border.

When compared with the various frameworks described in section 2.3 of chapter 2, the framework developed as a result of this research shares some similarities in structure. Their similarities include seeking out criteria, going through an evaluation or assessment phase and finally acceptance. In contrast, the BIM software selection framework has the added branch of the development or evolution of products. It also provides 2 different approaches to beginning the software selection process, depending on the need or aim of the company. Thus, although parallels can indeed be drawn between the framework resulting from this research and those presented in the literature review, this framework possesses some unique characteristics that enable it to stand on its own.

5.3.1 Limitations and future recommendations for future work

During the quantitative analysis, it was noted that the sample sizes for the criteria importance rankings were smaller than anticipated. This lack of sufficient responses thus affected the overall power of the study. The achieved power of approximately 60% is a major limitation of the qualitative analysis conducted, affecting the potential generalizability of the quantitative results. It is recommended that for future research would have to involve larger

samples and also include more sub sectors in the industry, in order to verify the generalizability and applicability of the importance criteria findings and observed contrasts in the needs and processes between the various disciplines in the industry that may exist.

Also, interviewed professionals pointed out that even after the initial adoption of a selected software, the solution may not be assimilated into the workflow due to some unforeseen issue – e.g., an underestimated learning curve, or technical difficulties with IT. In such cases, there would be an iteration of the steps – this however was not fully delved into as it was out of the scope of this research.

Moreover, future studies could further explore the development of in house solutions and vendor partnership for software extension customizations within firms in various sectors of the AEC industry. It would seem as though the rapid advancement of technology in the AEC industry is slowly bridging the gap between software engineering/development and construction – evident through the adoption of software engineering tactics to achieve progress on projects, e.g., Agile project management techniques and in-house product development.

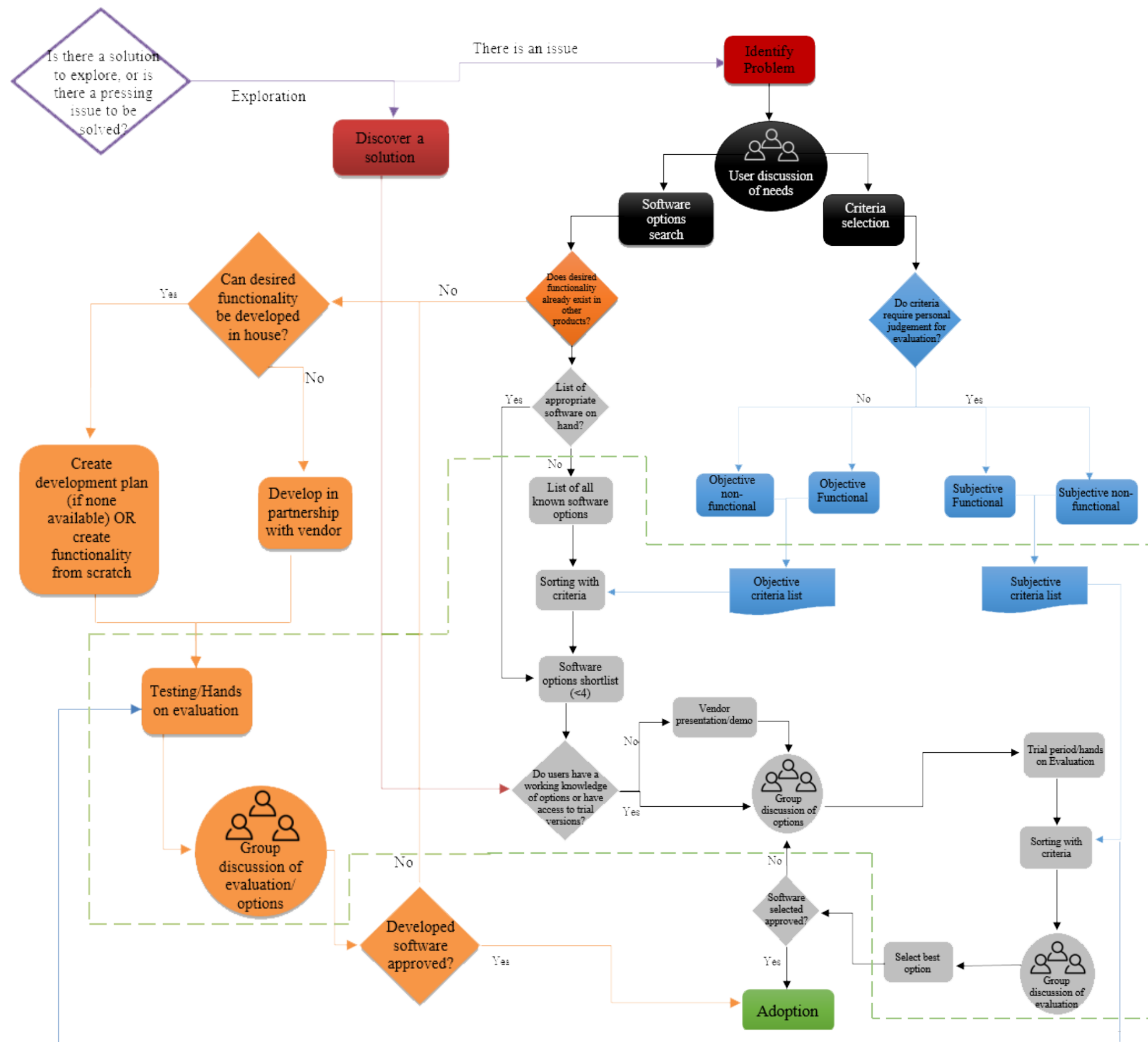


Figure 5.5 Finalized BIM software selection framework

Future testing would also be necessary in order to ascertain the applicability of the web based decision support system to a real-world scenario. A case study approach could be used in order to thoroughly investigate the gather feedback on user satisfaction and usability of the tool and framework.

Another approach could be taken from the work of Lu, Yu and Lu (2001), towards understanding and analyzing the DSS acceptance among individuals in the industry. The work of Lu et al., (2001) evaluated the user perceptions on using a DSS, in 4 areas: Ease of Use, Usefulness, Preferences and willingness. A similar test is recommended in order to determine the effectiveness of the WBDSS in the selection process described in the framework. For completeness, the tests could be conducted on BIM software users and non-BIM software users in the industry so as to elicit feedback from differing perspectives. One perspective on the apparent quality of the results from the web based decision support system and appropriateness of the framework; while the second perspective would be able to provide feedback on the viability and applicability of the web based decision support system in a real-world scenario.

Together, these responses gathered will be geared towards the validation of the web based decision support system and its ability to provide satisfactory and accurate results to its users.

APPENDIX A. FIRST PASS ON LIST OF CRITERIA

CRITERIA	SOURCE
Automated setup, change management, data management and updating, reducing traditional CAD management	Won & Lee (2010); AGCA (2006); Gu & London (2010); Arayici et al., (2011); Khemlani (2007); Ruiz (2009); NIBS (2007)
flexible modeling/ design freedom	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Multi-disciplinary association that serves architecture, structural engineering, and MEP	Khemlani (2007); Ruiz (2009)
Ability to support preliminary conceptual design modeling	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Full support for producing construction/as-built documents so that another drafting application need not be used	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); Gu & London (2010)
Built-in ability to generate highly-photorealistic renderings and animations	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); NIBS (2007); AGCA (2006)
Smart objects, which maintain associativity, connectivity, and relationships with other objects	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Co-ordination/Interference checking	Arayici et al., (2011); Khemlani (2007); AGCA (2006)
Support for construction-related tasks such as quantity take-off, estimating, and 4D scheduling	Khemlani (2007); AGCA (2006)
resulting file sizes	Arayici et al., (2011);
Ability to work on large projects	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)

Ability to support distributed work processes and share information, with multiple team members working on the same project	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); AGCA (2006); Gu & London (2010)
info delivery method; real time data	NIBS (2007); Dib, Chen & Cox (2012)
IFC compatibility, Support for 3D PDF for electronic publishing and distribution	Arayici et al., (2011); Khemlani (2007)
export and import capabilities to a variety of formats	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); Dib, Chen & Cox (2012); NIBS (2007)
Direct integration with external applications (energy, structural, project management, FM, space programming tools)	Khemlani (2007)
Integration with related disciplines such as urban design, landscape design, civil engineering, and GIS	Arayici et al., (2011); Khemlani (2007); NIBS (2007)
Quality of Help/technical support and supporting documentation, tutorials, and other learning resources	Arayici et al., (2011); Khemlani (2007); NIBS (2007); Gu & London (2010); AGCA (2006)
Intuitiveness and ease of use promising a short learning curve	Arayici et al., (2011); Khemlani (2007); AGCA (2006)
Extensibility and customization of the solution - programming and configuration	Arayici et al., (2011); Khemlani (2007)
Rule systems for automating trivial tasks	Khemlani (2007)
Number of third-party developers developing add-on applications for the tool	Khemlani (2007)
known successful BIM cases by major subcontractors/business partners	Won & Lee (2010)
Affordability - initial investment costs for hard & software, implementation and training	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)

Expected economic impact (ROI)	Won & Lee (2010); Gu & London (2010)
High level of detail ; data richness	Ruiz (2009); NIBS (2007); Dib, Chen & Cox (2012)
Information accuracy/input data to dimensional accuracy	NIBS (2007); Dib, Chen & Cox (2012); Arayici et al., (2011)
Availability of extensive content/object libraries	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Ease of use for editing and making custom components /libraries	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Operates in preferred operating environment/equipment (e.g., Windows, UNIX).	Ruiz (2009); AGCA (2006); Dib, Chen & Cox (2012)
How well it can be adopted without conflict with the company's traditional work process	NIBS (2007); Dib, Chen & Cox (2012); Gu & London (2010)
Is the software required by companies overall business strategy	Gu & London (2010)
The market share leadership position of the vendor offering the BIM solution	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Improved link from design to fabrication	Khemlani (2007)
Support for rapid prototyping/3D printing	Khemlani (2007)
Ability to be localized—to capture local building codes and standards	Khemlani (2007)
Support for LEED	Khemlani (2007)
Security and access controls	Khemlani (2007); Gu & London (2010)
Efficiency and speed of operations (how much time a user needs to create a good model)	Khemlani (2007)
How well current employees use software application	Won & Lee (2010)

Use of software application required by contract	Won & Lee (2010)
Ability to publish, share and view drawings and models	Ruiz (2009)
Recovery mechanism ensures data integrity to the business function level.	Ruiz (2009); Arayici et al., (2011)

APPENDIX B. SECOND PASS ON LIST OF CRITERIA

CRITERIA	SOURCE
History tracking, change management, data management and automated updating	Won & Lee (2010); AGCA (2006); Gu & London (2010); Arayici et al., (2011); Khemlani (2007); Ruiz (2009); NIBS (2007)
Flexible conceptual design modeling / design freedom	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Improved link from design to fabrication; support for rapid prototyping and 3d printing	Khemlani (2007)
Built-in ability to generate highly-photorealistic renderings and animations	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); NIBS (2007); AGCA (2006)
Co-ordination/interference checking	Arayici et al., (2011); Khemlani (2007); AGCA (2006)
Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	Khemlani (2007); AGCA (2006)
Ability to efficiently work on large projects without resulting in cumbersome file sizes	Arayici et al., (2011); Khemlani (2007); Ruiz (2009)
Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); AGCA (2006); Gu & London (2010); NIBS (2007); Dib, Chen & Cox (2012)
Security and access controls, with recovery mechanisms to ensure data integrity	Khemlani (2007); Ruiz (2009); Gu & London (2010)

IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dfx etc]	Arayici et al., (2011); Khemlani (2007); Ruiz (2009); NIBS (2007); Dib, Chen & Cox (2012)
Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines (urban design, landscape design, civil engineering, and GIS)	Arayici et al., (2011); Khemlani (2007); NIBS (2007)
Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources	Arayici et al., (2011); Khemlani (2007); Gu & London (2010); AGCA (2006); Dib, Chen & Cox (2012)
Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application	Arayici et al., (2011); Khemlani (2007); AGCA (2006)
Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]	Arayici et al., (2011); Khemlani (2007); Won & Lee (2010)
Number of third-party developers with add-on applications for the tool	Khemlani (2007)
Known successful BIM cases by major subcontractors/business partners	Won & Lee (2010)
Market share leadership position of the vendor offering the BIM solution	Khemlani (2007); Arayici et al., (2011); Ruiz (2009)
Initial investment costs for hard & software, implementation and training; expected ROI	Khemlani (2007); Arayici et al., (2011); Ruiz (2009); Won & Lee (2010); Gu & London (2010)
Availability of extensive out-of-the-box content/object libraries	Khemlani (2007); Arayici et al., (2011); Ruiz (2009)
Ease of editing and adding custom components /object libraries	Khemlani (2007); Arayici et al., (2011); Ruiz (2009)

How well it can be adopted, without conflict, into the company's traditional work process	Gu & London (2010); NIBS (2007); Dib, Chen & Cox (2012)
Ability to capture local building codes and standards / support for LEED	Khemlani (2007)
Use of software application required by contract/company's business strategy	Won & Lee (2010)
Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].	Ruiz (2009); Dib, Chen & Cox (2012); AGCA (2006)

APPENDIX C. PILOT SURVEY QUESTIONS

The following survey questions are adopted from Chen, Dib and Cox (2012)

PART 1 - COMPANY INFORMATION

Please fill in the information (or circle the appropriate choice) for each question

Q1. Please specify your company's primary type of business:

Q2. How many years has your company been using BIM software

a) less than 1 year b) 1 – 3 years c) 3 – 6 years d) more than 6 years

Q3. Please identify the BIM software applications used in your company by indicating how long the company has been using it (those that are not used can be left blank).

Software	Vendor	Software	Vendor
3D MEP/PREFAB		4D BIM	
Autodesk REVIT MEP	Autodesk	Synchro	Synchro Ltd
Bentley Hevacomp Mechanical Designer	Bentley	Vico Software	Trimble
AECOSim Building Designer	Bentley	Navisworks	Autodesk
4Ms Finehvac + Fineelec + Finesani	Ghery Technologies	Bentley Project Wise	Bentley
Digital Project MEP Systems Routing	Ghery Technologies	Innovaya	Innovaya
Auto CADMEP	Autodesk	Primavera	Oracle
Graphisoft MEP Modeler	Graphisoft	5D BIM	
Cadpipe HVAC	AEC Design Group	Innovaya	Innovaya
CAD MEP Plancal Nova	Trimble	Vico Software	Trimble
Trimble Pipe Designer 3d/Quickpen Piping	Trimble	Dprofiler	Beck Technology

Designer 3d			gy
MagiCAD	<i>Magiacad</i>	QTO	<i>Autodesk</i>
DDS-CAD MEP	<i>Nemetschek</i>	Coordination/Clash Detection	
CADMEP+	<i>MAP</i>	Navisworks	<i>Autodesk</i>
Plant 3d	<i>Autodesk</i>	Solibri	<i>Solibri</i>
Sketchup	<i>Trimble</i>	Vico	<i>Trimble</i>
Archicad	<i>Graphisoft</i>	Tekla BIMsight	<i>Tekla</i>
Mep Designer	<i>Trimble</i>	Smartplant Review	<i>Intergraph</i>
CADMEP	<i>Autodesk</i>	Bentley Project Wise	<i>Bentley</i>
EST MEP	<i>Autodesk</i>	Digital Project Designer	<i>Ghery Technologies</i>
CAM Duct	<i>Autodesk</i>	Rendering/Animation	
CAD MEP (Cadduct / Cadmech)	<i>MAP</i>	Navisworks	<i>Autodesk</i>
CAD Pipe Commercial Pipe	<i>AEC Design Group</i>	3d Max	<i>Autodesk</i>
Fabrication For ACAD MEP	<i>East Coast CAD/CAM</i>	Lumion 3d	<i>Lumion</i>

Q4. Please indicate any other BIM software used that was not included in the categories above:

Q5. Please indicate the number of projects that your company has utilized BIM in

a) 0 b) 1-5 c) 6-10 d) 11-20 e) 20-40 f) 40+

Q6. Please indicate the main project delivery method for those BIM-implemented projects (select one):

a) Design-Bid-Build b) Construction Management(CM) c) Design-Build

d) Integrated Project Delivery e) others (please specify)

Q 7. Please indicate the major building type for those BIM-implemented projects (select one):

a) Commercial b) Residential c) Educational d) Healthcare e) Industrial

f) Institutional g) Industrial h) Civil i) Entertainment j) Military

k) Transportation l) Others (please specify)

Q 8. Please indicate the total value of BIM-implemented projects (select one):

a) \$0 to \$ 20 million b) \$20-\$40 million c) \$40-\$100 million d) > \$100 million

Q 9. Please indicate the total annual billings of your company (select one):

a) \$0 to \$ 20 million b) \$20-\$40 million c) \$40-\$100 million d) > \$100 million

PART 2 - PERSONAL INFORMATION

Q10. Please specify your current position

Q11. Please indicate the number of BIM-implemented projects you have been involved in

Q12. Please indicate your direct working experience with BIM

a) < 1 year b) 1-3 years c) 3-5 years d) 5-8 years e) >8 years

Q13. Have you ever taken part in the software selection decision making process of BIM software in your company?

PART 3 - SOFTWARE SELECTION PROCESS

From this point on, questions appended with 'a' follow are diverted to participants involved in the selection process, while those appended with 'b' are diverted to participants not involved in the selection process.

Q1a. How many times have you taken part in the company's BIM software selection process?

Q 2a. Please describe your role in the selection process

Q3a. How many years have you used the selected BIM software:

Q4a. Were they selected during the same period?

Q5a. Out of the following list, please indicate which criteria were considered during your company's selection process by ranking its importance on a scale of 1 (not important) – 7 (very important).

Q5b. Out of the following list, please indicate which criteria you would consider when selecting BIM software in a company, by ranking its importance on a scale of 1(not important) – 7 (very important).

	CRITERIA	Rank
1	Flexible conceptual design modeling / design freedom	
2	Co-ordination/interference checking	
3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	
4	Ease of editing and adding custom components /object libraries	
5	Use of software application required by contract/company's business strategy	
6	In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents	
7	Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members	
8	IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dfx etc]	
9	Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application	
10	Initial investment costs for hard & software, implementation and training; expected ROI	
11	History tracking, change management, data management and automated updating	
12	Improved link from design to fabrication; support for rapid prototyping and 3d printing	
13	Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources	
14	Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].	

-
- 15 Ability to efficiently work on large projects without resulting in cumbersome file sizes
 - 16 Security and access controls, with recovery mechanisms to ensure data integrity
 - 17 Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]
 - 18 Known successful BIM cases by major subcontractors/business partners
 - 19 Number of third-party developers with add-on applications for the tool
 - 20 Market share leadership position of the vendor offering the BIM solution
 - 21 How well it can be adopted, without conflict, into the company's traditional work process
 - 22 Built-in ability to generate highly-photorealistic renderings and animations
 - 23 Direct integration with external applications (energy, structural, project management, FM, space programming tools etc.) from related disciplines
(urban design, landscape design, civil engineering, and GIS)
 - 24 Availability of extensive out-of-the-box content/object libraries
 - 25 Ability to capture local building codes and standards / support for LEED
-

Q6 a & b. Please indicate the criteria considered while selecting the software that was not included in the list before:

APPENDIX D. PHASE 2 UPDATED SURVEY

PART 1 - COMPANY INFORMATION

Please fill in the information (or circle the appropriate choice) for each question

Q1. Please specify your company's primary type of business:

Q2. How many years has your company been using BIM software

b) less than 1 year b) 1 – 3 years c) 3 – 6 years d) more than 6 years

Q3. Please identify the BIM software applications used in your company for
3d/4d/5d/Coordination/Visualization:

Q4. Please indicate the number of projects that your company has utilized BIM in

a) 0 b) 1-5 c) 6-10 d) 11-20 e) 20-40 f) 40+

Q5. Please indicate the main project delivery method for those BIM-implemented projects (select one):

Q 6. Please indicate the major building type for those BIM-implemented projects (select one):

Q 7. Please indicate the total annual billings of your company (select one):

b) \$0 to \$ 20 million b) \$20-\$40 million c) \$40-\$100 million d) > \$100 million

PART 2 - PERSONAL INFORMATION

Q9. Please specify your current position

Q10. Please indicate your direct working experience with BIM

b) < 1 year b) 1-3 years c) 3-5 years d) 5-8 years e) >8 years

Q12. Have you ever taken part in the software selection decision making process of BIM software in your company?

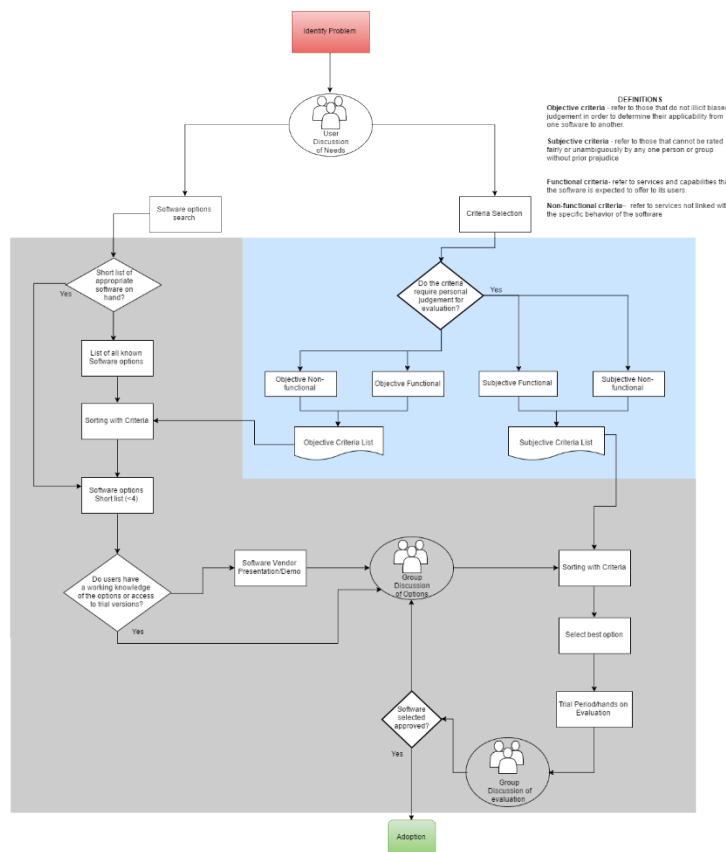
Q13. Out of the following list, please indicate which criteria were considered during your company's selection process by ranking its importance on a scale of 1 (not important) – 7 (very important).

	CRITERIA	Rank
1	Flexible conceptual design modeling / design freedom	
2	Co-ordination/interference checking	
3	Support for construction-related tasks such as quantity take-off, estimating, and 4d scheduling	

-
- 4 Ease of editing and adding custom components /object libraries
 - 5 Use of software application required by contract/company's business strategy
 - 6 In built multi –disciplinary ability [architecture, structural, MEP etc] for producing complete construction/as-built documents
 - 7 Ability to support distributed work processes and info delivery/publishing/sharing of real time data with multiple project team members
 - 8 IFC compatibility, support for 3d pdf; export & import capabilities [dwg, fbx, dwn, dfx etc]
 - 9 Intuitiveness of solution, ease of use to promise a short learning curve; how well current employees are able to use software application
 - 10 Initial investment costs for hard & software, implementation and training; expected ROI
 - 11 History tracking, change management, data management and automated updating
 - 12 Improved link from design to fabrication; support for rapid prototyping and 3d printing
 - 13 Availability/quality of help/technical support and supporting documentation, tutorials, other learning resources
 - 14 Application operates in preferred environment [e.g. 64/32-bit Windows, Mac OS, Unix].
 - 15 Ability to efficiently work on large projects without resulting in cumbersome file sizes
 - 16 Security and access controls, with recovery mechanisms to ensure data integrity
 - 17 Extensibility and customization of the solution [automated setup, programming and configuration of rules systems for trivial tasks, UI, etc]
 - 18 Known successful BIM cases by major subcontractors/business partners
 - 19 Number of third-party developers with add-on applications for the tool
 - 20 Market share leadership position of the vendor offering the BIM solution
-

-
- 21 How well it can be adopted, without conflict, into the company's
traditional work process
- 22 Built-in ability to generate highly-photorealistic renderings and
animations
- 23 Direct integration with external applications (energy, structural, project
management, FM, space programming tools etc.) from related disciplines
(urban design, landscape design, civil engineering, and GIS)
- 24 Availability of extensive out-of-the-box content/object libraries
- 25 Ability to capture local building codes and standards / support for LEED
-

Q14. Please indicate the criteria considered while selecting the software that was not included in the list before:



Q15. In your opinion, is the framework an accurate representation of the BIM software selection process your company and in industry?

Strongly Disagree	Disagree	Somewhat disagree	Not sure	Somewhat agree	Agree	Strongly agree
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q16. Please indicate your feedback or comments on the framework above (as it pertains to the selection process in industry, or in your own company).

APPENDIX E. PHASE 1 INTERVIEW PROTOCOL

PART 1 – SURVEY FEEDBACK

- In your opinion, were any of the questions ambiguous or misleading?
- In your opinion, was the use of any terminology in the criteria ambiguous?
- Would you reword or consolidate any of the criteria?
- What is your opinion on the following added criteria *[to be included only if any were added]*:

PART 2 – PROCESS DESCRIPTION

- Please describe the process involved with your BIM software selection?
- How long did the entire process take?
- How long did each step take?
- How many people were involved?
- With which method were the shortlisted software quantitatively evaluated?

APPENDIX F. PHASE 2 INTERVIEW PROTOCOL

1. How well does the framework shown before, represent the selection process for BIM software in your company/industry?
2. How well does the framework shown before, represent the selection process for software needed to enhance and manage your internal BIM workflow?
3. What aspects of the framework do you disagree with and why?
4. What aspects of the framework do you agree with and why?
5. What general tools/add-ins do you use to aid in your BIM workflow?
6. Does the tool/add-in introduce a new functionality or improve the existing functionality of your main BIM software platform?
7. Are the add-ins developed in house or purchased from a third party?

APPENDIX G. MANN WIHTNEY TEST FOR SIGNIFICANCE OUTPUT

Mann Whitney test for significant differences between mean ranking of criteria between

Electrical vs mech

	E_subcontractor			M_subcontractor			sig
	Mean	Median	Std. Deviation	Mean	Median	Std. Deviation	
criteria1	4.7647	5.0000	1.67815	5.5200	6.0000	1.66132	0.1260
criteria2	6.5882	7.0000	.93934	6.3200	7.0000	1.10755	0.2740
criteria3	5.3529	5.0000	1.72993	5.4400	6.0000	1.75784	0.8620
criteria4	5.9412	6.0000	1.19742	6.3600	7.0000	.81035	0.2790
criteria5	4.7059	5.0000	1.86295	5.4800	5.0000	1.32665	0.1700
criteria6	4.2941	4.0000	2.02376	5.2400	6.0000	1.80924	0.1250
criteria7	5.1176	6.0000	1.90008	5.2800	5.0000	1.54164	1.0000
criteria8	5.3529	6.0000	1.83511	5.8000	6.0000	1.73205	0.4290
criteria9	5.7647	6.0000	1.34766	6.1200	6.0000	.92736	0.4730
criteria10	4.8824	5.0000	1.49509	5.5600	6.0000	1.70978	0.0780
criteria11	5.1765	5.0000	1.50977	5.2800	6.0000	1.51438	0.8120
criteria12	4.9412	6.0000	2.22122	5.4000	6.0000	1.52753	0.7820
criteria13	4.9412	5.0000	1.85306	5.4800	6.0000	1.44684	0.3940
criteria14	4.9412	5.0000	2.19290	5.7600	7.0000	1.87705	0.2160
criteria15	5.1176	6.0000	2.17607	5.8800	7.0000	1.78699	0.2160
criteria16	5.1176	5.0000	1.72780	5.7600	6.0000	1.33167	0.2150
criteria17	5.0000	5.0000	1.50000	5.6000	6.0000	1.25831	0.1780
criteria18	4.7647	5.0000	1.67815	5.1200	5.0000	1.64114	0.4570
criteria19	4.5294	5.0000	1.50489	4.8000	5.0000	1.11803	0.6630
criteria20	4.5294	5.0000	1.66274	4.8000	5.0000	1.44338	0.6280
criteria21	5.1765	5.0000	1.50977	5.8000	6.0000	1.19024	0.1380
criteria22	3.4118	3.0000	1.90587	3.6800	4.0000	1.57374	0.5440

criteria23	3.4118	3.0000	2.06334	4.6400	5.0000	1.65529	0.0540
criteria24	5.0000	5.0000	1.83712	5.6400	6.0000	1.15036	0.3300
criteria25	4.4706	5.0000	2.03463	4.6800	5.0000	1.65126	0.8860

Mann Whitney test for significant differences between mean ranking of criteria between
Company size

comp_size	med_large			small_med			sig
	Mean	Median	Std. Deviation	Mean	Median	Std. Deviation	
criteria1	4.6607	5.0000	1.90002	4.8846	5.0000	1.96625	0.5940
criteria2	6.4107	7.0000	1.00502	6.1923	7.0000	1.47022	0.7600
criteria3	5.5714	6.0000	1.66086	5.1154	5.0000	1.63284	0.1410
criteria4	5.6607	6.0000	1.46817	5.4615	6.0000	1.52920	0.5210
criteria5	4.8036	5.0000	1.74168	5.2692	5.5000	1.51149	0.2010
criteria6	4.6786	5.0000	1.81014	4.8846	6.0000	1.92514	0.5440
criteria7	5.2321	5.0000	1.45216	4.6923	5.0000	1.99538	0.4540
criteria8	5.0893	5.5000	1.82186	5.6923	6.0000	1.56893	0.1540
criteria9	5.7143	6.0000	1.26080	5.4615	6.0000	1.63048	0.7250
criteria10	5.0714	5.0000	1.51186	5.7692	6.0000	1.72760	0.0140
criteria11	5.0000	5.0000	1.53741	4.5385	5.0000	2.04413	0.4580
criteria12	4.3036	4.5000	2.05311	4.2692	5.0000	2.25491	1.0000
criteria13	4.8214	5.0000	1.67448	5.0385	5.0000	1.68477	0.5910
criteria14	5.3929	6.0000	1.81588	4.9231	6.0000	2.29649	0.4100
criteria15	5.5536	6.0000	1.66154	5.2692	6.0000	2.06993	0.6630
criteria16	5.1607	5.0000	1.54657	5.0769	5.0000	1.97834	0.8330
criteria17	4.7321	5.0000	1.50745	4.6538	5.0000	1.97873	0.8710
criteria18	4.7321	4.5000	1.65684	4.7308	5.0000	1.71015	0.9150
criteria19	4.2679	4.0000	1.28617	4.1538	5.0000	1.78196	0.7860
criteria20	4.4107	4.5000	1.58145	4.1154	4.0000	1.96625	0.5920

criteria21	5.4286	6.0000	1.37321	5.3077	6.0000	1.56893	0.8410
criteria22	3.7679	4.0000	1.61798	4.0385	4.0000	1.68477	0.6030
criteria23	3.9464	4.0000	1.62279	4.3462	5.0000	1.93788	0.2810
criteria24	4.7500	5.0000	1.51658	4.9615	5.5000	2.00959	0.2320
criteria25	4.2321	4.0000	1.86831	4.1923	5.0000	2.03998	0.9800

Mann Whitney test for significant differences between mean ranking of criteria between Past
bim usage

Length_of_BIM_use	less than 6 y			more than 6 y			sig
	Mean	Median	Std. Deviation	Mean	Median	Std. Deviation	
criteria1	4.4815	5.0000	1.98785	4.8545	5.0000	1.87990	0.4270
criteria2	6.2593	7.0000	1.31829	6.3818	7.0000	1.09698	0.6570
criteria3	4.8148	5.0000	1.68790	5.7273	6.0000	1.56885	0.0080
criteria4	5.4074	6.0000	1.55066	5.6909	6.0000	1.45134	0.3810
criteria5	4.8148	5.0000	1.84051	5.0182	5.0000	1.60429	0.7740
criteria6	4.8889	5.0000	1.80455	4.6727	5.0000	1.86641	0.6310
criteria7	4.5185	5.0000	2.00711	5.3273	5.0000	1.38850	0.1580
criteria8	5.0741	6.0000	1.89992	5.3818	6.0000	1.69412	0.5680
criteria9	5.2963	6.0000	1.61280	5.8000	6.0000	1.23828	0.1910
criteria10	5.4444	6.0000	1.82574	5.2182	5.0000	1.49927	0.2790
criteria11	4.4444	5.0000	1.98714	5.0545	5.0000	1.54462	0.2140
criteria12	3.7778	4.0000	2.30940	4.5455	5.0000	1.97032	0.1430
criteria13	4.3333	4.0000	1.77591	5.1636	5.0000	1.56067	0.0390
criteria14	4.3333	5.0000	2.35339	5.6909	6.0000	1.60869	0.0160
criteria15	4.8148	5.0000	2.14901	5.7818	6.0000	1.51157	0.0470
criteria16	4.4444	5.0000	1.80455	5.4727	6.0000	1.52576	0.0100
criteria17	4.1111	5.0000	1.82574	5.0000	5.0000	1.50308	0.0400
criteria18	4.2593	4.0000	1.63125	4.9636	5.0000	1.64388	0.0750
criteria19	3.6296	4.0000	1.77911	4.5273	4.0000	1.16832	0.0180
criteria20	3.8148	4.0000	1.73287	4.5636	5.0000	1.65287	0.0530
criteria21	5.2963	6.0000	1.68283	5.4364	6.0000	1.30190	0.9840

criteria22	3.8889	4.0000	1.84669	3.8364	4.0000	1.53676	0.9840
criteria23	4.0000	4.0000	1.88108	4.1091	4.0000	1.66303	0.7700
criteria24	4.6296	5.0000	2.02196	4.9091	5.0000	1.49410	0.8230
criteria25	4.2963	5.0000	2.21559	4.1818	4.0000	1.76479	0.6790

APPENDIX H. SHAPIRO WILKS TEST OUTPUT

Tests of Normality							
	Con_Sub	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
criteria1	GC	.124	40	.120	.916	40	.006
	SubC	.188	42	.001	.881	42	.000
criteria2	GC	.344	40	.000	.637	40	.000
	SubC	.423	42	.000	.617	42	.000
criteria3	GC	.234	40	.000	.843	40	.000
	SubC	.227	42	.000	.826	42	.000
criteria4	GC	.139	40	.049	.918	40	.006
	SubC	.292	42	.000	.779	42	.000
criteria5	GC	.153	40	.020	.913	40	.005
	SubC	.220	42	.000	.881	42	.000
criteria6	GC	.160	40	.012	.930	40	.017
	SubC	.247	42	.000	.870	42	.000
criteria7	GC	.165	40	.008	.894	40	.001
	SubC	.187	42	.001	.874	42	.000
criteria8	GC	.186	40	.001	.910	40	.004
	SubC	.235	42	.000	.830	42	.000
criteria9	GC	.230	40	.000	.849	40	.000
	SubC	.225	42	.000	.812	42	.000
criteria10	GC	.195	40	.001	.884	40	.001
	SubC	.192	42	.000	.875	42	.000
criteria11	GC	.142	40	.042	.926	40	.012
	SubC	.199	42	.000	.871	42	.000
criteria12	GC	.201	40	.000	.883	40	.001
	SubC	.190	42	.001	.853	42	.000
criteria13	GC	.156	40	.016	.938	40	.030
	SubC	.199	42	.000	.878	42	.000
criteria14	GC	.215	40	.000	.851	40	.000

	SubC	.281	42	.000	.766	42	.000
criteria15	GC	.207	40	.000	.872	40	.000
	SubC	.266	42	.000	.738	42	.000
criteria16	GC	.156	40	.016	.921	40	.008
	SubC	.252	42	.000	.818	42	.000
criteria17	GC	.170	40	.005	.934	40	.021
	SubC	.183	42	.001	.883	42	.000
criteria18	GC	.187	40	.001	.902	40	.002
	SubC	.162	42	.007	.918	42	.005
criteria19	GC	.242	40	.000	.923	40	.010
	SubC	.191	42	.001	.927	42	.010
criteria20	GC	.145	40	.034	.927	40	.013
	SubC	.152	42	.016	.936	42	.020
criteria21	GC	.191	40	.001	.899	40	.002
	SubC	.251	42	.000	.834	42	.000
criteria22	GC	.211	40	.000	.926	40	.012
	SubC	.204	42	.000	.913	42	.004
criteria23	GC	.143	40	.040	.940	40	.036
	SubC	.197	42	.000	.920	42	.006
criteria24	GC	.227	40	.000	.917	40	.006
	SubC	.256	42	.000	.819	42	.000
criteria25	GC	.112	40	.200*	.926	40	.012
	SubC	.188	42	.001	.905	42	.002

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

APPENDIX I. MATLAB SIMULATION OUTPUT

	C2/A2		C2/A3		C2/A4		C2/A5	
WSM vs WPM consistency rate	944	0.944	928	0.928	931	0.931	930	0.93
WSM vs AHP consistency rate	949	0.949	938	0.938	941	0.941	932	0.932
WPM vs AHP consistency rate	991	0.991	963	0.963	925	0.925	913	0.913
WSM vs WPM inconsistency rate	56	0.056	72	0.072	69	0.069	70	0.07
WSM vs AHP inconsistency rate	51	0.051	62	0.062	59	0.059	68	0.068
WPM vs AHP inconsistency rate	9	0.009	37	0.037	75	0.075	87	0.087
All equal	942	0.942	917	0.917	902	0.902	889	0.889
All diff	2	0.002	16	0.016	36	0.036	44	0.044
WSM change	49	0.049	46	0.046	23	0.023	24	0.024
WPM change	7	0.007	21	0.021	39	0.039	43	0.043
AHP change	2	0.002	11	0.011	29	0.029	41	0.041
	C3/A2		C3/A3		C3/A4		C3/A5	
WSM vs WPM consistency rate	925	0.925	886	0.886	883	0.883	863	0.863
WSM vs AHP consistency rate	929	0.929	907	0.907	912	0.912	883	0.883
WPM vs AHP consistency rate	992	0.992	917	0.917	895	0.895	880	0.88
WSM vs WPM inconsistency rate	75	0.075	114	0.114	117	0.117	137	0.137
WSM vs AHP inconsistency rate	71	0.071	93	0.093	88	0.088	117	0.117
WPM vs AHP inconsistency rate	8	0.008	83	0.083	105	0.105	120	0.12
All equal	923	0.923	857	0.857	847	0.847	820	0.82
All diff	2	0.002	33	0.033	40	0.04	57	0.057
WSM change	69	0.069	60	0.06	48	0.048	60	0.06
WPM change	6	0.006	50	0.05	65	0.065	63	0.063
AHP change	2	0.002	29	0.029	36	0.036	43	0.043
	C4/A2		C4/A3		C4/A4		C4/A5	
WSM vs WPM consistency rate	904	0.904	891	0.891	864	0.864	835	0.835
WSM vs AHP consistency rate	905	0.905	902	0.902	889	0.889	895	0.895

WPM vs AHP consistency rate	991	0.991	913	0.913	889	0.889	852	0.852
WSM vs WPM inconsistency rate	96	0.096	109	0.109	136	0.136	165	0.165
WSM vs AHP inconsistency rate	95	0.095	98	0.098	111	0.111	105	0.105
WPM vs AHP inconsistency rate	9	0.009	87	0.087	111	0.111	148	0.148
All equal	900	0.9	855	0.855	823	0.823	798	0.798
All diff	4	0.004	40	0.04	45	0.045	51	0.051
WSM change	91	0.091	58	0.058	66	0.066	54	0.054
WPM change	5	0.005	47	0.047	66	0.066	97	0.097
AHP change	4	0.004	36	0.036	41	0.041	37	0.037
	C5/A2		C5/A3		C5/A4		C5/A5	
WSM vs WPM consistency rate	926	0.926	881	0.881	840	0.84	833	0.833
WSM vs AHP consistency rate	928	0.928	895	0.895	879	0.879	897	0.897
WPM vs AHP consistency rate	986	0.986	905	0.905	866	0.866	857	0.857
WSM vs WPM inconsistency rate	74	0.074	119	0.119	160	0.16	167	0.167
WSM vs AHP inconsistency rate	72	0.072	105	0.105	121	0.121	103	0.103
WPM vs AHP inconsistency rate	14	0.014	95	0.095	134	0.134	143	0.143
All equal	920	0.92	842	0.842	801	0.801	798	0.798
All diff	6	0.006	42	0.042	56	0.056	44	0.044
WSM change	66	0.066	63	0.063	65	0.065	59	0.059
WPM change	8	0.008	53	0.053	78	0.078	99	0.099
AHP change	6	0.006	39	0.039	39	0.039	35	0.035
	C6/A2		C6/A3		C6/A4		C6/A5	
WSM vs WPM consistency rate	911	0.911	879	0.879	841	0.841	850	0.85
WSM vs AHP consistency rate	909	0.909	904	0.904	865	0.865	868	0.868
WPM vs AHP consistency rate	974	0.974	905	0.905	864	0.864	846	0.846
WSM vs WPM inconsistency rate	89	0.089	121	0.121	159	0.159	150	0.15

WSM vs AHP inconsistency rate	91	0.091	96	0.096	135	0.135	132	0.132
WPM vs AHP inconsistency rate	26	0.026	95	0.095	136	0.136	154	0.154
All equal	897	0.897	846	0.846	791	0.791	788	0.788
All diff	14	0.014	37	0.037	62	0.062	74	0.074
WSM change	77	0.077	59	0.059	73	0.073	58	0.058
WPM change	12	0.012	58	0.058	74	0.074	80	0.08
AHP change	14	0.014	33	0.033	50	0.05	62	0.062
	C7/A2		C7/A3		C7/A4		C7/A5	
WSM vs WPM consistency rate	912	0.912	872	0.872	863	0.863	825	0.825
WSM vs AHP consistency rate	916	0.916	898	0.898	881	0.881	865	0.865
WPM vs AHP consistency rate	976	0.976	893	0.893	875	0.875	821	0.821
WSM vs WPM inconsistency rate	88	0.088	128	0.128	137	0.137	175	0.175
WSM vs AHP inconsistency rate	84	0.084	102	0.102	119	0.119	135	0.135
WPM vs AHP inconsistency rate	24	0.024	107	0.107	125	0.125	179	0.179
All equal	902	0.902	834	0.834	814	0.814	763	0.763
All diff	10	0.01	43	0.043	58	0.058	77	0.077
WSM change	74	0.074	59	0.059	61	0.061	58	0.058
WPM change	14	0.014	64	0.064	67	0.067	102	0.102
AHP change	10	0.01	38	0.038	49	0.049	62	0.062

APPENDIX J. JAVASCRIPT CODE FOR WBDSS CALCULATIONS

```

(function (){
    "use strict"
    //step3; gathering the evaluation matrix and feeding it to the eigenV generator
    document.getElementById("eval-criteria").addEventListener("submit",gather_eval);
    function gather_eval(event)
    {
        event.preventDefault();

        var crit_rank_311=Number(document.getElementById("3custom1criteria1").value);
        //console.log(crit_rank_311);
        var crit_rank_312=Number(document.getElementById("3custom1criteria2").value);
        //console.log(crit_rank_312);

        var crit_rank_321=Number(document.getElementById("3custom2criteria1").value);
        //console.log(crit_rank_321);
        var crit_rank_323=Number(document.getElementById("3custom2criteria3").value);
        //console.log(crit_rank_323);

        var crit_rank_332=Number(document.getElementById("3custom3criteria2").value);
        //console.log(crit_rank_332);
        var crit_rank_333=Number(document.getElementById("3custom3criteria3").value);
        //console.log(crit_rank_333);

        if(crit_rank_311==0)
        {
            crit_rank_311=1/crit_rank_312;
        }
        else if(crit_rank_312==0)
        {
            crit_rank_312=1/crit_rank_311;
        }

        if(crit_rank_321==0)
        {
            crit_rank_321=1/crit_rank_323;
        }

        else if(crit_rank_323==0)
        {
            crit_rank_323=1/crit_rank_321;
        }

        if(crit_rank_332==0)
        {
            crit_rank_332=1/crit_rank_333;
        }

        else if(crit_rank_333==0)
        {
            crit_rank_333=1/crit_rank_332;
        }

        var arr_lv1l = [1,crit_rank_311,crit_rank_321];
    }
}

```

```

var arr_lvl2 = [crit_rank_312,1,crit_rank_332];
var arr_lvl3 = [crit_rank_323,crit_rank_333,1];

var fin_eval_mat = math.matrix( math.concat([arr_lvl1],[arr_lvl2],[arr_lvl3],0));

var eval_eigenV=geteigenV(fin_eval_mat);
console.log('eval_eigenV');
console.log(eval_eigenV);

//store eval crit eigenv in the JSON
var eval_eigenvector = { "evalEV":eval_eigenV};
var myJSON_evalEV = JSON.stringify(eval_eigenvector);
localStorage.setItem("eval_EV", myJSON_evalEV);

}

//step4; gathering the evaluation matrix for each alt comparison per criteria and feeding it to the eigenV
generator
document.getElementById("alteval").addEventListener("submit",gather_alteval);
function gather_alteval(event)
{
    event.preventDefault();

    var alt_rank_c1a1 =Number(document.getElementById("c1alt1").value);
    console.log("Going through alteval");
    var alt_rank_c1a2 =Number(document.getElementById("c1alt2").value);
    //console.log(crit_rank_312);

    var alt_rank_c2a1 =Number(document.getElementById("c2alt1").value);
    //console.log(crit_rank_321);
    var alt_rank_c2a2 =Number(document.getElementById("c2alt2").value);
    //console.log(crit_rank_323);

    var alt_rank_c3a1 =Number(document.getElementById("c3alt1").value);
    //console.log(crit_rank_332);
    var alt_rank_c3a2 =Number(document.getElementById("c3alt2").value);
    //console.log(alt_rank_333);

    //a1 and a2 against criteria 1
    if(alt_rank_c1a1==0)
    {
        alt_rank_c1a1=1/alt_rank_c1a2;
    }
    else if(alt_rank_c1a2==0)
    {
        alt_rank_c1a2=1/alt_rank_c1a1;
    }

    //a1 and a2 against criteria 2
    if(alt_rank_c2a1==0)
    {
        alt_rank_c2a1=1/alt_rank_c2a2;
    }

    else if(alt_rank_c2a2==0)
    {

```

```

        alt_rank_c2a2=1/alt_rank_c2a1;
    }

    //a1 and a2 against criteria 3
    if(alt_rank_c3a1==0)
    {
        alt_rank_c3a1=1/alt_rank_c3a2;
    }

    else if(alt_rank_c3a2==0)
    {
        alt_rank_c3a2=1/alt_rank_c3a1;
    }

    //set up the individual alt comp matrices
    var arr1_lv11 = [1,alt_rank_c1a1];
    var arr1_lv12 = [alt_rank_c1a2,1];

    var arr2_lv11 = [1,alt_rank_c2a1];
    var arr2_lv12 = [alt_rank_c2a2,1];

    var arr3_lv11 = [1,alt_rank_c3a1];
    var arr3_lv12 = [alt_rank_c3a2,1];

    var crit1alt_eval_mat = math.matrix( math.concat([arr1_lv11],[arr1_lv12],0));
    var crit2alt_eval_mat = math.matrix( math.concat([arr2_lv11],[arr2_lv12],0));
    var crit3alt_eval_mat = math.matrix( math.concat([arr3_lv11],[arr3_lv12],0));

    //call on the geteigenV to produce the indv eigenvectors for the alternate matrices
    var crt1alt_eigenV =geteigenV(crit1alt_eval_mat);
    var crt2alt_eigenV =geteigenV(crit2alt_eval_mat);
    var crt3alt_eigenV =geteigenV(crit3alt_eval_mat);

    console.log('crit/alts_eigenV');
    console.log(crt1alt_eigenV);
    console.log(crt2alt_eigenV);
    console.log(crt3alt_eigenV);

    //store crit/alts eigenv in the JSON
    var critalteval_eigenvector = {
    "crit1alts_evalEV":crt1alt_eigenV,"crit2alts_evalEV":crt2alt_eigenV,"crit3alts_evalEV":crt3alt_eigenV};
    var myJSON_critaltevalEV = JSON.stringify(critalteval_eigenvector);
    localStorage.setItem("critalt_eval_EV", myJSON_critaltevalEV);

    //call the final function to give the final results
    var rahp_results=r_ahp_calc();

    //finds the largest value in the results
    //var highest = math.max(rahp_results);
    //console.log('highest');
    //console.log(highest);
    var testify=document.getElementById("highest");

    testify.innerHTML=;

```

```

}

//this is for 'step 1' - with the automated sorting of the photos based on the checked sorting criteria
document.getElementById("sorting").addEventListener("submit",toggleVisibility);
function toggleVisibility(event)
{
    event.preventDefault();

    //creating and pointing variables that will be used later to check if the checkboxes are checked lol
    var img1 = document.getElementById("img1");
    var img2 = document.getElementById("img2");
    var img3 = document.getElementById("img3");
    var img4 = document.getElementById("img4");
    var img5 = document.getElementById("img5");
    var img6 = document.getElementById("img6");

    //value of true or false if its checked or not is extracted from user input
    var chk1 = document.getElementById("sort1").checked;
    var chk2 = document.getElementById("sort2").checked;

    //loops that determines the photos that show
    //first check box option
    if(chk1 ==true && chk2 ==true)
    {
        img1.innerHTML ='<input type="checkbox" name="OPTION1aaa"
id="option1" onchange="showmybutton()"/> Option1a';
        //img2.innerHTML ='';

        img3.innerHTML ='<input type="checkbox" name="option2aa" id="option2"
onchange="showmybutton()"/> Option2a';
        //img4.innerHTML ='';

        img5.innerHTML ='<input type="checkbox" name="option3aa" id="option3"
onchange="showmybutton()"/> Option3a';
        //img6.innerHTML ='';
    }
    else
    {
        img1.innerHTML ='<input type="checkbox" name="OPTION1bbb" id="option1"
onchange="showmybutton()"/> Option1b';
        //img2.innerHTML ='';

        img3.innerHTML ='<input type="checkbox" name="OPTION2bb" id="option2"
onchange="showmybutton()"/> Option2b';
        //img4.innerHTML ='';

        img5.innerHTML ='<input type="checkbox" name="option3bb" id="option3"
onchange="showmybutton()"/> Option3b';
    }
}

```

```

//img6.innerHTML = '';
    }
}

```

```

function geteigenV(input_matrix)
{
    var result;
    var input_size=math.size(input_matrix);
    var val=math.subset(input_size, math.index([1]));
    //check if this is a 2x2 or 3x3 matrix, then execute the appropriate code

    if(val== 3)
    {
        //////////////////////////////////////
        console.log('size being used');
        console.log(val);
        //concatenates the arr's as the rows of the final matrix made
        var matrix =math.matrix( input_matrix);

        //find max of each column to be used for normalizing the rahp way
        //var highest_incols = math.max(matrix,0);
        //var highest_col1=( math.subset(highest_incols, math.index([0])));
        //var highest_col2=( math.subset(highest_incols, math.index([1])));
        //var highest_col3=( math.subset(highest_incols, math.index([2])));
        //var max_mat = math.matrix(math.concat([highest_incols],[highest_incols],[highest_incols],0));

        //summing the columns of the matrix to be used for normalizing the ahp way
        var summat_col1 = ( math.subset(matrix, math.index(0, [0])))+( math.subset(matrix,
math.index(1, [0])))+( math.subset(matrix, math.index(2, [0])));
        var summat_col2 = ( math.subset(matrix, math.index(0, [1])))+( math.subset(matrix,
math.index(1, [1])))+( math.subset(matrix, math.index(2, [1])));
        var summat_col3 = ( math.subset(matrix, math.index(0, [2])))+( math.subset(matrix,
math.index(1, [2])))+( math.subset(matrix, math.index(2, [2])));

        var sum_cols=[summat_col1,summat_col2,summat_col3];

        var sum_mat = math.matrix(math.concat([sum_cols],[sum_cols],[sum_cols],0));

        //calculating the normalized matrix
        var norm_mat = math.dotDivide(matrix,sum_mat);//max_mat was replaced here

        //calculating the eigenvector/weight vector
        //var eigenV/w
        var sizebysize=math.size(matrix);
        var size = ( math.subset(sizebysize, math.index([1])));
        //summing the rows
        var
        lv11=(math.sum((math.subset(norm_mat,math.index(0,0))), (math.subset(norm_mat,math.index(0,1))), (math.sub
set(norm_mat,math.index(0,2)))))/size;
    }
}

```

```

var
lv12=(math.sum((math.subset(norm_mat,math.index(1,0))),
(math.subset(norm_mat,math.index(1,1))),
(math.subset(norm_mat,math.index(1,2)))/size;
var
lv13=(math.sum((math.subset(norm_mat,math.index(2,0))),
(math.subset(norm_mat,math.index(2,1))),
(math.subset(norm_mat,math.index(2,2)))/size;

var w=[lv11,lv12,lv13];
}
////////////////////////////////////
else if(val== 2)
{
//concatenates the arr's as the rows of the final matrix made
var matrix =math.matrix( input_matrix);

//find max of each column to be used for normalizing the rahp way
//var highest_incols = math.max(matrix,0);
//var highest_col1=( math.subset(highest_incols, math.index([0]));
//var highest_col2=( math.subset(highest_incols, math.index([1]));
//var max_mat = math.matrix(math.concat([highest_incols],[highest_incols],0));

//summing the columns of the matrix to be used for normalizing the ahp way
var summat_col1 = ( math.subset(matrix, math.index(0, [0]))+( math.subset(matrix,
math.index(1, [0])));
var summat_col2 = ( math.subset(matrix, math.index(0, [1]))+( math.subset(matrix,
math.index(1, [1])));

var sum_cols=[summat_col1,summat_col2];

var sum_mat = math.matrix(math.concat([sum_cols],[sum_cols],0));

//calculating the normalized matrix
var norm_mat = math.dotDivide(matrix,sum_mat);//max_mat was replaced here

//calculating the eigenvector/weight vector
//var eigenV/w
var sizebysize=math.size(matrix);
var size = ( math.subset(sizebysize, math.index([1]));
//summing the rows
var
lv11=(math.sum((math.subset(norm_mat,math.index(0,0))),
(math.subset(norm_mat,math.index(0,1)))/size;
var
lv12=(math.sum((math.subset(norm_mat,math.index(1,0))),
(math.subset(norm_mat,math.index(1,1)))/size;

var w=[lv11,lv12];
}

//checking the consistency
var alpha = math.multiply(sum_cols,w);//highest_incols was replaced here

var CI = (alpha - size) / (size - 1);

// Populate the RI matrix
var RI = [0,0,.58, .9 ,1.12, 1.24, 1.32 ,1.41, 1.45, 1.49];

if ( ( CI / RI[size] ) < 0.1 )

```

```

        {
            result = 1;
            //1 is a good thing. means you can move on with life
            return w;
            console.log('consistency. we want 1');
            console.log(result);
            console.log(w);
        }
        else
        {
            result = 0;
            //show some kind of error that tells them to try again
            console.log('consistency. we want 1');
            console.log(result);
            window.alert('Input is inconsistent. Review and try again.')
        }
    }
}

function r_ahp_calc()
{
    //this takes the first eigenV created for the criteria comparison; and multiplies it
    //by a matrix which is made up of the individual eigenV created from the comparison
    //of the software alternatives to one another per criteria
    //the result is a vector with the final scores of each software alternative

    //first , retrieve the json data eigen v for the softare alt. comparisons and eval criteria eigen v
    var evaluation_crit_EV = localStorage.getItem("eval_EV");
    var objE = JSON.parse(evaluation_crit_EV );

    var critalt_EVs = localStorage.getItem("critalt_eval_EV");
    var objAC = JSON.parse(critalt_EVs);

    //fetch the eigenv for the evaluation criteria comparison
    var eigenV_EC = objE.evalEV;

    //fetch the eigenv for the criteria/alternatives comparison
    var eigenV_AC1 = objAC.crit1alts_evalEV;
    var eigenV_AC2 = objAC.crit2alts_evalEV;
    var eigenV_AC3 = objAC.crit3alts_evalEV;

    //arrange the extracted vectors into a single ACmatrix
    var major_alt_mat = math.matrix(math.concat([eigenV_AC1],[eigenV_AC2],[eigenV_AC3],0));

    //transpose it so they're in the right format
    var major_alt= math.transpose(major_alt_mat);

    //final step of multiplication
    var rahp_results=math.multiply(major_alt,eigenV_EC);

    var oneUp = math.subset([rahp_results],math.index(0,0));

    var oneDown=math.subset([rahp_results],math.index(0,1));

```

```
var Above = oneUp * 100;
var Below = oneDown * 100;

//store the results in a JSON
var calc_results = { "top":Above, "bottom":Below};
var myJSON_finalcalcs = JSON.stringify(calc_results);
localStorage.setItem("AHPscores", myJSON_finalcalcs);

}

})();
```

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VITA

Richelle Fosu

EDUCATION

2013-2017 (August) Doctor of Philosophy in Technology

Purdue University - West Lafayette, IN

Dissertation title: BIM Software Selection in The U.S. AEC Industry: Developing a Unified, Streamlined Framework and Tool for decision-making.

Advisor/Committee Chair: Professor Connolly

2011-2013 MSc in Computer Graphics Technology

Purdue University - West Lafayette, IN

Thesis Title: Investigating the effect specific credits of the LEED EBOM rating system have on the energy performance of an existing building (The American Railway Building on the Purdue University Campus).

2008-2011 BSc in Electrical Engineering and Computer Science

Jacobs University - Bremen, Niedersachsen, Germany

Thesis title: Multi resolution display of large cities

AWARDS

2017	Advanced Graduate Teaching Certificate Award
2017	Purdue Service Learning Grant. Project Title: Exploring Alien Planets- Learning Basic Robotics Programming [for GK-12 Program]
2016	Polytechnic Institute Summer Research Grant Award
2013	Ross Fellowship Award

TEACHING EXPERIENCE

Purdue University

2017	Instructor of record (CGT 164 – Summer Online Session) Handled administrative and instructive duties associated with the course.
2017	Curriculum, Course Design & Development Designed and developed course outlines and content towards the ongoing efforts in the future expansion of the BIM major within the CGT department.
2014-2017	Teaching Assistant - Residential Construction Graphics (CGT 262) Facilitated discussions during the absence of primary instructor
2015-2017	Teaching Assistant - BIM for Commercial Documentation (CGT 360) Facilitated discussions during the absence of primary instructor
2016	Instructor of record (CGT 262, 360) Prepared and gave lectures, created exams and class activities. Handled administrative duties associated with the course, during the sabbatical of the primary professor.
2011-2016	Lab Instructor - Construction Graphics for Civil Engineering (CGT 164) Provided instruction during lab sessions on construction graphics principles.

TEACHING INTERESTS

Engineering and construction graphics

Digital design and documentation of the built environment

Mixed reality visualization and BIM in construction and design

RESEARCH INTERESTS

Technology enhanced learning

Technology enhanced teaching methods

Sustainable Design and analysis with BIM

Construction technologies

COMMUNITY ENGAGEMENT

2017 Purdue GK-12 Program - Tecumseh Junior High

2017 Purdue Space Day Educational Outreach - Miami Elementary

PROFESSIONAL EXPERIENCE

2016 Virtual Design Construction Engineer

McCarthy Building Companies, Phoenix, Arizona

- Modeled and created lift drawings of concrete structures for various projects
- Created solar point and pile drawings as well as solar layouts for pursuits
- Set up model for viewing in Virtual Reality Environment

2010-2011 3D Modeler & Programmer

DFKI - German Institute of Artificial Intelligence, Bremen, Germany

- Modeled, textured and rendered lunar crater - including surroundings – from given point cloud data for project RIMRES.
- Refined and reconstructed 3d models of various robot prototypes
- Programmed portions of in-house simulation environment using C++

PROFESSIONAL CERTIFICATIONS

2015 LEED Green Associate

2014 Autodesk Building Performance Analysis Certificate

PROFESSIONAL AFFILIATIONS

2017 Paper Reviewer - American Society of Engineering Education Zone II Conference

2016 American Society of Engineering Education (ASEE)- Engineering Design
Graphics Division Member

2013 Golden Key International Honor Society

TEACHER TRAINING

Educational Methods in Engineering (ENE 68500)

Grant and Proposal Writing

Increase Student Engagement with Virtual Reality Experiences

Making Bold Moves: Designing Remarkable Learning Environments.

College Teaching Workshop Series - Micro Teaching

College Teaching Workshop Series - Creating an Effective Syllabus

SKILLS

BIM Technologies: Autodesk Revit, AutoCAD, Navisworks Manage, Sketchup, Bluebeam

Visualization: Blender 3d, Photoshop, After Effects

Programming languages: Familiarity in programming with C++, HTML5, JavaScript

Languages: English – Fluent | German – Intermediate level

PUBLICATIONS

- Fosu, R., & Sukumar, K., & Connolly, P. E. (2016), Spatial Visualization Ability and Learning Style Preference Assessment Among Construction Related Undergraduate Engineering and Technology Students. Paper presented at 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana. 10.18260/p.25855
- Fosu, R., Suprabhas, K., Rathore, Z., Cory, C. (2015). Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) – a literature review and future needs, Proceedings of the 32nd International Conference of CIB W78, Eindhoven, The Netherlands, 196-204
- Fosu, R. (2015). Examining 4d and 5d BIM software capabilities. Journal of the National Institute of Building Sciences, 3(6), 18-22.