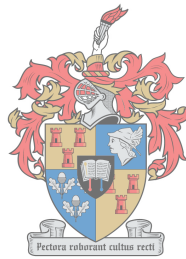


A Building Information Modelling-based approach towards improving the constructability of suspended floor slabs

by
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December 2018

Declaration

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

This work was done under the guidance of Professor J.A. Wium, at the University of Stellenbosch, South Africa

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Date

In my capacity as supervisor of the candidates's thesis, I certify that the above statements are true to the best of my knowledge.

Prof. J.A. Wium

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Abstract

Poor coordination between designers and contractors is a regular occurrence within the Architecture, Engineering and Consulting (AEC) industry. The poor coordination often results in unpractical designs which require unnecessary extra cost and time to fix. This study aimed to reduce the occurrence of unpractical designs by investigating how Building Information Modelling (BIM) can be used as a tool to implement a constructability analysis process which analyses the constructability of suspended floor slabs and their supports.

Autodesk Revit was chosen as the BIM software used for the development of the constructability analysis process because of Autodesk Revit's increasing popularity within the South African consulting industry. The scope of the research was limited to suspended floor slabs and their supports and the inputs from contractors and consultants within the Cape Town and Stellenbosch areas of the Western Cape of South Africa.

The research objectives for this study were as follows: (i) identify all the factors which affect the constructability of suspended floor slabs; (ii) determine possible constructability verifications from interviews and select verifications as examples of how a constructability analysis process could be implemented in BIM (iii) provide visual representations of the potential end-product, and (iv) develop a general guideline for the implementation of a constructability analysis process.

Constructability is affected by a range of factors. These factors were analysed in terms of their compatibility within BIM. The implementable factors, along with information found from a case study and from literature, were used to derive questions for structured interviews conducted with experienced contractors. Constructability problems encountered with the construction of suspended floor slabs and their supports were identified through the interviews. The information and tacit knowledge obtained from the interviews were used to identify possible verifications which can form part of the proposed constructability analysis process. The logic behind five chosen verifications were developed and these formed part of the process of developing the constructability analysis process. Proposed representations of the five verifications were also given.

A second round of interviews was conducted with experienced consultants to validate the

proposed process and obtain their preferences in terms of the implementation thereof. The consultants' inputs were used to further develop representations of how the proposed suspended floor slab constructability analysis process can be implemented. General guidelines for the implementation of a constructability analysis process aimed at any type of structural element was then developed.

It was found that BIM can be used as a tool to enhance constructability during the design phase. It was also established that contractors and consultants could benefit from the proposed process and they see the need for further development thereof. This study demonstrated that the development of a process which improves constructability during the design phase can be usefull.

Opsomming

Swak koördinasie tussen ontwerpers en kontrakteurs gebeur gereeld in die konstruksie bedryf. Die swak koördinasie lei dikwels tot onpraktiese ontwerpe wat onnodige koste en tyd benodig om reg te stel. Hierdie studie ondersoek hoe Bou-inligtingmodellering (Engels = ‘Building Information Modelling’ (BIM)) gebruik kan word as 'n instrument om 'n boubaarheids proses te implementeer wat die boubaarheid van gesuspendeerde vloerblaaie en hul ondersteunings analiseer.

Die BIM-sagteware wat gebruik is, was Autodesk Revit en dit is gekies weens Autodesk Revit se toenemende gewildheid in die Suid-Afrikaanse konsultasiebedryf. Die omvang van die navorsing was beperk tot gesuspendeerde vloerblaaie en hul ondersteunings en die insette verkry van kontrakteurs en konsultante in die Kaapstad en Stellenbosch gebiede van die Wes-Kaap van Suid-Afrika.

Die navorsingsdoelwitte vir hierdie studie was soos volg: (i) identifiseer al die faktore wat die boubaarheid van gesuspendeerde vloerblaaie beïnvloed; (ii) om moontlike boubaarheids verifikasies te bepaal deur onderhoude en om verifikasies te kies om te dien as voorbeelde vir hoe 'n boubaarheids proses geïmplementeer kan word in BIM; (iii) om visuele voorstellings van die potensiële eindproduk te verskaf; (iv) om algemene riglyne te ontwikkel vir die implementering van 'n boubaarheids proses.

Boubaarheid word geïmpakteer deur 'n verskeidenheid van faktore. Hierdie faktore is ontleed in terme van hul moontlike implementasie binne BIM. Die implementeerbare faktore, tesame met inligting uit 'n gevallestudie en die literatuur, is gebruik om vrae op te stel vir gestruktureerde onderhoude wat met ervare kontrakteurs gevoer was. Die mikpunt van die onderhoude was die identifisering van boubaarheids probleme wat ondervind is met die konstruksie van gesuspendeerde vloerblaaie en hul ondersteunings. Die inligting en stilswyende kennis wat deur die onderhoude verkry is, is gebruik om moontlike verifikasies te identifiseer wat deel kan maak van die voorgestelde boubaarheids proses. Die logika agter vyf gekose verifikasies is ontwikkel en vorm deel van die ontwikkeling van die boubaarheids proses. Moontlike grafiese voorstellings van elke verifikasie is ook gegee.

'n Tweede rondte onderhoude is gevoer met ervare konsultante om die voorgestelde proses te

valideer asook om hul voorkeure te verkry ten opsigte van die implementering daarvan. Algemene riglyne is ook ontwikkel vir die implementering van 'n boubaarheids proses wat op enige tipe strukturele elemente gebruik kan word.

Daar is bevind dat BIM as 'n instrument gebruik kan word om die boubaarheid van projekte gedurende die ontwerpfasie te verbeter. Daar is ook vasgestel dat kontrakteurs en konsultante voordeel kan trek uit die voorgestelde proses en dat hulle die noodsaaklikheid sien vir die ontwikkeling daarvan. Hierdie studie het die nuttigheid getoon van die ontwikkeling van 'n proses wat boubaarheid verbeter gedurende die ontwerpfasie.

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Abbreviations

AEC	Architecture, Engineering and Construction
AHP	Analytical Hierarchy Process
BIM	Building Information Modelling
CAD	Computer-aided Design
ECSA	Engineering Council of South Africa
ELECTRE	Elimination and choice expressing the reality
GDP	Gross Domestic Product
GUI	Graphical User Interface
ID	Identification
IFC	Industry Foundation Classes
MCDM	Multiple Criteria Decision Making
MEP	Mechanical, Electrical and Plumbing services
NHBRC	National Home Builders Registration Council
PROMOTHEE	Preference Ranking Organisation Method for Enrichment Evaluations
SACPCMP	South African Council for Project and Construction Management Professions
SANS	South African National Standard
SAQA	South African Qualifications Authority
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

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CHAPTER 1

Introduction

1.1 INTRODUCTION

This study investigates ways in which the constructability of suspended floor slabs and their supports can be improved with the use of Building Information Modelling (BIM) as a tool. The improvement of the constructability of suspended floor slabs and their supports refers to increasing the ease and efficiency with which they are built and thus decreasing costs and the time required for their construction. The logic behind selected constructability verifications are given. The selected verifications form part of the development of the proposed constructability analysis process. A representation of the proposed implementation of the process is also given, along with guidelines based on the preferences of consultants for the implementation of a constructability analysis process in BIM.

1.2 BACKGROUND

The degree of integration of constructability information into the planning and design phases varies significantly. It often occurs that designers and owners develop drawings and specifications with limited consideration of how the structures are to be built. Research has shown that substantial time and cost savings can be achieved in projects where construction impacts are identified and considered in the planning and design phases (Tatum, Vanegas & Williams, 1986) (Paulson, 1976).

With the increase in the complexity of modern day construction projects, the need for innovation, the vast amounts of sometimes ambiguous information available, and new relationships amongst the stakeholders, the issue of constructability becomes increasingly important (Kifokeris & Xenidis, 2017). It is recognised that the integration of information regarding the construction in the early stages of a project provides a good opportunity for significant time and cost savings. It is important that design professionals need to be aware of the possible problems and claims that can result from a design's constructability profile (Hanlon & Sanvido, 1995).

When a project has inherent constructability problems, the results of litigation can involve

change order disputes and issues, delay claims and owner dissatisfaction. In more extreme cases, direct claims could be made against the company responsible for the design. The claims could be for poor plans, estimates, specifications or schedules that made the project either difficult to build, more time consuming or more costly than had been planned for.

To integrate information regarding constructability into the design phase efficiently and effectively, it should be organised and be accessible in a format that is easy to use and practical (Hanlon & Sanvido, 1995). An even more effective improvement, would be possible if the design software was able to identify possible future constructability problems.

BIM is becoming increasingly popular internationally and the benefits of its use have proven to be immense. Using BIM to increase the constructability of projects could result in significant advantages in terms of time and cost savings (Young, Jones, Bernstein & Gudgel, 2009).

This thesis aims first to identify constructability aspects of suspended floor slabs and their supports and secondly, to show that BIM can be used as a tool to facilitate a constructability improvement process. As BIM is becoming increasingly popular and being implemented in several stages of construction projects, implementing a process which aims to improve the constructability of suspended floor slabs during the conceptual and design phases could prove to be beneficial.

Common constructability problems encountered in the construction industry were identified through interviews with experienced contractors in the industry. Using the identified problems, a constructability analysis process was developed and proposed representations were given. The process was validated with experienced consultants in the civil engineering consulting industry. Preferences of consultants in the implementation of the process were also determined.

1.3 DEFINITIONS OF KEY TERMINOLOGY

Building Information Modelling – Refers to a process which is three-dimensional model-based and gives professionals within the Architectural, Engineering and Construction (AEC) industry tools and insight to more efficiently plan, design, construct and manage infrastructure and buildings (Autodesk: What is BIM?, n.d.)

Constructability – Refers to the ease and efficiency in which a structure is built and how the

construction of the structure can be made easier and more efficient (*Buildability: An assessment*, 1983)

Constructability analysis process – A process which analyses a design by identifying possible constructability problems which could arise during the construction thereof

Constructability concern – A problem which could potentially arise during construction due to poor constructability or the lack in consideration thereof during the design phase

Verification – Refers to the process of establishing whether a certain design aspect is at its optimum constructability level

1.4 RESEARCH QUESTIONS

It was decided to focus on improving constructability through the use of BIM, by specifically focussing on the construction of suspended floor slabs and their supports. The decision to focus on suspended floor slabs was made, because no substantial research had been done that was aimed at improving the constructability of floor slabs. The decision was also made because suspended floor slabs were one of the structural elements most commonly found in any construction project. This led to the following research questions:

- 1) Can constructability problems be improved through the use of BIM?
 - 1.1) What factors affect constructability?
 - 1.2) Which of these factors are implementable in BIM?
 - 1.3) What are the advantages, disadvantages and typical applications of the common suspended floor slab types used in the South African construction industry?
 - 1.4) What problems are encountered in the construction of suspended floor slabs and their supports?
 - 1.5) What verifications can be implemented in a BIM process to analyse constructability?
 - 1.6) What is the logic behind a process to determine constructability?
 - 1.7) What are the preferences of consultants for verifications of constructability?

1.5 PROBLEM STATEMENT

A big problem in the construction industry is a lack of integration between the design and the construction of a project (Zin, 2004). Designers often do not give proper consideration to the constructability of a design whilst designing. This may have detrimental effects on the planned cost, time schedule and quality of the project. It could also have an effect on safety during

construction (Khan, 2015a). This study will address the identification of possible constructability concerns during the design stage, resulting in potential cost and time savings and also an increase in the quality of the end-product.

The use of BIM in the construction industry is becoming more popular and was identified by the researcher as a tool to assist in identifying possible constructability concerns during the design phase. Thus, BIM (Autodesk Revit is the software that was used) was investigated for its suitability as a tool to identify potential constructability concerns. The researcher also investigated how consultants, or designers, would prefer such a constructability analysis process to be implemented.

1.6 RESEARCH AIMS

The aim of the research is to develop a process with which BIM can be used to verify the constructability of a design for suspended floor slabs and their supports. A selected number of constructability verifications will be developed to serve as examples of how the process can be implemented within BIM. The development of the verifications will contribute towards determining how the constructability analysis process can be implemented. The aim is to develop the verifications to an extent where it can easily be used to program the proposed process for implementation in BIM.

The proposed process will be limited to an analysis of the common suspended floor slab types used in the South African construction industry. The feedback from contractors will be used to identify the most significant problems regarding the constructability of suspended floor slabs. The process will provide constructability concerns, advantages and important constructability characteristics to consider regarding suspended floor slabs and their supports. The process will assist users in increasing the constructability of their designs.

1.7 RESEARCH OBJECTIVES

The objectives required to satisfy the aim of the research will involve:

- Identify all the factors which affect the constructability of suspended floor slabs
- Determine possible constructability verifications from interviews and select verifications to serve as examples of how a constructability analysis process could be implemented in BIM

- Provide visual representations of the potential end-product
- Develop a general guideline for the implementation of a constructability analysis process

1.8 SIGNIFICANCE OF THE RESEARCH

Poor coordination between designers and contractors is the norm (Khan, 2015a) and this can be improved through this study. Part of the aim is to make sure that consultants and designers are at least made aware of the possible constructability concerns associated with their designs. This study also determines the preferences of potential future users in the implementation of a constructability analysis process.

The significance of the study lies in the improvement of the constructability of suspended floor slabs and their supports. Construction companies will receive designs that have improved constructability thus, reducing the cost and time needed for the construction. Consultants and designers can produce designs that have improved constructability, resulting in fewer changes and a better reputation amongst clients and contractors.

1.9 SCOPE, LIMITATIONS AND ASSUMPTIONS

The research scope focussed on precast and in-situ-cast concrete suspended floor slabs. It is also based on interview participants from the Cape Town and Stellenbosch areas of the Western Cape Province of South Africa. Due to the opinions and preferences of contractors and consultants from only these areas being obtained, it should be noted that the constructability problems encountered, and the preferences of consultants for the implementation of a proposed process, could differ in other countries. It is assumed that the data obtained from the interviews serves as a representation of the whole of South Africa.

This study is subject to various limitations. This research study investigates the possibility only of Autodesk Revit for the implementation of a constructability analysis process and does not consider any other type of BIM software. It also does not include the programming of any new plug-ins for Autodesk Revit. Autodesk Revit was used as it is available at Stellenbosch University.

Another limitation of this study is the small number of constructability verifications used to illustrate the proposed process. All the the identified potential verifications were analysed

according to two criteria and the verifications which received the highest rankings were selected to be developed. Only five verifications were selected and this small number was chosen due to the verifications only being used to illustrate how the constructability analysis process can be implemented and to show the capacity of Autodesk Revit to incorporate the proposed process. By determining how the verifications can be implemented within Autodesk Revit, it could then be determined how the constructability analysis process should be implemented.

1.10 BRIEF CHAPTER OVERVIEW

The layout of the thesis along with a brief discussion of the contents of each chapter is given below.

Chapter 1: Introduction – the introductory chapter represents and discusses the study background, key terminology used, the research questions, problem statement, aims, objectives, the significance of the research, its scope, limitations and assumptions, and the layout of this thesis.

Chapter 2: Literature Study – the literature study comprises research regarding typical ways of measuring project success, the definition of constructability, benefits and barriers of constructability, project factors affecting constructability, BIM implementation, Industry Foundation Classes (IFC), current use of BIM in the construction industry, previous studies on constructability and BIM, decision-making methods and their uses.

Chapter 3: Suspended Floor Slabs – the literature study regarding the most common suspended floor slab types used in the South African construction industry comprises an overview, advantages and disadvantages and typical applications of each type.

Chapter 4: Methodology – the research methodology chapter provides information regarding the classification of the research methodology and the research instruments used.

Chapter 5: Interviews and results- a description of the first round of interviews undertaken, the interviewees, the process used to derive the interview schedule and the representation and analysis of the interview results are given in this chapter.

Chapter 6: Development of Verifications – the logic and proposed representation of each of the identified constructability verifications are discussed and illustrated in this chapter.

Chapter 7: Process Validation – the derivation of the questions asked during the second round

of interviews, the interviewees, and the results are discussed in this chapter. Illustrations of the implementation of the proposed process and general guidelines on the preferences of consultants in the implementation of a constructability analysis process is also given.

Chapter 8: Conclusions and Recommendations – conclusions and recommendations are made in this chapter.

1.11 CHAPTER SUMMARY

This chapter has described the need for integrating constructability information into the planning and design phase of a construction project. Poor integration of constructability information during the planning and design phases can result in large, and possibly detrimental, change order disputes and problems, delay claims and owner dissatisfaction. BIM has been chosen as a possible tool for increasing the integration of constructability information during the planning and design phases because of its increasing popularity (Young *et al.*, 2009).

A gap in the available knowledge regarding the constructability of suspended floor slabs was identified (See Chapter 2). A lack in research exists regarding any process which could identify possible constructability concerns associated with suspended floor slabs and their supports during the design stage. No formal method exists which aids designers in reducing the potential constructability problems of their suspended floor slab and support designs. The aim of this study is to develop such a process and give a representation of how it can be implemented.

To reach the aim of the study, it is required that modern constructability problems that are commonly encountered must first be identified. The maximum number of problems should be identified, whereafter verifications of possible constructability problems, or concerns, should be identified by analysing the collected data. From this, only a few verifications are developed in order to show the capacity of BIM to implement a constructability analysis process. Constructability, BIM and their interoperability should, however, first be thoroughly investigated

CHAPTER 2

Literature study on constructability and BIM

The content for Chapter 2 is shown in Figure 2.1 compared to the subsequent chapters

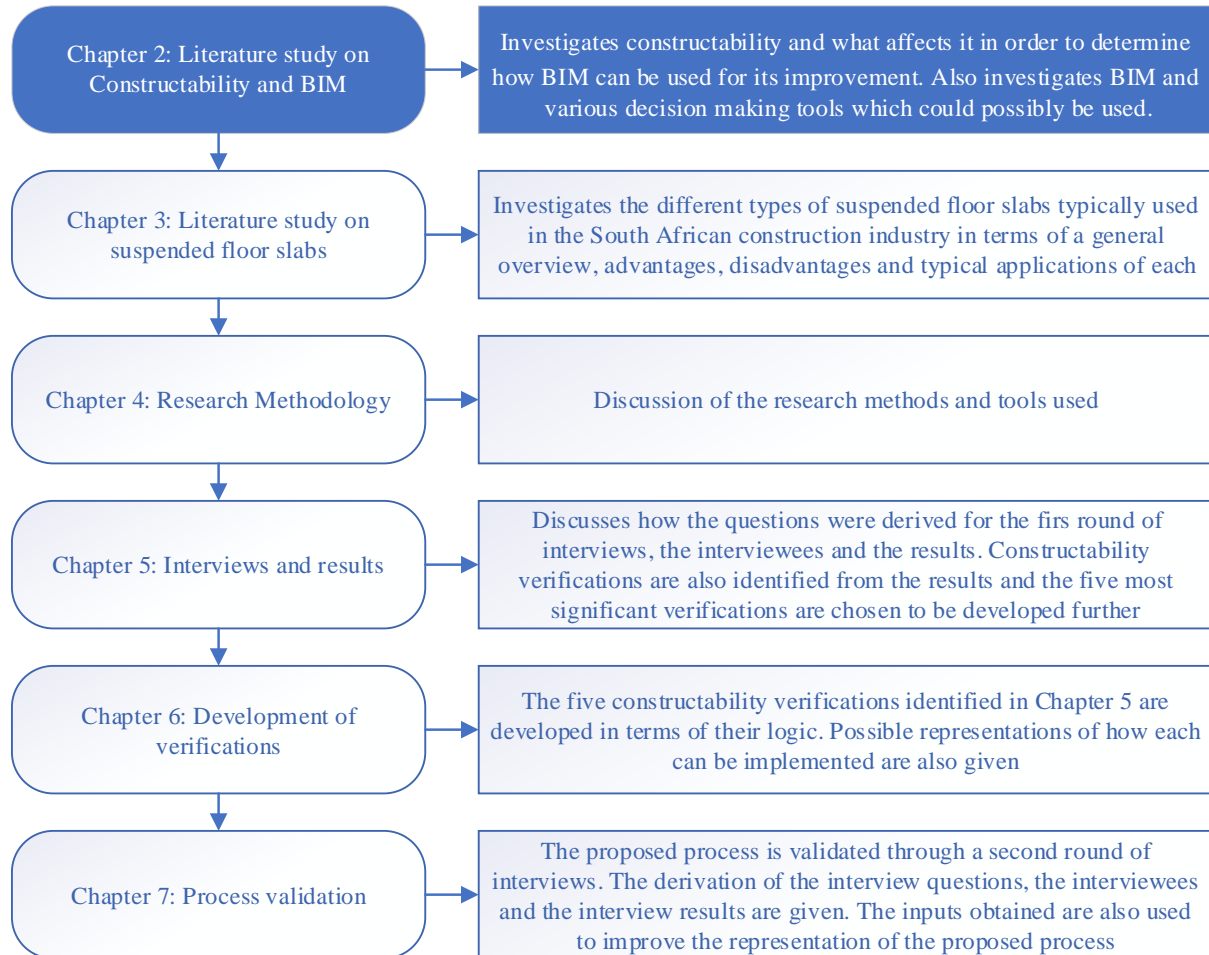


Figure 2.1: The content scope and research stage of Chapter 2 compared to the other chapters

2.1 INTRODUCTION

Improved constructability can have a significant influence on the success of a construction project. Reduced costs and duration, enhanced quality of a project, increased owner satisfaction and enhanced trust and partnering among the project teams are amongst the most significant advantages of improved constructability (Pocock, Kuennen, Gambatese & Rauschkolb, 2006). From the literature, the ways in which enhanced constructability can have a significant impact on overall project success become clear.

This chapter aims, first, to investigate the significance of the construction sector to the economy

of South Africa, in order to obtain an indication of the possible impact surrounding this field of study. The criteria for measuring project success are then determined to obtain an indication of what project characteristics can be improved in order to improve overall project success.

The impact of constructability on the success of a project was determined next, whereafter an investigation of constructability was undertaken. This was done by first defining constructability and identifying its advantages and the barriers for its optimum consideration during the design stage. Thereafter, the factors which affect constructability were identified and grouped under the following headings: site conditions and resources, document control, standardisation and repetition, safety, ease of construction and planning. The factors identified are all analysed further in terms of their compatibility with BIM.

The applicability of the identified factors to the improvement of the constructability of suspended floor slabs and their supports are also determined. It was decided to focus on the constructability of suspended floor slabs and their supports due to no substantial research having been done in this regard and suspended floor slabs being some of the structural elements most commonly found in any construction project.

Because of BIM's increasing popularity within the Civil Engineering industry, it was identified as a possible tool for the implementation of a process which could analyse constructability during the design phase of a project. An investigation was thus done into BIM. The current use of BIM, how it works and its Industry Foundation Classes was investigated.

Thereafter, the current use of BIM for construction applications was investigated in order to determine how it is already being used within the industry. Research into previous studies regarding the implementation of BIM for improving constructability was also done. This was done to identify how this research could fit into what has already been done regarding the improvement of constructability through the use of BIM. Previous similar studies was also investigated to determine and gain background knowledge of how similar studies were executed.

The general aim of this study was to develop a process with which BIM can be used to verify the constructability of a design for suspended floor slabs and their supports. Considering the aim, it was deemed necessary to investigate different decision-making methods available, with

the prospect of implementing one, or possibly more, of these methods to assist in determining the level of constructability of a design.

The global aim of this research is to improve the constructability of any type of design within BIM, and this study will focus on suspended floor slabs and their supports. This study will act as a starting point for the improvement of constructability with the use of BIM. In order to achieve the aim of this study, an investigation must be done into the existing knowledge relevant to this research field. The aim of this chapter is thus to investigate constructability and BIM through an in-depth literature study.

2.2 CONSTRUCTION INDUSTRY SIGNIFICANCE AND CONSTRUCTION PROJECT SUCCESS

The architecture, engineering and construction (AEC) industry has been a large contributor to the global economy. The industry involves a vast range of professions and manufacturing and production firms. Even after the global financial recession of the late 2000s and early 2010s, which impacted the AEC industry directly, the industry remains a major contributor to the gross domestic product (GDP) of South Africa. According to Kifokeris and Xenidis (2017), the AEC industries in major countries or federations, such as the European Union, the United Kingdom, the United States, Australia, China, Hong Kong and Indonesia generated between 4% and 10% of each country's or federation's GDP. In South Africa, the construction industry in 2016 contributed 3.9% towards the country's GDP (Crampton, 2016). The efficient construction of projects can thus have a significant influence on a country's GDP. If costs and time can be saved, it could result in more funds and manpower being aimed at new projects.

In general, the success of construction projects is measured according to four distinctive criteria (Poon, Potts & Cooper, 1999):

- Time
- Cost
- Quality of deliverables
- Client satisfaction

The first three criteria are historically more common, but Poon *et al.* (1999) added client satisfaction as it was always present as a strategic dimensional output. The elements of each criteria are shown in Figure 2.2. It can be seen that if any of the aforementioned criteria can be

improved, with client satisfaction being directly influenced by the other three, the overall success of a project is also improved. The concept of constructability was identified as any possible way in which to improve the overall success of a project.

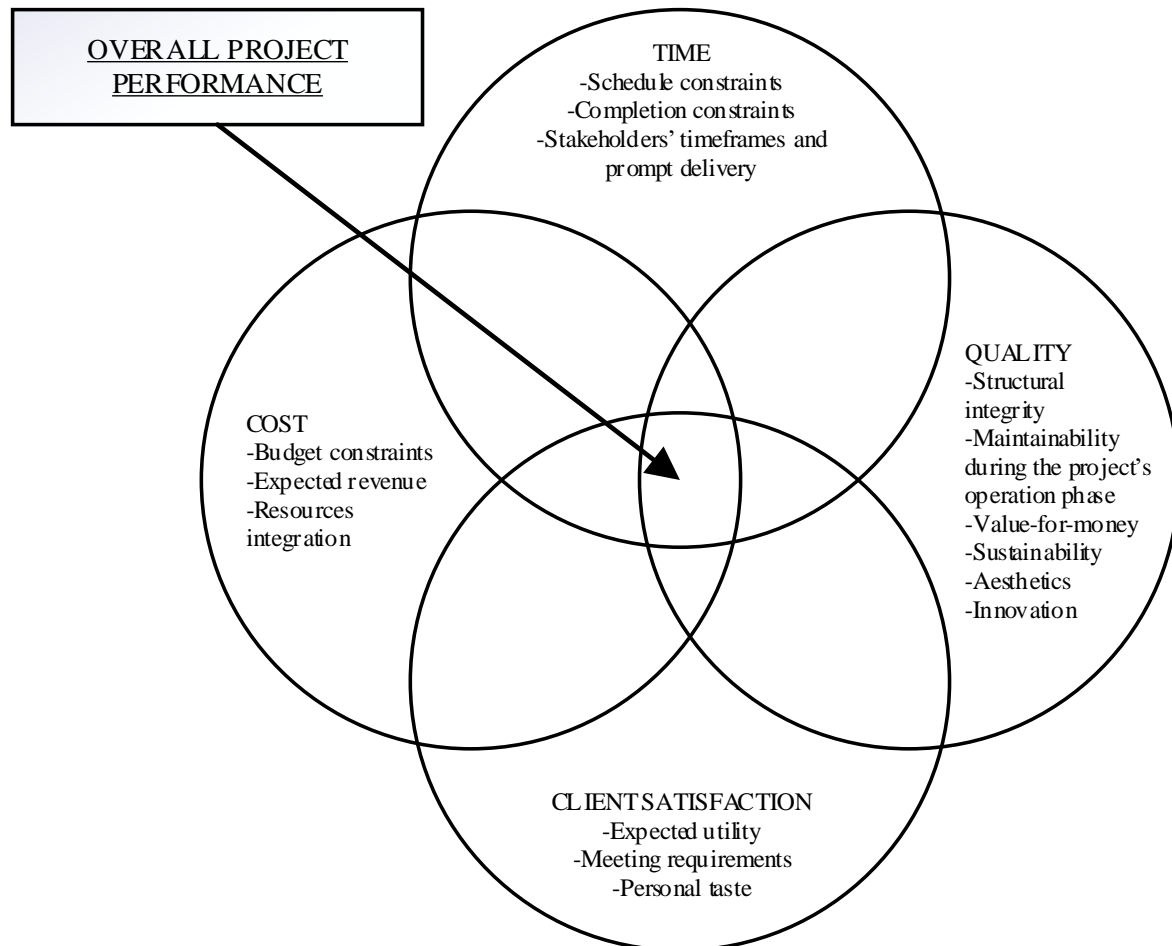


Figure 2.2: Overall project performance (Kifokeris & Xenidis, 2017)

Through the ages, a major problem occurring on construction sites has been the poor integration between the design and the actual construction (Zin, 2004). In order to reach project objectives more successfully, i.e. improved cost and time efficiency, better quality of work and improved client satisfaction, the concept of constructability was presented in the 1970s (Zolfagharian, Nourbakhsh, Mydin, Zin & Irizarry, 2012). This was followed by a multidisciplinary stream of research, led by the conceptualisation and studies pertaining to buildability or, more specifically, the concept of constructability (Tatum, 1993). This stream of research continues today.

2.3 CONSTRUCTABILITY

2.3.1 Introduction

The concept of constructability allows for the integration of the knowledge and the experience of design engineers and construction managers. This results in the minimisation, or even the elimination, of redesign and rework on construction sites (Zolfagharian *et al.*, 2012). Kifokeris and Xenidis (2017) went further and wrote that the implementation of constructability in various ways can result in the improvement of all the aspects of a project's overall performance. They also wrote that it facilitates the optimisation of project constraints and also introduces a more collaborative system for the management of the whole project lifecycle. Constructability is discussed in the subsection that follows.

2.3.2 Definition

The term constructability refers to how easily and efficiently a structure can be built and also how the construction of the structure can be made easier and more efficient (*Buildability: An assessment*, 1983). The Construction Industry Research and Information Association's definition of constructability was one of the first actual definitions of the term. Since then various new definitions have emerged and are all based on an individual project's requirements and needs and sometimes also specifically from the designers' point of view.

The Construction Industry Institute (CII) later better defined constructability as 'the optimum use of construction knowledge and experience in planning, procurement, engineering and field operations to achieve overall objectives' (*Constructability: A primer*, 1986). More recently, McDowall (2008) further defined constructability as:

- The extent of the design of a building facilitating the ease of the construction, subjected to requirements set for the completed building
- A system that aims at achieving the optimum integration of construction experience and knowledge in planning, procurement, engineering and field operations in the construction process and also balancing the different project and environmental constraints to achieve the project objectives

From literature, it is evident that most definitions to date are in accordance with the Construction Industry Institute's definition of constructability. Thus, for the purposes of this research, this is the definition that will be considered to apply when reference is made to constructability.

2.3.3 Barriers

In order to fully comprehend why constructability is not seen as a priority, nor implemented to its full potential, the barriers to the implementation of constructability need to be investigated and determined. Several studies have been done to determine the barriers which are preventing the optimal implementation of constructability in construction projects. The Construction Industry Institute (1993) identified several major barriers in their 1993 review of constructability implementation. These barriers include (*Preview of constructability implementation*, 1993):

- Complacency with the status quo
- Lump-sum competitive bidding
- Reluctance to invest initial resources
- Delay of construction input into the process
- Lack of mutual respect between designers and constructors

In a survey done by Jergeas and Van der Put (2001), the most significant barriers set against achieving the potential benefits of the implementation of constructability were determined. The most significant barriers were found under the following three constructability principles:

- Involvement of construction personnel from the start of the project
- Improvement in the efficiency of the construction
- Innovation in the construction methods used and the use of advanced computer technology

The identified barriers to the early involvement of construction personnel were found to be the following (Jergeas & Van der Put, 2001):

- A lack of mutual respect, trust and credibility among project participants
- Ineffective traditional contracting practices that involve constructors only when the design and specifications have already been substantially developed
- Owners having a lack of desire and commitment to allocating resources and funds towards constructability implementation

The barriers to greater efficiency in the construction were found to be the following (Jergeas & Van der Put, 2001):

- Congestion around certain construction sites, especially those that are next to existing operating facilities

- Specifications that are too rigid and thus limit design flexibility, because the specifications are being prepared by designers with a lack of practical field experience
- A lack of communication and partnering between constructors and designers

The barriers to innovation in construction methods and the use of advanced computer technology are the following (Jergeas & Van der Put, 2001):

- Avoidance of risks, lack of trust by the owners and a lack of knowledge of the latest construction methods
- Perceived or real high cost of using advanced computer technologies, which especially occurs in isolated locations where sophisticated telecommunications links are required
- Time and cost required to train staff to an adequate level in the use of the latest computer systems or software, which also changes frequently

In a survey done by Pocock *et al.* (2006) in the United States of America where the participants were asked to vote for the most significant barriers to constructability implementation, it was found that the most significant barriers were:

- Lack of open communication between constructors and designers
- Lack of construction experience amongst designers
- Difficulties in the coordination of the disciplines involved
- Inadequate resources
- The type of project delivery method and contract used
- Constructability is not part of the design process
- Implementation is too costly
- Terminology is inconsistent
- Implementing constructability can result in lengthening the project

The survey also received written responses from the participants which added the following barriers to constructability to the list (Pocock *et al.*, 2006):

- Public owners are under substantial pressure to reduce the costs of projects, which results in designers neglecting constructability in an attempt to reduce design fees
- Design and building codes do not require constructability
- Crew level workers are ignored
- Design engineers are defensive and they lack experience
- There is a lack of emphasis on constructability in engineering education

In a study done by Arditi, Asce and Toklu (2002), which focussed on the implementation of constructability within design firms, it was found that incomplete specifications, faulty working drawings and adverse relationships amongst project participants were the main barriers.

2.3.4 Benefits

As a motivation for the chosen research topic of this study, the benefits of improved constructability were researched. In a survey done by Pocock *et al.* (2006) it was found that the most significant possible benefits of improved constructability were:

- Minimisation of contract disputes and change orders
- Reduction in project costs
- Improved project quality
- Shorter project duration
- Improved owner satisfaction
- Improved trust and partnering within project team
- Improved safety
- The provision of a construction plan or methods that requires fewer special skills and equipment

From the above, it can be concluded that the benefits of effective implementation of constructability in a construction project are significant. In the modern AEC industry, the profit margins are small due to the competitiveness of the industry. The limited number of available projects and the competitiveness in the tendering for these projects results in companies having to find new and innovative ways of reducing their input costs.

It can also be concluded from the identified barriers and benefits of implementation of constructability, that the earlier within the lifecycle of a project that constructability is considered, the larger the potential benefits in terms of cost, schedule, quality and owner satisfaction. The factors that affect the constructability of a construction project will be identified next, along with their applicability when using BIM.

2.4 FACTORS AFFECTING CONSTRUCTABILITY AND THEIR POSSIBLE APPLICATION IN BIM

A literature study was done in search of opinions on the factors which affect constructability. A keyword search was undertaken for the term constructability and a range of studies was found which investigated the factors affecting it. These studies, along with the factors they identified, are summarised in Table 2.1. The factors that were identified by two or more studies were then chosen, along with a few factors that were identified by a single study, but which were considered to be relevant enough to be further investigated. The chosen factors were then grouped under the headings shown in Figure 2.3. It should, however, be noted that none of the studies undertaken considered the South African construction industry.

The factors are discussed in the subsections that follow, along with their applicability, and their compatibility with BIM. A basic description of BIM will first be given in order to provide the reader with a background to BIM, whereafter each factor affecting constructability is discussed and analysed in terms of its compatibility to BIM. The analysis was done by the researcher in terms of the possibility of a factor being addressed and brought to the notice of the design team through the use of BIM, or whether the relevant information regarding the factor could be captured in BIM.

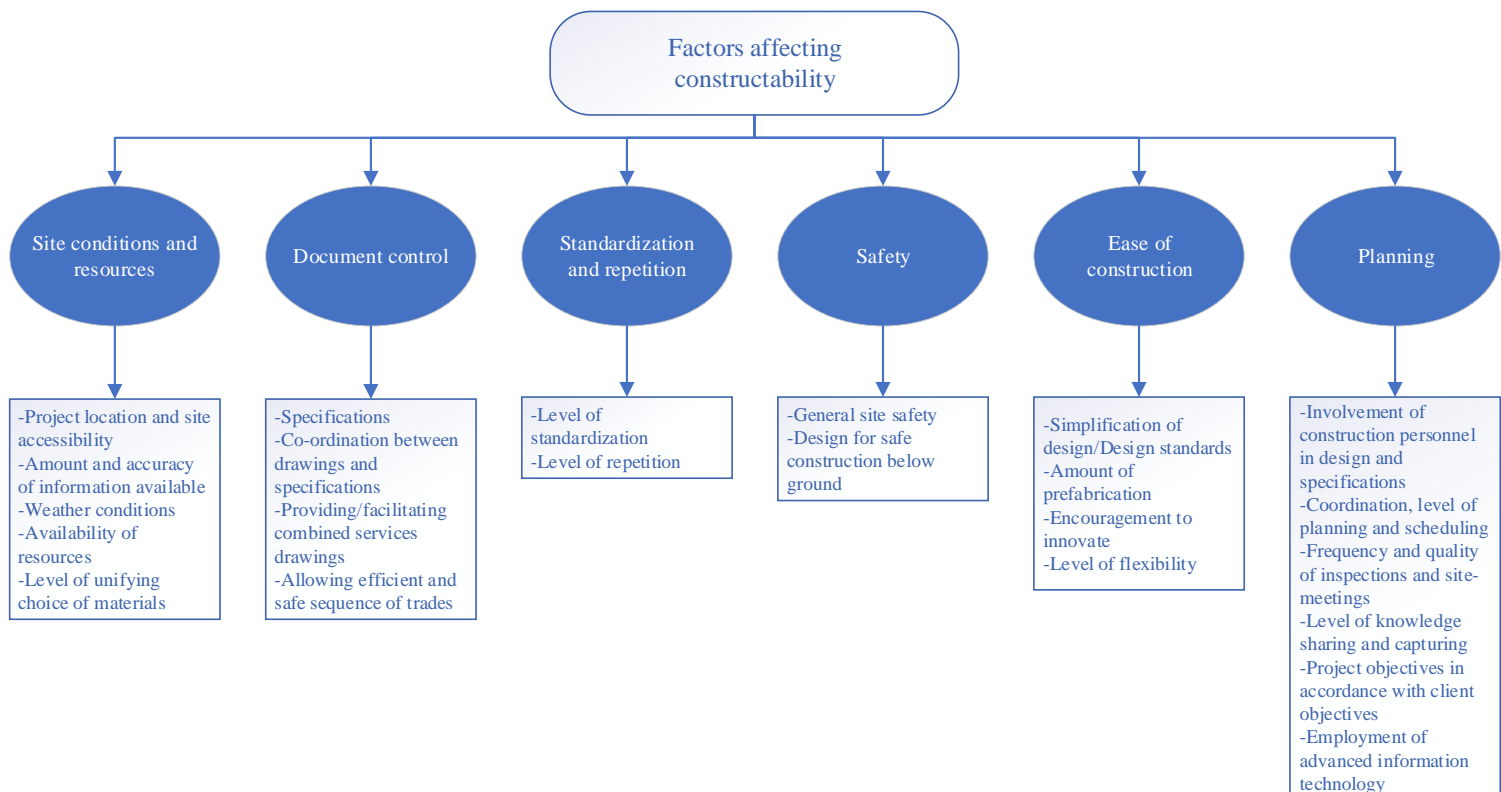


Figure 2.3: Chosen groupings for factors affecting constructability

Table 2-1: Previous studies on factors affecting constructability

Previous studies	Arditi <i>et al.</i> (2002)	Khan (2012)	Khan (2015)	Lam, Wong, Chan. (2006)	(Lam, Chan, Wong & Wong, 2007)	Wong (2006)	Vardhan (1992)	Windapo and Ogunsanmi (2014)
Design Practices	X							
Project delivery method	X							
Project size	X							
Project type	X							
Client type	X							
Project location and Site accessibility	X		X	X	X	X	X	
Simplification of design (allowing easy installation & connections)/ Design standards	X	X	X	X	X	X	X	X
Level of involvement of construction personnel in design		X	X			X		
Standardisation/ Repetition		X	X	X	X	X	X	
Coordination, Level of planning (site layout, storing) & Scheduling		X	X	X	X	X	X	X
Amount and accuracy of information available (site conditions, weather, etc.)		X		X		X		
Award of works (services, sub-contractors, etc.)		X						
Frequency and quality of inspections and site-meetings		X		X				
Level of knowledge sharing and capturing		X	X					
Integration of different disciplines and services			X					
Amount of prefabrication			X		X	X		X
Weather Conditions			X			X		
Specifications (Construction personnel input, unambiguous)			X	X	X			X
Encouragement to innovate			X			X		X
Availability of resources (materials, skilled labour)			X			X	X	
Recycling & waste management			X					
Employment of advanced information technology			X					
Design for safe construction below ground				X		X		
Co-ordination between drawings & specifications				X				
Providing/ facilitating combined services drawings				X				X
Allowing efficient and safe sequence of trades				X	X			X
General site safety				X		X		
Level of flexibility allowing contractors to choose construction methods/approaches					X	X		
Level of unifying choice of materials						X	X	
Project objectives in accordance with client objectives							X	

2.4.1 Understanding BIM

BIM has been defined as a technology, or system, which represents an accurate virtual model of a structure or building. BIM can also be seen as an Information Technology-enabled approach involving the application and the maintenance of a digital model, or representation, of a structure which includes all its information throughout all the stages of a project (Kekana, Aigbavboa & Thwala, 2015). The three-dimensional model of the structure will include all its exact dimensions, orientations, information regarding materials used, etc. BIM has various applications and benefits, and these were investigated and are discussed further in Section 2.5.

2.4.2 Factors affecting constructability

2.4.2.1 Site condition & resources

a) Project location and site accessibility

Constructability can be enhanced when the design promotes the accessibility of material, manpower and equipment (O'Connor, Rusch & Schulz, 1987). The consideration of site accessibility is important, and is especially important in cases where construction sites are limited in terms of the available space, where road capacities are restricted, where work needs to be done at high elevations, sites with steep grade changes, sites where multiple contractors are performing work, or sites with extreme weather and/or environmental conditions. It is important that site accessibility is planned for in terms of storage spaces, the different project elements and what each requires: access lanes, crane placements, etc. (Windapo & Ogunsanmi, 2014).

The location of a project determines how far a given construction site is from suppliers of concrete, precast members, scaffolding and formwork subcontractors, etc. These considerations are, however, the responsibilities of project team leaders and they ultimately affect the details which will be stored and reflected in the BIM model.

Because BIM is able to incorporate geographical information regarding any specific site, BIM can be used to plan the best ways of accessing a construction site, as well as planning the space use and logistics of a site. BIM is thus an effective tool to use for site planning.

b) Amount and accuracy of information available

If site conditions are not considered in advance they can cause delays in construction (Adams,

1989). A thorough investigation of the site and the condition of the ground needs to be carried out before the commencement of the design phase. The implementation of these thorough investigations was found to play an important part in reducing contractual variations (Chan & Yeong, 1995).

Important information that needs to be collected regarding the condition of the site includes the physical dimensions of the site, the underground conditions, the composition of the terrain, possible destabilising foundations occurring on adjacent sites, the presence of boreholes and the presence of cables and pipes. A survey also needs to be done of all adjacent sites and/or buildings (Lam *et al.*, 2006).

BIM is able to incorporate vast amounts of information regarding projects, which includes information regarding the site characteristics, but the actual collection of information still needs to occur first. BIM can thus only be used as a tool to store the collected information.

c) Weather Conditions

Constructability can be improved when the design incorporates and facilitates the construction occurring during possibly adverse weather conditions (O'Connor *et al.*, 1987). This is important in areas where the climate can be a challenge for the smooth functioning of construction activities. The constructor and the designer both need to be sensitive towards their planning in such areas. Quality control is a major problem in these cases (Khan, 2015b).

Designers have to do suitable investigation in advance in order to formulate ways in which the effects of rain and temperature extremes can be minimised. Some measures that can be undertaken are making allowance for large enclosed areas which can function as space for storage and fabricating workshops. Specifications to overcome the effects of adverse weather include the use of specially formulated admixtures, the paving of the site before construction commences to eliminate potentially muddy operations and maximising the amount of work that can be completed off-site (Khan, 2015b).

BIM can be used as a project planning tool to incorporate the possibility of adverse weather conditions during the execution of a project, but the incorporation of the possible adverse weather conditions into the project's time planning remains the responsibility of the relevant project team and its participants.

d) Availability of resources

It is advised that materials that are difficult to obtain should be avoided (O'Connor *et al.*, 1987). Engineers and architects should give preference to, and first consider, local materials, labour, conditions and construction methods (Glavinich, 1995). This can result in fewer project delays and also fewer additional expenditures.

The availability of resources for a project is the responsibility of the relevant project team member(s) and only the information regarding the chosen resources can be incorporated into BIM.

e) Level of unifying choice of materials

Unifying the decision on materials chosen for a project can increase constructability by minimising the number of coordination problems that are likely in designs that require many different types of material (Griffith & Sidwell, 1995). This does, however, not entail that the range of materials to be used need be restrictively specified. The dimensions of building elements should reflect the available material sizes and should be designed to minimise labour requirements and wastage of materials through unnecessary special cutting (Griffith & Sidwell, 1995).

BIM can be seen as a tool to assist in the unification of decisions on materials. Information regarding all the materials used in a project can be captured in a BIM model and this can be used to enhance the final decision for unification of materials.

2.4.2.2 Document control

a) Specifications

O'Connor *et al.* (1987) mentioned that construction personnel should be invited to give input during the finalising of the preferred specifications and methods, but it is important that design configurations not be constrained by doing so. Specifications should also allow for cost effective but acceptable alternatives, in case the views of construction personnel vary. Special or customised material or equipment should also be avoided in specifications. Specification must be as unambiguous and realistic as possible.

Due to BIM's three-dimensional representation capability, it can easily be used to plan the

necessary construction techniques and equipment requirements. This makes the use of BIM an effective tool for ensuring and encapsulating construction personnel's preferences in terms of the design and specifications.

b) Coordination between drawings and specifications

The coordination regarding the format and requirements of specifications, design drawings and schematic diagrams must be reviewed with special care to avoid any ambiguities, discrepancies and possible misunderstandings before these documents are distributed.

One of BIM's many advantages are its capability to produce fabrication/shop drawings. Along with its capability for being used as an aid to ensure that specifications are realistic and well-planned, it can enhance the coordination between the required drawings and the project-specifications.

c) Providing/facilitating combined services drawings

The provision of combined services drawings in several combinations can enhance the constructability of a project by aiding the constructor in planning (Lam *et al.*, 2006).

A feature of BIM known-as 'clash detection', facilitates the detection of possible clashes between services, reinforcement, etc. during the design stage. This feature results in significant long-term cost, time and energy savings. BIM's ability to provide fabrication/shop drawings also ensures planning and construction are less ambiguous and has fewer problems pertaining to the realisation of a design.

d) Allowing efficient and safe sequence of trades

It is of critical importance that compatibility must be ensured between the large numbers of sub-assemblies and components of a building, together with the sequence of trades during construction. This will result in a smoother workflow and less wastage of materials and man-hours (Lam *et al.*, 2006). It is, however, also important that the focus should be on keeping the sequence safe and within regulations.

BIM can be used to plan the inter-operability of the sequence of trades which will occur during a project. BIM's ability to facilitate project planning and schedule planning makes it an effective tool to use for all the planning involved in a project.

2.4.2.3 Standardisation and repetition

a) Level of standardisation

The standardisation of building elements enhances constructability by reducing learning time and increasing speed of construction. Standardisation involves incorporating more readily available standard products in the design and encouraging their usage where possible (Khan, 2012). A reduction in the variety in a project can also lead to discounts on a larger amount of the same material, simplified process of procurement and material management (Khan, 2015b).

BIM can be used as a tool to enhance the standardisation of a project. All the available sizes and dimensions used in a project are easily accessible and standard sizes available can be loaded onto BIM if necessary. BIM can be used to compare the connection layouts and member dimensions to the standard connections and sizes available.

b) Level of repetition

Standardisation and repetition go together in terms of constructability. An increase in standardisation leads to more repetition in the work. The increase in repetition of grids, sizes of components and connection details will facilitate faster construction and also lead to an increase in construction quality.

BIM can be used to assess the level of repetition which will occur during a project. Because BIM incorporates all member dimensions and connections, it can be used to enhance repetition and reduce the learning curve which will be required on site.

2.4.2.4 Safety

a) General site safety

Designers must be conscious of safety on site, as accidents can have long-lasting economic and moral effects on the project. Unsafe circumstances on site can also lead to significant delays. Safety regulations for construction sites are very detailed and any form of non-compliance with these regulations can have detrimental effects on a project. From the start of a project, designs must facilitate a working environment that is safe, especially in earth and foundation works, in the handling of equipment and with regard to access (Adams, 1989).

BIM can be used to a certain extent in planning for safety on site. It can be used to plan how

excavations will occur, how certain slopes must be supported, how accessibility will occur at unsafe heights, the storage of dangerous substances, etc.

b) Design for safe construction below ground

When any construction will take place below ground, designers must consider the possibilities of unsafe circumstances occurring, such as the collapse of unstable surrounding earth and neighbouring foundations, creating unstable conditions (Lam *et al.*, 2006). Designers need to consider how excavations and evacuations will take place.

BIM can be used to plan which slopes will require supporting, how excavations will occur and how the neighbouring geotechnical or structural conditions will affect a given construction site. The investigation of condition of the site and neighbouring sites remains, however, the responsibility of the those who are appointed to do it.

2.4.2.5 Ease of construction

a) Simplification of design/ Design standards

Constructability is increased when designers consider efficient construction in their designs. Khan (2015b) developed some principles for the simplification of designs, being:

- A minimum number of elements, parts and components should be used for assembly
- Readily available materials, in common sizes and configurations, should be used
- Simple and easy to install connections that minimise the requirement for highly skilled labour should be used
- Designs should minimise construction task interdependencies

Qualified construction personnel should be asked to review the design before it is finalised.

BIM is able to assist in the planning and implementation of all the abovementioned principles of design simplification. All the principles mentioned can be implemented and improved with the use of BIM, making BIM a effective tool in enhancing constructability through the simplification of designs.

b) Amount of prefabrication

O'Connor *et al.* (1987) identified that constructability is enhanced if prefabricated work is planned for in advance. Designs with prefabricated work needs to be incorporated in advance

to facilitate the entire process of manufacturing, transporting and installation. All the necessary planning should be taken care of in the conceptual planning stage. The prefabricated items should be analysed in the early stages of the design phase. The use of prefabrication, together with efficient and proper planning, can lead to many benefits, such as improved task productivity, better safety, improved quality control, less scaffolding being required and better parallel sequencing of different construction activities being possible.

BIM can be used as a tool to produce the necessary drawings of precast elements which can be given to precast manufacturers to ensure that the members required are correctly sized. BIM can also be used to plan for the transporting and installation of precast members, which makes it an effective tool to enhance and improve the use of precast members in a construction project.

c) Encouragement to innovate

O'Connor *et al.* (1987) stated that good management practices create an atmosphere where past construction methods and practices are challenged, and innovative ideas are rewarded. They stressed the importance of developing good ideas and documenting success. They also identified common innovation practices that can enhance constructability. These include:

- Sequencing of the use of common equipment such as cranes, hoisting equipment, and scaffolding. This should especially be done on sites where the equipment will be used by several sub-contractors. This can result in reduced confusion and also in less congestion on site
- Reducing the need for temporary lighting systems by installing lighting systems at an early stage
- Possibly speeding up work by erecting platforms and stairs at an early stage
- Use of advanced methods such as ground freezing and steam curing
- Use of modern formwork systems such as flying formwork
- Advances in hand tools can result in an increase in safety, mobility, reliability and accessibility
- Innovative temporary facilities such as easier erectable tents for work space
- Constructability tends to make processes more automated. Construction processes can be sped up by using remote controlled welding systems, fully automated concrete batch plants, automated concrete floor finishers and fire proofing through the use of robots for spraying

BIM can, like most other design software typically used, facilitate in the visualisation of designs which, in turn, gives the user the opportunity to consider different design alternatives, and this increases the possibility of innovation. BIM can thus also be used as a tool only to facilitate in increasing innovation. All the abovementioned ideas can either be planned or implemented within BIM.

d) Level of flexibility

Designs should specify their desired results and allow contractors some margin for choosing the best construction approaches or methods, e.g. piling methods, formwork systems (*Constructability manual*, 1996). Designs should also be adaptable, with interchangeable components providing room for possible changes to suit certain circumstances.

Through the use of its three-dimensional visualisation features, BIM can be used to develop designs which are flexible in terms of the required construction methods and components needed.

2.4.2.6 Planning

a) Involvement of construction personnel in design and specifications

Khan (2012) advised that experienced construction personnel should be involved from the start of the design phase, as they would ultimately have to construct the facility as effectively as possible. Their expertise can help in identifying areas where standardisation can be incorporated in the design, help minimise accessibility problems on site, etc. (Khan, 2015b). An added benefit is better cooperation between the contractor and other project participants throughout the project. Gil, Tommelein and Ballard (2004) classified the advantages of contractor inputs in early stages into four main areas:

- 1) Development of more creative solutions
- 2) Construction capabilities and fabrication knowledge
- 3) Knowledge of construction space needs
- 4) Reliability of suppliers and supplier lead time knowledge

This is, however, not always possible, as the type of procurement method used for a project plays a major role in the possibility of involving a contractor in the design phase.

Although the level of involvement of construction personnel in designs and specifications relies on how important consultants consider it to be, BIM can easily be used as a tool to incorporate the inputs of contractors. A further benefit of using BIM is that contractors do not have to physically meet with designers to discuss the drawings, they can give inputs from anywhere in the world through the use of cloud storage. This makes the coordination much faster and more efficient.

b) Coordination, level of planning and scheduling

Coordination has been defined as the effective harmonisation of planning and accomplishing of goals. It can be seen as the most important, and also sensitive, problem pertaining to management (Khan, 2015b). Coordination can also be seen as a bridge that fills the voids that are created in numerous departments as a result of the changing situations within the system, its policies and procedures (Chitkara, 1998).

Accessibility, distribution and storage must be planned for at the drawing board stage. It is of extreme importance to thoroughly plan and schedule the layout and detailing activities, since they have to be programmed in advance in order to effectively precede the fabrication and installation. Sufficient lead time must also be given for delivery of materials and other dependent activities (Khan, 2012). Layouts must enable the optimum use of all the mechanical plants, particularly the movement of building materials. Locations that are suitable for the bases of cranes should be identified and left clear as far as possible.

Khan (2012) also advised the following aspects of designs and the planned work sequence in order to improve constructability:

- Designs should assist the work sequencing in such a way that the different trades or specialisation work can be completed with as few site visits as possible
- Reduce the risk of damage to completed adjacent elements with a minimum of special protection requirements
- Sequencing should enable each operation to be completed independently and without interruption
- Sequencing should assist in the coordination of the different trades and minimise delays

As previously mentioned, BIM can be used as a tool for all the planning and scheduling involved in a construction project. It could, however, occur that no BIM models have yet been

developed when certain important decisions have to be made at the start of a project. This, however, would depend on the willingness of project members to incorporate modern technologies.

c) Frequency and quality of inspections and site-meetings

Certain members of the project team should be identified at an early stage of the project and made responsible for constructability. The responsibilities of each member must be clearly defined at the beginning of the project. Full time inspections by the head engineer are extremely important and should happen at regular intervals. The designer(s) should also frequently execute site visits and these visits must be planned so as to not affect the pace of the work and thus ensure that no 'short-cuts' are taken (Khan, 2012).

BIM can be used only as a tool to plan for constructability; but site meetings, site visits and inspections to ensure constructability remain the responsibility of the project members assigned to do it.

d) Level of knowledge sharing and capturing

Knowledge capturing is becoming an increasingly important undertaking in the modern competitive construction industry (Olatokun & Pathirage, 2015). A large part of the priceless knowledge gained by individuals during construction is not effectively documented, because communication channels are unreliable. Proper records should be created and maintained of all previous successful solutions, methods or approaches and their results. It is also advisable that unsuccessful solutions be documented, to avoid similar mistakes in the future (Khan, 2012). This database of information could become invaluable.

With BIM's information capturing ability, new experiences, knowledge and lessons learned can be captured within BIM. This is possible through the development of a add-on or a database.

e) Project objectives in accordance with client objectives

It is important that the individual perceptions of designers and constructors be integrated with the objectives of the owner. Only thereafter can a guiding set of project objectives be determined and this will also allow designers and contractors to work together more efficiently. The set of objectives will then serve as a measure regarding the optimisation of the chosen

design (Vardhan & Yates, 1992).

BIM is able to create detailed three-dimensional representations of its designs, which can then be shown to clients to give them an indication of the end-product. The clients could then comment on the proposals and, through coordination, a model can be adjusted until all project participants are satisfied.

f) Employment of advanced information technology

Design software (e.g. BIM) can be used to plan site accessibility, work flow, logistics, etc. It can also be used to incorporate past lessons learned with regard to design and construction (Khan, 2015b). The benefit of the ability to use advanced information technology to improve designs in terms of constructability, resulting in time, cost and energy saving, is immense.

2.4.3 Applicability of factors affecting constructability to suspended floor slabs and BIM

As previously mentioned, this study focusses on the improvement of the constructability of suspended floor slabs and their supports. The applicability of the factors affecting constructability to suspended floor slabs, along with the factors' compatibility with the BIM software, is summarised in Table 2.2. A factor is seen as being directly applicable to suspended floor slabs if it is able to directly influence the efficiency of the construction of a suspended floor slab. The BIM compatibility of the factors is based on the discussions given in Section 2.4.2. The factors' applicability to suspended floor slabs and compatibility to BIM is also based on the judgement of the researcher.

From Table 2.2 it can be concluded that a majority of the factors affecting constructability are applicable to suspended floor slabs and their supports and are also compatible with BIM. Compatibility with BIM refers to BIM's ability to assist in the improvement of a constructability factor. The factors which are applicable to suspended floor slabs and compatible in BIM will be the focus of the first round of interviews which is discussed further in detail in Chapter 5. These factors form part of the areas focussed on for the derivation of the questions to be asked during the first round of interviews. BIM will be further addressed in the subsection that follows.

Table 2-2: Summary of the factors affecting constructability's applicability to suspended floor slabs and their compatibility with BIM

Factors affecting constructability	Directly applicable to suspended floor slabs (X)	BIM compatible (X)
Project location and site accessibility	X	X
Amount and accuracy of information available	X	
Weather conditions	X	
Availability of resources (materials, skilled labour)	X	
Level of unification in choice of materials	X	X
Specifications (construction personnel input and unambiguity)	X	X
Co-ordination between drawings & specifications	X	X
Providing/ facilitating combined drawings for services	X	X
Allowing efficient and safe sequence of trades	X	X
Level of standardisation	X	X
Level of repetition	X	X
General site safety	X	X
Design for safe construction below ground		X
Simplification of design/Design standards	X	X
Level of prefabrication	X	X
Encouragement to innovate		X
Level of flexibility allowing contractors to choose construction methods/approaches	X	X
Level of involvement of construction personnel in design	X	X
Coordination, level of planning & scheduling	X	X
Frequency and quality of inspections and site-meetings	X	
Level of sharing and capturing of knowledge	X	X
Project objectives in accordance with client's objectives	X	X
Employment of advanced information technology	X	X

2.5 BIM (BUILDING INFORMATION MODELLING)

2.5.1 Introduction

In the past, the design process followed in the construction industry, from conceptual design to construction, relied on the systematic multi-stage issuing of specifications and drawings to contractors. BIM, however, brings together the data from different components and forms a coherent set of information available for all project participants.

BIM, more specifically Autodesk Revit, was used in this study as the software on which the proposed constructability analysis model is represented. BIM is becoming increasingly popular

around the world in the construction industry (Young *et al.*, 2009). It is still rarely used in South Africa, but research regarding its applications and advantages has been done to a significant extent (Goldswain, 2016). As BIM forms an important part of this research project, a study into BIM was performed and is presented in the subsections that follow.

2.5.2 Current implementation

BIM is most often used for the following purposes, as reviewed by Azhar (2011):

- Visualisation: Three-dimensional models can be easily generated
- Fabrication/shop drawings: It is easy to generate fabrication/shop drawings for various systems
- Code reviews: Officials may use this technology for building reviews
- Cost estimation: BIM has built-in cost estimation features
- Construction sequencing: BIM can be used to effectively coordinate fabrication, delivery schedules, and ordering of materials
- Detection of interference, collision and conflict: BIM models are created to scale three-dimensionally and can be instantly and automatically checked for any sites of interference
- Forensic analysis: A BIM model can be adapted to illustrate potential failures, evacuation plans, leaks, etc.
- Facilities management: BIM models can be used for planning the use of space, renovations and maintenance operations

Several studies have added the following more current uses of BIM to Azhar's list:

- Design coordination (Lee & Kim, 2014)
- Safety planning and management during construction (Li, Lu, Hsu, Gray & Huang, 2015)
- Hazard identification and/or prevention (Zhang, Sulankivi, Kiviniemi, Romo, Eastman & Teizer, 2015)
- Automated review of design (Lee, Lee, Jeong, Sheward, Sanguinetti, Abdelmohsen & Eastman, 2012)
- Construction risk management (Tomek & Matějka, 2014)
- Labour productivity improvement (Poirier, Staub-French & Forgues, 2015)
- Planning for geotechnical and safety protective equipment (Wang, Zhang & Teizer, 2015)

In order to obtain a better understanding of how BIM's software works, a study was done into its so-called 'Industry Foundation Classes'.

2.5.3 Industry Foundation Classes (IFC)

As part of the aim of the research, which is to develop a process with which BIM can be used to verify the constructability of a design for suspended floor slabs and their supports, an investigation was undertaken into how BIM works. A BIM system is an object-oriented type of Computer-aided Design (CAD) system. As an example, in an object-oriented system a wall would be perceived by the system as an object that would have the properties of a real wall. These properties would include thickness, length, height and also non-geometric characteristics such as material, suppliers, cost, etc. The characteristics of the objects are called Building Object Behaviours (BOB) (Muller, Garbers, Esmanioto, Huber, Loures & Canciglieri, 2017). These characteristics require special concern and care in terms of interoperability, because this information has to be correctly and efficiently transferred to the agents involved in the design and construction. BIM is, however, also a type of parametric modelling and differs from CAD modelling as regards the following characteristics (Lee, Sacks & Eastman, 2006) :

- Shapes can be generated and manipulated and constraints and new parametric relations can be added by users. The shapes could also be changed by editing the pre-defined parameters.
- Three-dimensional modelling should preferably be used by parametric systems, since two-dimensional systems would not represent a complex model sufficiently.
- This type of system should also preferably be feature and object-based. It is possible to constrain these objects together if deemed necessary.

Interoperability inefficiencies could result in rework, uncertainty, unacceptability of the reliability of the data and mismatched information. This led to professionals in the AEC industry creating the International Alliance for Interoperability (IAI), which later changed to BuildingSMART. BuildingSMART aims to promote and improve interoperability and innovation in software used in the AEC industry (Muller *et al.*, 2017). In an effort to improve interoperability, BuildingSMART developed Industry Foundation Classes (IFC) (Eastman, Teicholz, Sacks & Liston, 2011). IFC can be described as a neutral standard with a main goal of standardising the different classes of an object-oriented system within an open format. This allows multiple applications to use it to share data (BuildingSMART: Technical vision, n.d.). IFC is well-known and widely used in the AEC industry and in facility management, because

it is registered by the International Organisation for Standardisation (Lee, Eastman & Solihin, 2016).

Following research into both constructability and BIM, it was decided to investigate their interoperability and also to determine the current use of BIM within the construction industry. This was done as described in the subsection that follows.

2.6 CONSTRUCTABILITY AND BIM

2.6.1 Current use of BIM in the construction industry

The United States National BIM Standard Part 1 describes BIM as follows: ‘A Building Information Model (BIM) is a digital representation of the physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onwards’ (*National Building Information Modelling standard part-1: Overview, principles and methodologies*, 2007). BIM integrates all project information into a three-dimensional model. BIM is being used as a technological tool that can be used for a range of construction applications including:

- Quantity and cost estimation (Monteiro & Poças Martins, 2013)
- Design error identification through clash detection (Azhar, Nadeem, Mok & Leung, 2008)
- Design quality enhancement (Becerik-Gerber, Gerber & Ku, 2011)
- Communication amongst the parties involved (Fischer & Kunz, 2004)
- Retention of information and knowledge (Li, Lu & Huang, 2009)
- Improvement of collaboration and integration (Taylor & Bernstein, 2009)
- Inventory management (Hardin & McCool, 2009)
- Construction activity guidance and tracking (Hardin & McCool, 2009)
- Planning prefabrication and modularisation (Lu & Korman, 2010)
- Site planning (Sulankivi, Mäkelä & Kiviniemi, 2009)
- Improvement of safety planning and management (Azhar, Behringer, Sattineni & Maqsood, 2012)
- Constructability analysis and construction planning (Hijazi, Alkass & Zayed, 2009)

From the above, it is evident that BIM has the capability to significantly improve

constructability in a construction project.

2.6.2 Previous studies regarding constructability and BIM

A comprehensive study was undertaken into the most relevant previous studies involving the use of BIM for the improvement of constructability. This was done through the use of a keywords search with the words ‘constructability’ and ‘Building Information Modelling’ in popular databases. The databases used were Compendex, Scopus, Web of Science and Google Scholar. It was found that numerous previous studies had been done on the potential of BIM for improving constructability in construction projects and these are discussed further.

Chen, Xu, Xue, Zhong, Liu and Lu (2017) proposed a physical internet-enabled BIM model which collects and also communicates real-time information regarding a project, to ultimately improve the energy efficiency of prefabricated construction. A prototype was tested on a project in Hong Kong. From this study, it is evident that BIM can be used to improve the efficiency of precast construction.

Mansuri, Chakraborty, Elzarka, Deshpande and Gronseth (2017) presented a methodical approach which leverages data from a structural BIM model and uses it with a cascading tool to generate the formwork schedule for a project. The model estimated the minimum formwork material required, which could also be reused throughout the project, thus ultimately optimising the efficiency of formwork.

Substantial research into the capability of BIM to improve construction waste management has also been done. Construction waste (also known as construction and demolition waste) is the surplus and damaged materials and products which arise from construction, demolition and renovation activities (Roche & Hegarty, 2006). It can thus be concluded that improved constructability leads to the production of less construction waste, directly relating construction waste management (also known as lean construction) to numerous aspects of constructability.

Porwal and Hewage (2012) used BIM as a hub for communicating information regarding the project amongst the various design teams, and then implemented an optimisation algorithm that minimises reinforcement waste. Cheng and Ma (2013) developed a system compatible with BIM that estimates demolition and renovation waste. Lu, Webster, Chen, Zhang and Chen

(2017) proposed a prototypical framework of a computational BIM for construction waste management. The framework consisted of a database of the average waste generation levels for different construction schemes and methods. Other similar studies have also been done focussing specifically on construction waste management. From the various past studies that have been done, it can be concluded that BIM certainly has the potential to significantly improve constructability of construction projects and that further investigation into this area is needed.

With regard to systems which generate a constructability, or buildability, score, the most popular among these are the Singapore Buildable Design Appraisal System (BDAS). The system was developed to measure the impact of the building design on the labour usage. This system generates a buildability score out of 100 points for any given structure. 50 points of the maximum score pertain to the buildability of the structural system used, 40 points pertain to the wall system that was used, and the remaining points pertain to other buildable design features. The system takes into account the amount and types of each of the building elements used and then generates the aforementioned scores by multiplication by an appropriate labour-saving index. For example, if a building is fully precast it would have a labour-saving index of 1.00, but if it only has precast slabs it would have a labour-saving index of 0.75 (*Guide to the Buildable Design Appraisal System*, 2005). In this system, a design with a high buildable score will result in a more efficient usage of labour, therefore resulting in higher labour productivity on site. The entire system is based on principles of simplicity, standardisation and single integrated elements. From this, it can be concluded that the impact of higher levels of standardisation, simplicity and also repetition, have significant impacts in increasing the buildability or constructability.

In a study that was undertaken by Tauriainen, Puttonen, Saari, Laakso, and Forsblom (2014), the authors developed a model which generates a constructability score for a construction project. The model generated a score out of a possible 100 points based on certain constructability aspects. These constructability factors were all general constructability rules or guidelines. These rules pertained to the construction of foundations and footings, the standardisation and repetition of elements, and the handling and characteristics of precast members, joints and connections. The model used a decision-making method called the Analytical Hierarchy Process (AHP), which is discussed in Section 2.7.1, to determine the weights of the different constructability factors (Tauriainen *et al.*, 2014). The user could

personally set the weights of importance of the different constructability factors, which meant that the contractors and designers could collaborate and determine which constructability factors would be the most important for a specific project.

A somewhat similar study was undertaken by Zolfagharian and Irizarry (2017), who identified 79 different constructability attributes to develop a constructability assessment model. The model was aimed at commercial construction projects in the United States. Similarly to Tauriainen *et al.* (2014), this model also incorporated the AHP to generate a constructability score in assessing the constructability of various construction systems and design alternatives. The authors wrote in their conclusion that the next step of the research would be to integrate the model into Building Information Modelling. This should be done to help designers to more easily and quickly explore different design options and to assist designers in improving the constructability of their designs (Zolfagharian & Irizarry, 2017).

From this, the need for the development and implementation of an accurate and practical constructability assessment model in Building Information Modelling is once again confirmed. After the investigation of the study done by Tauriainen *et al.* (2014), it was initially decided that a similar type of model would be developed. The use of a decision-making method to generate a score that represented the constructability of a floor slab after it had been designed in BIM, was considered. The application (or not) of one of these methods is discussed in Section 2.7.7. Research into different decision-making methods that could possibly have been used in the model is reported in the subsection that follows.

2.7 DECISION-MAKING METHODS

Several decision-making methods exist which were considered for use in the generation of an ease-of-constructability score for suspended floor slabs and their supports. As previously mentioned, Tauriainen *et al.* (2014) used the AHP to assist in generating their constructability score. This method, along with other similar available methods, are briefly investigated, followed by the conclusion arrived at regarding the use of a decision-making method for the purposes of this study.

2.7.1 Analytical Hierarchy Process (AHP)

The AHP method takes the different criteria considered for a decision and then does pairwise comparisons, with the use of eigenvectors, to determine the best possible alternative (Sabaei,

Erkoyuncu & Roy, 2015).

A major disadvantage of the AHP method is the significant impact that the chosen relative importance of each criterium has on the resulting score. Another disadvantage is the unreasonably large number of pairwise comparisons that it could require.

2.7.2 Elimination and choice expressing the reality (ELECTRE)

Developed in 1968, ELECTRE is an outranking method that is based on partial aggregation. The basic principle of this method is the ranking of alternatives based on a discordance and concordance index. The index is calculated using data that is extracted from a decision table (Sabaei *et al.*, 2015).

A disadvantage of the method is the fact that the outranking results in the strengths and the weaknesses of the different alternatives not being identified, and also the impacts and results of their use not being verified (Konidari & Mavrakakis, 2007).

2.7.3 Multiple Criteria Decision Making (MCDM)

The MCDM method was developed by Kazaz and Ulubeyli (2009) and is based on the ELECTRE method. It was developed to assist in choosing between different types of construction equipment (Kazaz & Ulubeyli, 2009). The method considers the various corresponding characteristics of the alternatives considered and then ranks them in order of priority.

A disadvantage of the MCDM is the fact that it does not have the option of ranking the various subfactors of the main considerations (e.g. cost), in comparison to each other, but that these subfactors are instead directly compared to the subfactors of other main considerations (Lombard, 2011).

2.7.4 Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE)

Brans and Vique (1985) formulated PROMETHEE to assist in the decision-making between options. The method ranks different options based on their scores, which are calculated for certain chosen criteria. The method is based on outranking and does not eliminate any of the

alternatives, but rather ranks the alternatives according to the chosen criteria and according to the decision-maker's preference.

A disadvantage of the PROMETHEE method is that it requires the assignment of weights, but does not provide a clear method, or even assist in, assigning these weights and relies solely on the ability of the decision-maker to assign weights (Hester & Velasquez, 2013).

2.7.5 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is an approach which aims at identifying alternatives which are not only the closest to an ideal solution, but also the farthest from a negative ideal solution, within a multi-dimensional computing space (Deng, Yeh & Willis, 2000). Using the criteria factors of the options considered, a decision matrix is created, which is then normalised and from here the ranking of the options is calculated using a formula (Lombard, 2011).

A significant disadvantage of the method is that, due to its use of a Euclidean distance, the correlation of the different attributes is not considered (Hester & Velasquez, 2013).

2.7.6 Hybrid decision-making method

The hybrid decision-making method implements the TOPSIS method in assessing the alternatives and then uses the PROMOTHEE method to rank the different alternatives (Razmi & Sangari, 2008). Due to it implementing both the methods, it inherits both the PROMOTHEE method's unclear manner of assigning weights and the TOPSIS method's lack of considering the correlation of the different attributes.

After consideration of the use of a decision-making method to generate a ease-of-constructability score for the designs of suspended floor slabs and their supports, a decision was made regarding its use and is discussed in Section 2.7.7.

2.7.7 The use of decision-making methods

It was initially contemplated to develop a model which would consider all the aspects that would influence the constructability of a floor slab and its supports, and then generate a constructability score. The decision-making methods would then have been used to assist in the generation of the constructability score. There was, however, a concern regarding the use

of these decision-making methods.

The concern was with regard to the actual constructability score calculated. Determining a constructability score by using some formula for a given floor slab and its supports could result in giving an inaccurate representation of the actual situation. The potential concerns could occur as a result of the weights that the user had assigned to the constructability factors. It could potentially be that the factors that the user had initially identified as less important could, in the end, have been the most significant factors. The user could have said, for example, that the availability of resources was the most important factor (which would be an obvious chain of thought for a project in a secluded area) and that the level of standardisation was less important, and when construction commenced, the level of standardisation could be poor and have resulted in the project taking much longer to complete. Also, a certain slab could, for example, could have received a constructability score of 90 out of a possible 100 points. It can be concluded that a designer would think that this would be a high constructability score. The ten points that were lost could potentially have a far more significant impact on overall constructability than initially anticipated.

It was finally decided to not attempt to generate a constructability score and let the constructability analysis process identify potential concerns, no matter their possible significance, and to then notify the user of the software thereof. The user will then be able to use their own judgement in rectifying an concern or ignoring it. Potential ways in which a constructability problem can be rectified could also be given.

2.8 CHAPTER SUMMARY

The need for improved project delivery in the construction industry is becoming increasingly important. Project delivery can be achieved through the minimisation of rework and redesign, both of which regularly result in the reduction of profit margins for engineering consultants and contractors alike. Improved integration of design and construction will result in the saving of both time and money.

Previous studies involving the use of BIM to improve constructability show that BIM can prove to be effective in the improvement of constructability, not only by creating a space where contractors and designers can collaborate in the planning and design of a project, but also by

its adoption to analyse the constructability of a project. It was evident that BIM has the potential to significantly improve constructability and it was decided to focus on improving the constructability of floor slabs and their supports by using BIM.

Decision-making methods can serve as helpful tools in deciding between alternatives, but their use in determining the weights of the different factors involved in constructability to ultimately generate a constructability score has its downfalls. Different decision-making methods exist and were investigated, but it was decided to rather develop a process that identifies possible constructability concerns specifically for a floor slab, instead of generating a constructability score.

Instead of generating a constructability score for a BIM user, it was decided that a BIM process which identified the possible areas, points or characteristics of a slab which could pose concerns in terms of effective constructability, would be more effective. A user would be notified of these possible constructability concerns, or bad constructability practices, during the design phase and the user could then decide on how to approach the rectification of the concern. In this way, no specific concerns are given greater importance, nor is a misperception formed of the overall constructability of the floor slab and its supports.

From the literature study undertaken, it was evident that the constructability of suspended floor slabs and their supports can be improved by focussing on the improvement of a wide range of factors. It was also evident that the decision to focus on suspended floor slabs would fit into studies which have already been done regarding the improvement of constructability with the use of BIM. No previous studies have been done in this regard. Figure 2.4 shows a summary of the identified constructability affecting factors which are applicable to suspended floor slabs, and their supports, and compatible with BIM. Figure 2.4 also shows a summary of the previous similar studies investigated in this chapter.

After completion of the literature study and considering how constructability is influenced by a vast number of factors, the decision was made to develop a process that analyses a suspended floor slab and its supports by pointing out possible problematic areas in terms of constructability. The process is aimed at the most common types of suspended floor slabs used in the South African construction industry. These types would thus have to be investigated. This is reported in the section that follows.

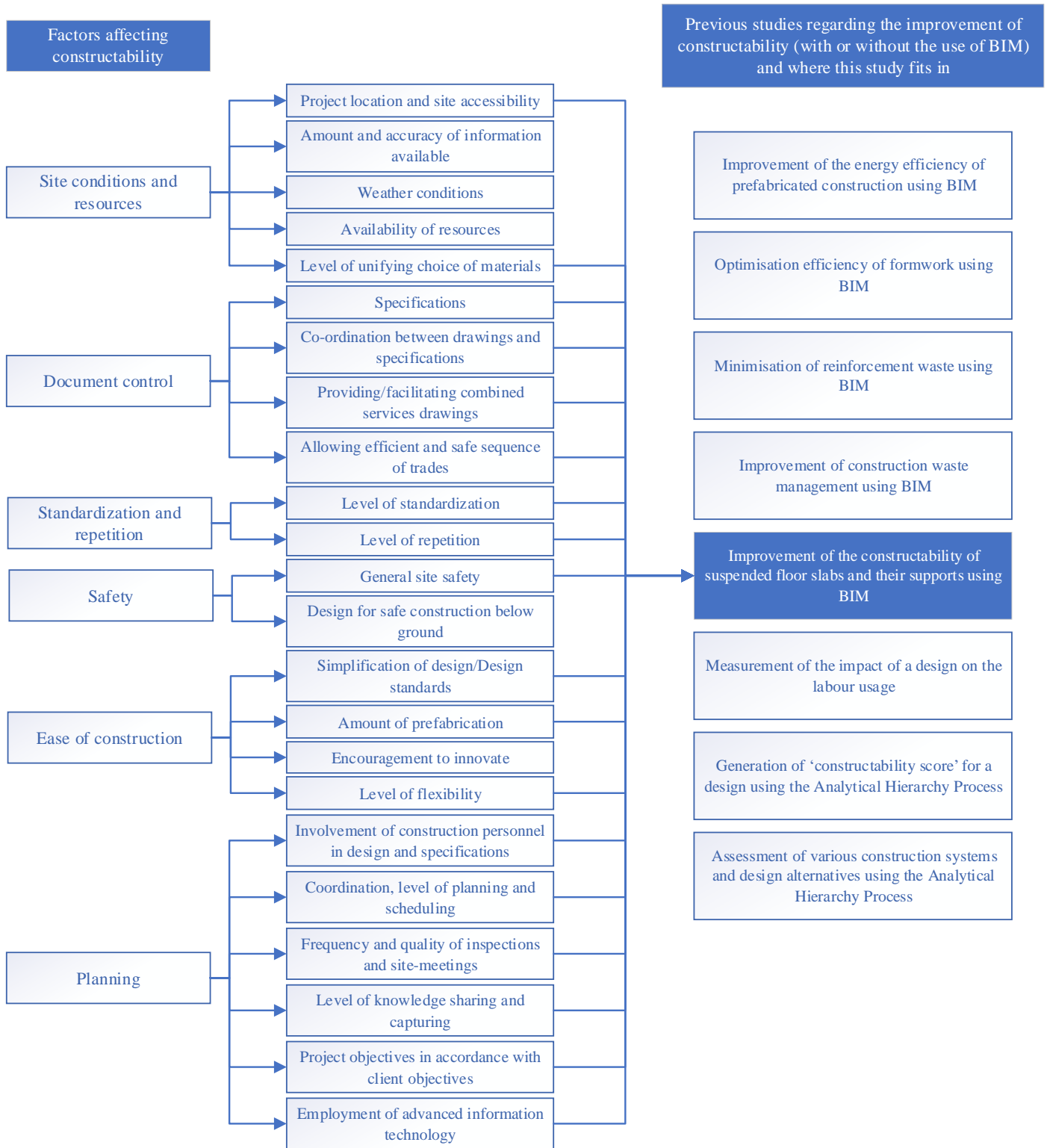


Figure 2.4: Summary of the identified BIM-compatible constructability affecting factors applicable to suspended floor slabs and a summary of previous similar studies investigated

CHAPTER 3

Suspended floor slabs

Figure 3.1 shows the content and the research stage compared to the other chapters.

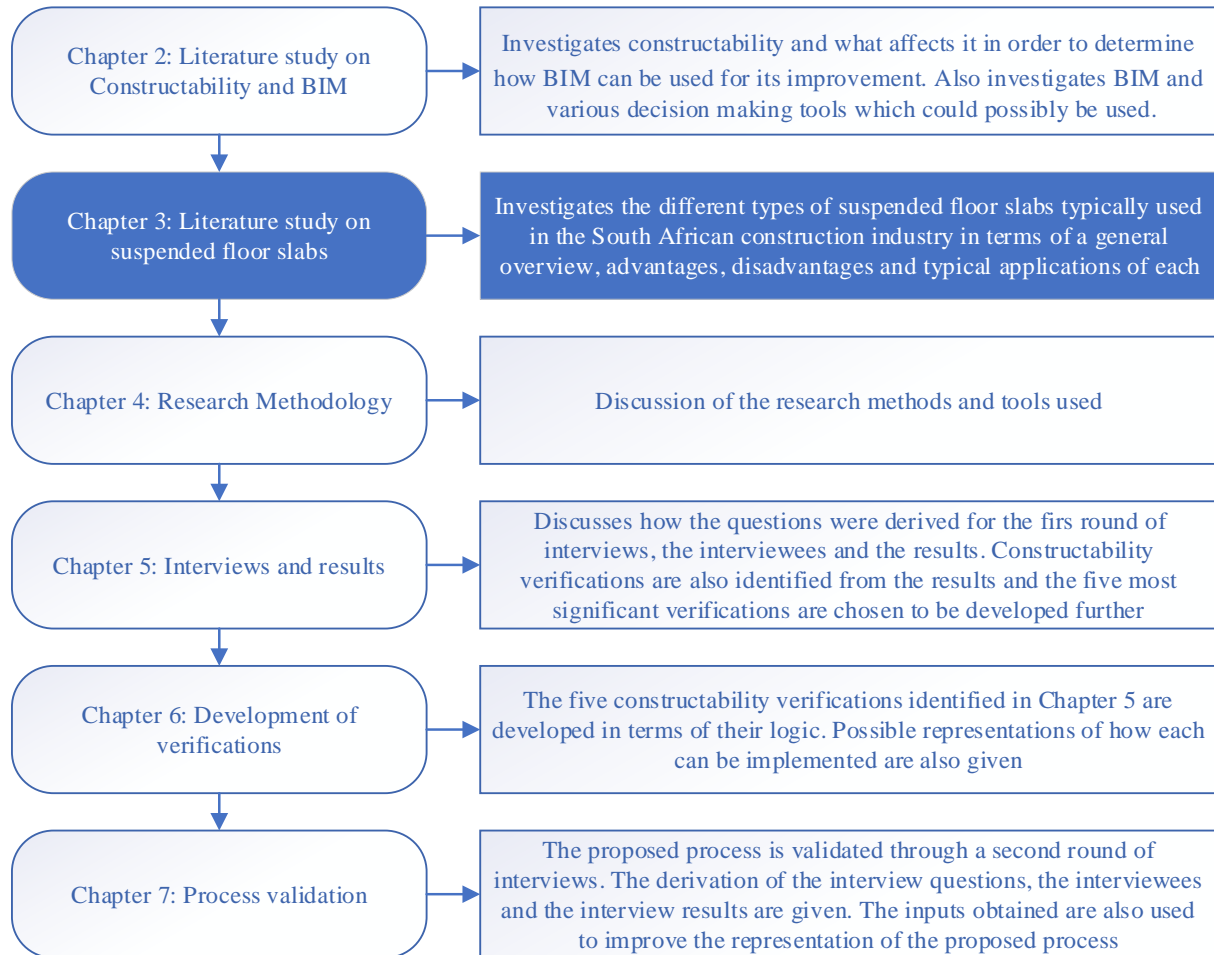


Figure 3.1: The content and research stage of Chapter 3 compared to the other chapters

3.1 INTRODUCTION

Suspended floor slabs are floors which are not in direct contact with the earth. Suspended floor slabs form an essential part of building frames, with the purpose of providing flat and safe useable surfaces. Suspended floor slabs can be supported either by beams, which in turn could be supported by columns, or directly by columns, or by load-bearing walls (Robberts & Marshall, 2010).

The loading imposed on a floor, along with the loading caused by its own weight, are distributed to its supports. The support conditions of a floor slab are an important aspect from

an analysis point of view, as the supports determine how bending moments are distributed and thereby determine a floor slab's structural behaviour (Robberts & Marshall, 2010).

Different types of suspended floor slabs exist, each having its own typical applications, construction methods, advantages and disadvantages. These features, along with descriptions and illustrations of each type, will be further investigated in this chapter. This chapter serves as a literature study into the types of suspended floor slab commonly used in the South African construction industry. The slab types identified are either constructed in-situ using cast concrete, or are precast elements.

The in-situ-cast concrete slab types identified include the following:

- Flat slabs
- One-way spanning slabs
- Two-way spanning slabs
- Coffer slabs
- Post-tensioned slabs

The precast concrete slab types identified include the following:

- Hollow-core slab systems
- Rib and block slab systems

In order to provide the background of suspended floor slabs needed to assist in this research, the aforementioned slab types will now be discussed. The aim of this chapter is to present the most commonly used suspended floor slab types used within the South African construction industry in terms of a general overview of each, advantages and disadvantages associated with each type and their typical applications.

3.2 FLAT SLABS

3.2.1 Overview

The first commonly used suspended floor slab type identified is the flat slab. The name is based on the behaviour of flat slabs, which resembles that of flat plates (Anitha, Rahman & Vijay, 2007). Flat slabs are supported by columns and the loads on the slab are distributed from the slab to the supporting columns. Flat slabs are constructed by pouring and compacting in-situ-cast concrete onto formwork where the required reinforcement has already been placed in the

desired position. Variations exist of the connections between the horizontal slab and the supporting columns of flat slabs (Robberts & Marshall, 2010).

The most common types of flat slab are shown in Figure 3.2. The first type of flat slab is the regular flat slab, which consists of only the horizontal slab and the supporting columns. The second type of flat slab commonly used, is a flat slab with drop panels. The purpose of the drop panels is to increase the shear strength and negative moment capacity of a slab and to reduce deflection by stiffening the slab. This can lead to an increase in the cost-effectiveness of a flat slab. Another type of flat slab is a flat slab with column heads. The purpose of column heads is to also increase the shear strength of a slab, but also to reduce the moment in a slab by reducing the effective or clear span of the slab (Jain, 2017). Flat slabs can also be built which have both drop panels and column heads, combining the advantages, and disadvantages, associated with each.

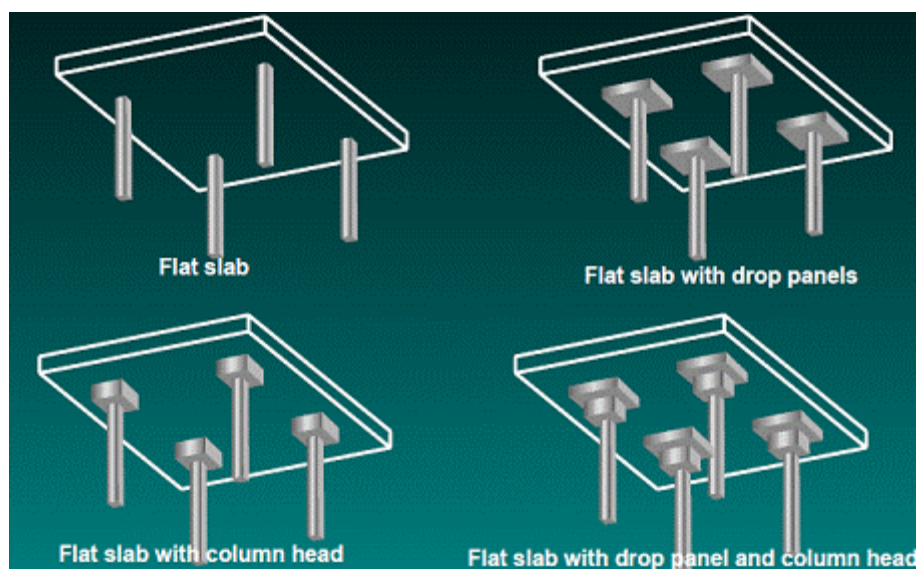


Figure 3.2: Flat slab types (Anitha, Rahman & Vijay, 2007)

3.2.2 Advantages and disadvantages

Flat slabs without drop panels or column heads can be constructed at a relatively fast pace, as the framework needed is simplified. Flat slab systems can significantly reduce the floor-to-floor height, resulting in lowering the overall building height and effectively producing more floors, or useful space, for lower building heights. Flat slabs have also been found to be relatively flexible in terms of late changes in design. Because flat slabs have no beams, a flexibility is given in terms of partitioning and services channelling, which makes them very popular. Flat slabs also have the added benefit of creating the possibility of adding architectural finishes directly to the underside of the slab (Jain, 2017).

Flat slabs do, however, have certain disadvantages which might make designers opt for another slab type. Deflections, punching shear and any holes in the flat slab around the slab-column connections can cause significant structural problems (Goodchild, 1997). Due to these potential problems, drop panels or column heads might be required, which in turn complicates formwork, resulting in additional costs and time which might defeat the purpose of installing flat slabs by reason of their fast construction.

3.2.3 Typical application

As most flat slabs are easy and quick to construct, having no beams and allowing for easy service distribution, they are popular for use in offices, hotels, hospitals and flat blocks. Flat slabs are very economical for square, or almost square, panels with spans between 5 and 9 m (Goodchild, 1997).

3.3 ONE-WAY SLABS

3.3.1 Overview

Another commonly used slab type is the one-way spanning slab. One-way spanning slabs are the most basic slab form (Goodchild, 1997). Like flat slabs, one-way spanning slabs are also constructed in-situ with cast concrete poured and compacted onto formwork, where the desired reinforcement is already placed into position. One-way spanning slabs are named according to the way loads are transferred in them. Consider a slab that is supported by beams, or walls, on two opposite edges (See Figure 3.3). If a load is to be applied to the centre of the slab, the load would be distributed to the opposite beams through bending moments which develop within the slab. Reactions and shear forces at supports are calculated by considering a strip of the slab (running perpendicular between the two opposing beams) as a beam and using simple statics. In a similar manner, the loads in the beams would be transferred to the columns. Because the slab only transmits the loads in one direction, the slab is commonly referred to as a one-way spanning slab (Robberts & Marshall, 2010).

One-way spanning slabs and two-way spanning slabs (discussed in Section 3.4) can be very similar and the general rule for differentiating between the two types is by the long span to short span ratio. Considering a rectangular one-way or two-way spanning slab, if the longer span is equal to, or more than, twice the length of the shorter span, it can be considered a one-way spanning slab. This is because of the slab then bending in one direction only (or mostly),

which is the direction along the shorter span. Minimum reinforcement, also known as distribution steel, is however still provided along the longer span, in order to distribute the load evenly and to resist shrinkage and temperature stresses (Krishna, 2017).

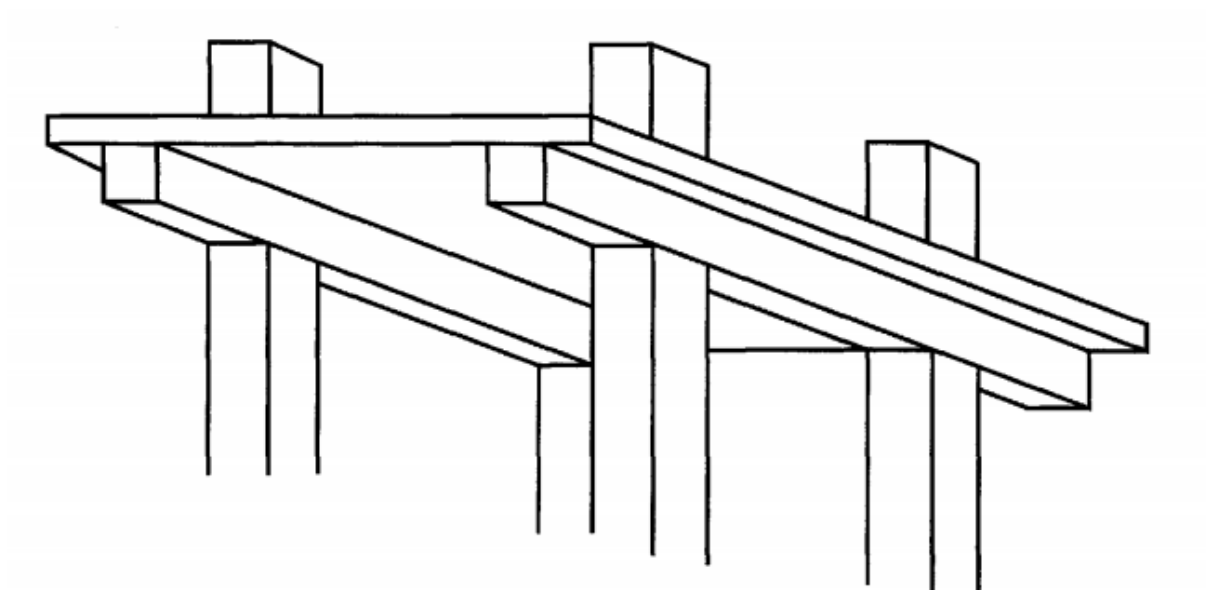


Figure 3.3: One-way spanning slab (Bing, 2014)

3.3.2 Advantages and disadvantages

The most significant advantages associated with one-way spanning slabs are their simplicity of design and construction and their flexibility in terms of the placement of holes for service placement or for other uses. The placement of holes in one-way spanning slabs causes relatively few structural problems (Goodchild, 1997).

The down-stand beams associated with one-way spanning slabs are the source of most problems associated with these slabs. Their down-stand beams might require greater storey heights, decrease the cycle speed of formwork erection and also reduce the level of flexibility in terms of the location of partitions and the distribution of horizontal services (Goodchild, 1997).

3.3.3 Typical application

One-way spanning slabs are most often used for utilitarian purposes in warehouses, retail developments, office buildings, stores and similar types of buildings. They can be economical for spans between 4 and 8 m (Goodchild, 1997).

3.4 TWO-WAY SLABS

3.4.1 Overview

Two-way spanning slabs are very similar to one-way spanning slabs, differing in only certain aspects. Figure 3.4 is an illustration of a two-way spanning slab. They, similar to flat and one-way spanning slabs, are also constructed in-situ-cast with concrete poured and compacted onto formwork where the required reinforcement is already placed into position. Two-way spanning slabs are supported on beams (or walls) along all four edges. A load applied to a two-way spanning slab would also be distributed to the supporting beams and then to the columns supporting the beams, as with one-way spanning slabs. Two-way spanning slabs under a distributed load would have a deflected form with curvatures in two perpendicular directions. Due to bending moments being proportional to curvature, bending moments would thus occur in two perpendicular directions. Due to this phenomenon, these slabs are referred to as two-way spanning slabs (Robberts & Marshall, 2010).

Due to the bending moments occurring in two perpendicular directions, reinforcement is therefore required in both directions in a two-way spanning slab. One-way spanning slabs could also have beams along all four edges, but a slab is typically considered a two-way spanning slab when the long span to short span ratio is less than two, as mentioned in Section 3.3.1 (Krishna, 2017).

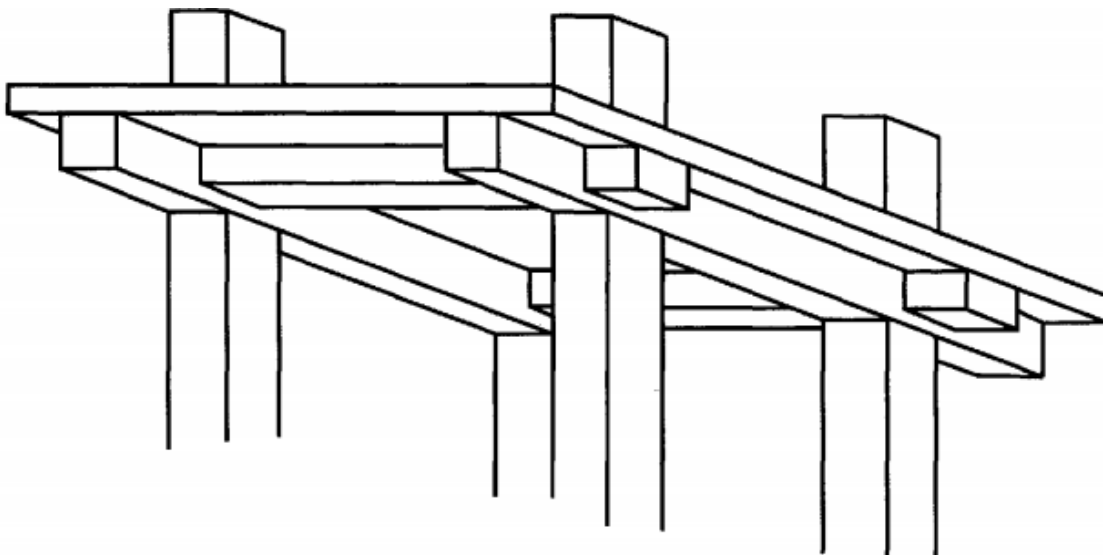


Figure 3.4: Two-way spanning slab (Bing, 2014)

3.4.2 Advantages and disadvantages

Two-way spanning slabs are economical for relatively longer spans and they have the added benefit of being more economical in the handling of higher loads as well. Two-way spanning

slabs are, however, less simple in design and have even less flexibility in terms of partition placement and horizontal service distribution than one-way spanning slabs. The presence of beams might require a greater storey height, resulting in the reduction of vertical height efficiency. Due to the way two-way spanning slabs are designed, a regular column layout is required, which reduces flexibility in terms of floor layout. The down-stand beams used by two-way spanning slabs also prevent fast formwork cycles (Goodchild, 1997).

3.4.3 Typical application

The characteristics of two-way spanning slabs make them utilitarian, good for use in warehouses, retail developments, stores and similar building types. This is because of their capacity to carry relatively high loads, which makes them practical for use in areas where items will be stored. Two-way spanning slabs are economical in span ranges of between 9 and 12 m (Goodchild, 1997).

3.5 COFFER SLABS

3.5.1 Overview

A coffer slab (also known as a waffle slab) is a slab type which has holes in its soffit, which gives it the appearance similar to a waffle. Coffers slabs consist of concrete beams in several rows which are constructed at right angles to each other. They are also constructed in-situ, using cast concrete poured and compacted onto formwork where the required reinforcing is placed into position beforehand. Reinforcement is typically provided between the holes and steel meshing on top of the holes. The hollows between the beams are formed by placing Polymerizing Vinyl Chloride (PVC) trays (also known as pods) into the desired positions before concrete pouring commences. The trays are usually tapered to assist in their removal (Krishna, 2017).

The most commonly used types of coffer slabs are shown in Figure 3.5. Different shapes of pods can be used, but the most significant difference between the different types used is the location or presence of beams. The first type (slab illustration on the left of Figure 3.5), is known as a coffer slab with integral beams. The indentations directly between columns are omitted and these areas act as normal beams. The second most commonly used type (slab illustration on the right of Figure 3.5), is the basic coffer slab and is designed as a flat slab (Goodchild, 1997).

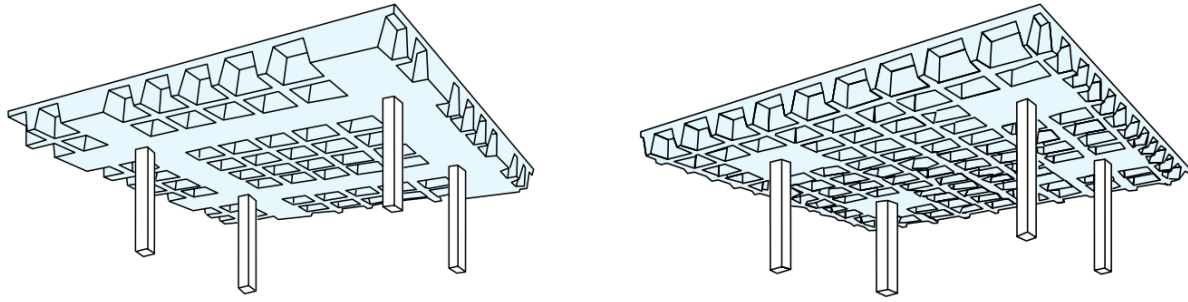


Figure 3.5: Coffers slabs (Goodchild, 1997)

3.5.2 Advantages and disadvantages

Due to coffer slabs being lighter in weight because of the indentations incorporated into them, they are able to span longer distances and carry relatively heavier loads than flat slabs. Another advantage resulting from their indentations, is the significant amount of savings in terms of material needed (Krishna, 2017). Their waffle-like appearance could also give them an added aesthetic characteristic if it is preferred (Goodchild, 1997).

The construction of coffer slabs is however relatively costly due to the extra trays that are required and the higher level of skilled labour that is also required (Krishna, 2017). Their construction is also a very cumbersome process and the placement of their reinforcement can be difficult (Goodchild, 1997).

3.5.3 Typical application

Coffer slabs are typically used in areas where large spans are required to avoid the interference of columns with the required space. This makes them popular for use auditoriums, cinemas and lobbies (Krishna, 2017). They are economical in square panels with spans of up to 12 m (Goodchild, 1997).

3.6 POST-TENSIONED SLABS

3.6.1 Overview

Post-tensioning is a technique which preloads concrete in a way which reduces, or even eliminates, tensile stresses induced by live and dead loads. Concrete is compressed using high strength tensioned steel strands which are placed in metal ducts (also known as tendons) and is arranged to pass through the floor or roof concrete slab. Figure 3.6 is a photograph showing how these strands are arranged prior to concrete pouring. The strands are grouped in sets and

when the poured concrete has hardened to a satisfactory level, the sets of strands are gripped by a hydraulic jack which is then used to tension the strands to a certain predetermined force. After the strands have been tensioned, they are anchored at each end to ensure that the tensioning in the strands remains (Kumara, 2011).



Figure 3.6: Post-tensioned slab prior to concrete pouring (Post-tensioning, n.d.)

The post-tensioning of concrete provides a solution to overcome the natural weakness of concrete to resist tensile forces and further, to make better use of concrete's strength in compression. If the strands are curved to a desired profile and anchored appropriately, they will exert beneficial upward forces which will counteract the loads applied. An appropriate curve and anchorage will also exert compression on the perimeter of the member, which complements concrete's natural compressive strength. Figure 3.7 shows an illustration of the shape of an appropriate strand profile.

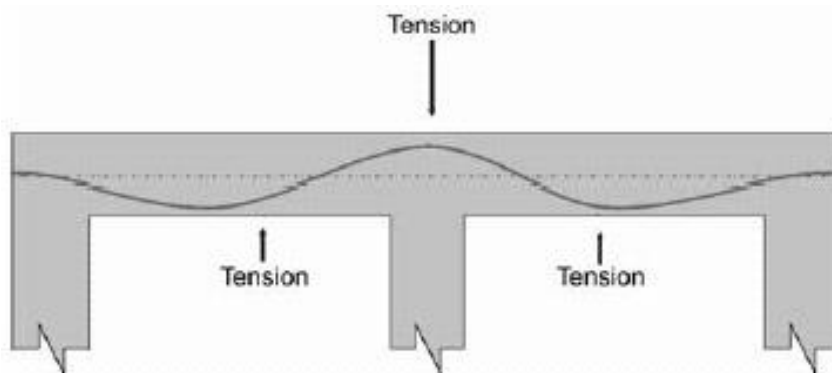


Figure 3.7: Strands profile (Vasshaug, 2013)

3.6.2 Advantages and disadvantages

Post-tensioned floors offer a range of advantages which can result in post-tensioned slabs being chosen over in-situ-cast reinforced concrete floor slabs. These advantages include (Kumara, 2011):

- Longer clear spans can be achieved
- Thinner slabs, resulting in more effective use of height
- Lighter structures
- Less cracking from shrinkage than regular in-situ-cast slabs
- Reduction in deflection
- Enhanced water tightness
- Fewer construction joints
- Decreased scaffolding costs

There are, however, also certain disadvantages associated with post-tensioned slabs, which could be significant enough to turn the decision against their implementation. These disadvantages include (Kumara, 2011):

- The services of trained operatives are needed, which results in additional people operating on site
- Additional work, such as hole drilling in shuttering and fixing of anchorage blocks is required on site
- Special tools and materials are required, such as stressing jacks, ducts, strands and anchorages
- Additional risks arise during the stressing of strands
- Undesired vibrations due to a lighter and thinner slab

3.6.3 Typical application

Due to their advantages of reduced slab thickness and enhanced deflection and cracking control, post-tensioned slabs are popular for use in car parks and office buildings. It should be noted that post-tensioned slabs differ in terms of variations in beam placement or the addition of ribs to the slabs themselves, which could increase or decrease the economical span ranges. Post-tensioned slabs are typically most economical in span lengths of between 9 and 18 m (Goodchild, 1997).

3.7 HOLLOW-CORE SLABS

3.7.1 Overview

The first precast slab type used in the South African construction industry to be described is the hollow-core slab. A hollow-core slab is a concrete member which is precast and also contains continuous voids which reduce its weight. Both attributes therefore contribute to reducing its cost. Hollow-core slabs are used primarily as floor or roof decking systems but can also be used as wall panels or bridge decking units (Buettner & Becker, 1998) .

Two basic variations of the hollow-core slab that are commonly used are either the normal hollow-core slabs or the pre-stressed hollow-core slabs, which are made with prestressing strands. The strands used in hollow-core slabs may include just about every type and size of strand produced, but the trend leans toward the use of strands of relatively large diameter and low relaxation (Buettner & Becker, 1998).

These slab systems will typically either be manufactured in a factory with a production line or on the site where they are to be used. Variations also exist in terms of the shape of the cores (voids). Structural topping will usually be cast on top of the slab element after it has been placed in position. Figure 3.8 shows a typical cross-section of a hollow-core slab (Buettner & Becker, 1998).

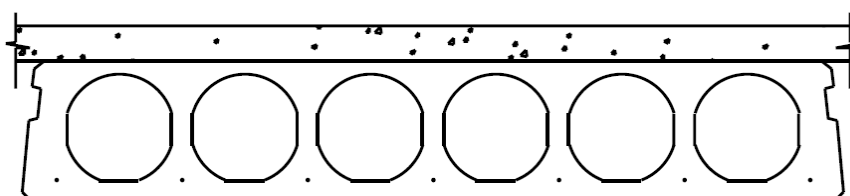


Figure 3.8: Hollow-core cross-section with structural topping (Buettner & Becker, 1998)

3.7.2 Advantages and disadvantages

Hollow-core slabs are known for being economical and efficient roof and floor systems. Their installation is relatively fast in comparison with in-situ-cast slab systems and they also require significantly less, if any, formwork or propping. They can be used for a wide range of spans and they can carry a relatively high amount of loading (Goodchild, 1997). Depending on the strand thickness and strand cover, it has been proven that hollow-core slabs achieve excellent fire ratings. Ratings as high as 4 hours have been achieved. It has also been proven that hollow-core systems have excellent sound transmission characteristics (Buettner & Becker, 1998).

A crane is, however, a necessity during the installation process of hollow-core slabs. Cranage can prove to be critical in the use of hollow-core slabs and might cause a contractor to opt for some other slab system (Goodchild, 1997). The necessity for hiring a crane, or cranes, and the acquisition of hollow-core slabs, infer costs which could make a hollow-core slab system, even with the elimination of formwork, a less economical slab system choice. The possibility also exists that a project could be too far from the nearest hollow-core supplier to make their use economical. Hollow-core slabs also require either walls or beams as supports, which can impact construction progress and floor-to-floor heights.

3.7.3 Typical application

Because hollow-core slab systems are economical across a relatively wide range of loadings and spans, they are used in a wide range of building types. They are popular for use in flats, office blocks, hospitals, factories, hostels, hotels, schools, townhouses, shopping malls, car parks and even for water reservoir roofs. Hollow-core systems typically come in thicknesses of between 110 mm and 250 mm, widths of 1,2 m and in lengths up to 11 m, depending on what is required. Standard increments between these ranges are typically offered by manufacturers, but specific lengths, thicknesses and widths can also be manufactured as required (*Hollow-core slab systems*, 2008).

3.8 RIB AND BLOCK SLABS

3.8.1 Overview

The second, suspended precast slab type, is the rib and block slab system, also known as the beam and block slab system, which is a one-way spanning flooring system. The system consists of pretensioned and reinforced precast concrete ribs which support concrete filler blocks. The filler blocks can also be made of burnt clay, shale, fired briquettes or expanded polystyrene blocks. A meshed structural topping would typically be applied to the top of the slab (Khuzwayo, 2015). Figure 3.9 is an illustration of a typical 200 mm rib and block slab system.

Temporary propping underneath the slab systems would generally be provided for longer spans until the full composite action has been developed. The propping is typically provided underneath the ribs, as they are carrying the load from both the structural topping and the blocks (Khuzwayo, 2015). Figure 3.10 shows a typical propping layout

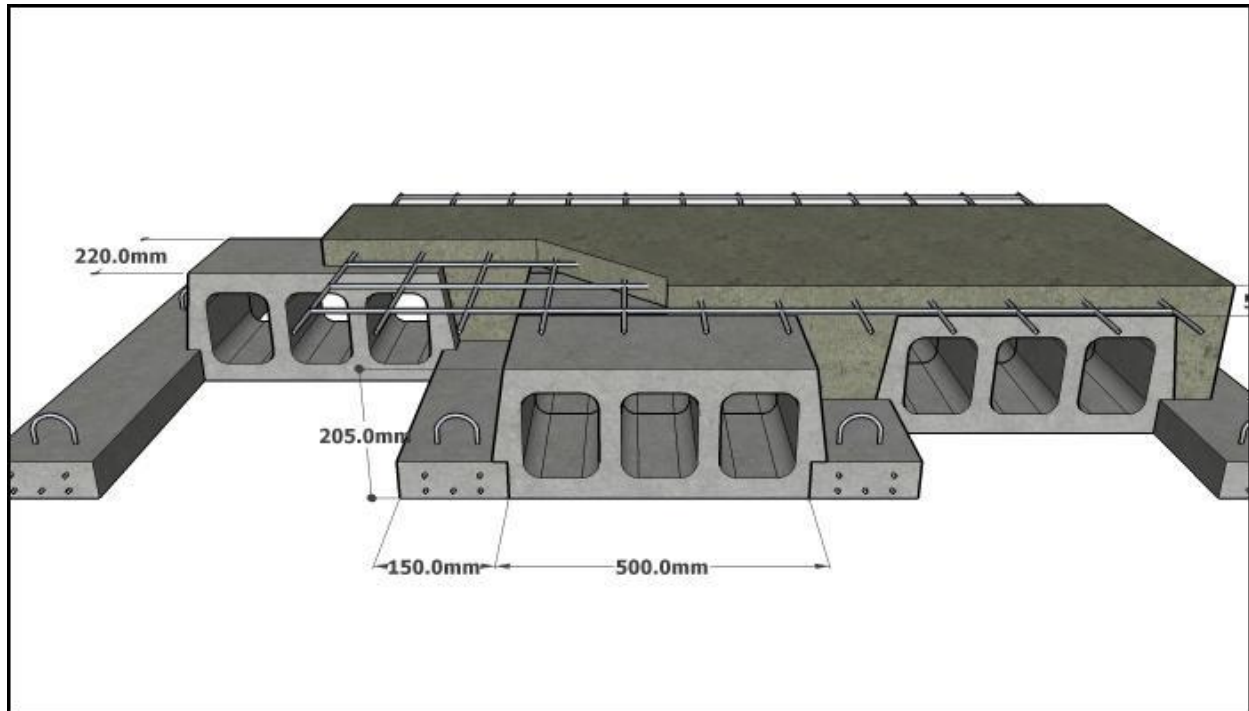


Figure 3.9: Typical 200 mm rib and block slab system (Nyati Slabs South Africa: 200 mm Rib and Block, n.d.)



Figure 3.10: Propping of a conventional Rib and Block system (Nyati Slabs South Africa: Rib and block propping, n.d.)

3.8.2 Advantages and disadvantages

Rib and block slab systems have been proven to be economical and structurally sufficient for medium length spans and a versatile alternative to the conventional in-situ-cast reinforced concrete slabs. Rib and block systems are easy to install, requiring a minimum amount of

equipment. They can be manhandled and are ideal for use in areas with restricted access. They also eliminate the need for formwork and the minimum, if any, propping is typically required (Goodchild, 1997).

Their spans and load capacity are, however, limited to certain ranges, which could make their use unsuitable for a number of applications (Goodchild, 1997). The effects of differential shrinkage have been identified in both continuous and simple spans and this could prove to be concerning (Khuzwayo, 2015).

3.8.3 Typical application

Rib and block systems are popular for use in residential, industrial and commercial building schemes. They have been proven to be structurally sufficient and economical for spans up to 7.5 m. The systems normally cater for slab thicknesses of 150, 170, 200 and 255 mm. The 170 mm and 255 mm thick slabs are convenient, as they are at typical brick height increments, making them especially popular for residential use. The most common rib spacings are 560, 600 and 650 mm (Khuzwayo, 2015).

3.9 CHAPTER SUMMARY

The aim of this chapter was to present the most commonly used suspended floor slab types used in the South African construction industry. Five different types of in-situ-cast slab and two different precast slab types were investigated in terms of their general characteristics, construction, advantages, disadvantages and application. Some of the slab types can be found in different forms or variations, but only the general characteristics of each type were investigated. It should be noted that other slab types could possibly be found in South Africa, but considering that these are the most common types used, these were chosen to be investigated.

A summary of the typical applications and typical span lengths for each slab type is shown in Table 3.1. These factors are to be considered when a choice is made for a specific slab type. The typical applications of the different slab types are often the same, which could make the span lengths the decisive factors in the choice of slab type.

Table 3-1: Summary of the typical applications and span lengths for the different slab types investigated

Suspended floor slab type	Typical application	Typical span lengths
Flat slab	Offices, hotels, hospitals and flat blocks	5 to 9 m
One-way spanning slab	Warehouses, retail developments, office buildings and stores	4 to 8 m
Two-way spanning slab	Warehouses, retail developments, stores and storage facilities	9 to 12 m
Coffer slab	Auditoriums, cinemas and lobbies	Up to 12 m
Post-tensioned slab	Car parks and office buildings	9 to 18 m
Hollow-core slab	Flats, office blocks, hospitals, factories, hostels, hotels, schools, townhouses, shopping malls, car parks and water reservoir roofs	Up to 11 m
Rib and block slab	Residential, industrial and commercial building schemes	Up to 7.5 m

The information gathered in this chapter will serve as background knowledge to assist in the interviews which will be conducted to gather the necessary constructability information, including problems pertaining to these suspended slab types (see Chapter 5 for the description of the interviews conducted). It was deemed important that the interviewer should have some general knowledge regarding the suspended slab types before the interviews were conducted, in order to make the interview process as effective as possible and to also assist in designing the questions to be asked during the interview to be as realistic and applicable as possible.

The interviews, along with all the research instruments used in this research project, are described and discussed in the following chapter on the methodology followed.

CHAPTER 4

Research methodology

Figure 4.1 shows the content and the comparative research stage of Chapter 4.

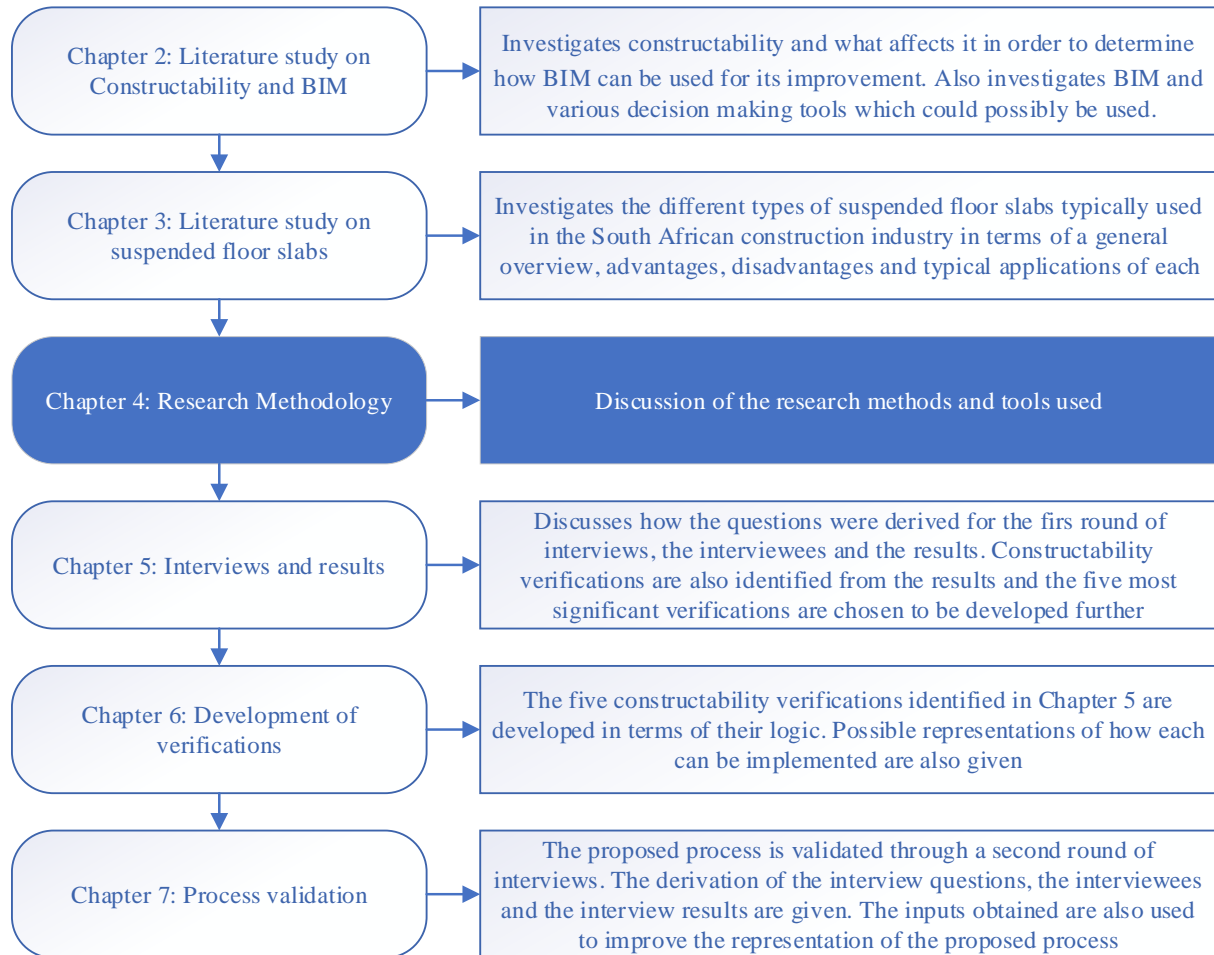


Figure 4.1: The content and research stage of Chapter 4 compared to the other chapters

4.1 INTRODUCTION

The research methodology used in this study is presented in this chapter. The chapter gives an overview of the research approach used in order to enable the reader to form a clear understanding of the process followed. General research methodologies are investigated and discussed and the information is used to determine an appropriate research methodology for this research. The reasons for using each of the specific methodology types is also discussed.

A combination of research instruments was used to achieve the aim of this study. This chapter describes the different research instruments, along with the objectives of each and mitigation

and contingency plans for the disadvantages associated with each. An overview of the entire interview process used to collect the data required, and to validate the study, is also described. The results of the interviews are given in Chapters 5 and 7.

4.2 RESEARCH METHODOLOGY OVERVIEW

An overview of the research methodology used is presented in brief, whereafter the motivation and research instruments used is described in the sections that follow. This is done first in order to provide the reader a background into what was done. A mixed-method design approach is used in this study, which is aimed at the development of a constructability analysis process. Figure 4.1 shows the research methodology used to gather information regarding constructability. The entire process was divided into four phases (as labelled in Figure 4.2).

During phase 1, a desktop study was conducted to identify factors which affect the constructability of suspended floor slabs and their supports. The desktop study comprised of a literature study, a case study by Wium (2013) and a thesis by Kuo (2012). The case study and thesis are further discussed in detail in Section 5.2. The factors, which are also shown under phase 1 in Figure 4.2, were divided into two separate groups for each source. The factors were seen as being either able to be implemented in BIM or being project-specific parameters.

During phase 2, a first round of interviews was conducted with eight experienced contractors. The aim of the interviews was to identify the constructability verifications which can be implemented in BIM. The factors which were identified as BIM-implementable during phase 1, were used to derive the questions asked during the first round of interviews. From the information gathered through the interviews, constructability problems associated with the construction of suspended floor slabs were identified. From this, all the useful constructability verifications which are BIM-implementable were developed.

During phase 3, five verifications were chosen from the list of verifications identified in phase 2 by using two criteria. Only the verifications which received the highest scores using the criteria were developed. The verifications were explored to assist in the development of the proposed constructability analysis process. These five verifications were developed in terms of the logic behind their implementation within a constructability analysis process. The development of each of the five verifications was supplemented by the use of flow diagrams,

examples and representations of their possible implementation within Autodesk Revit.

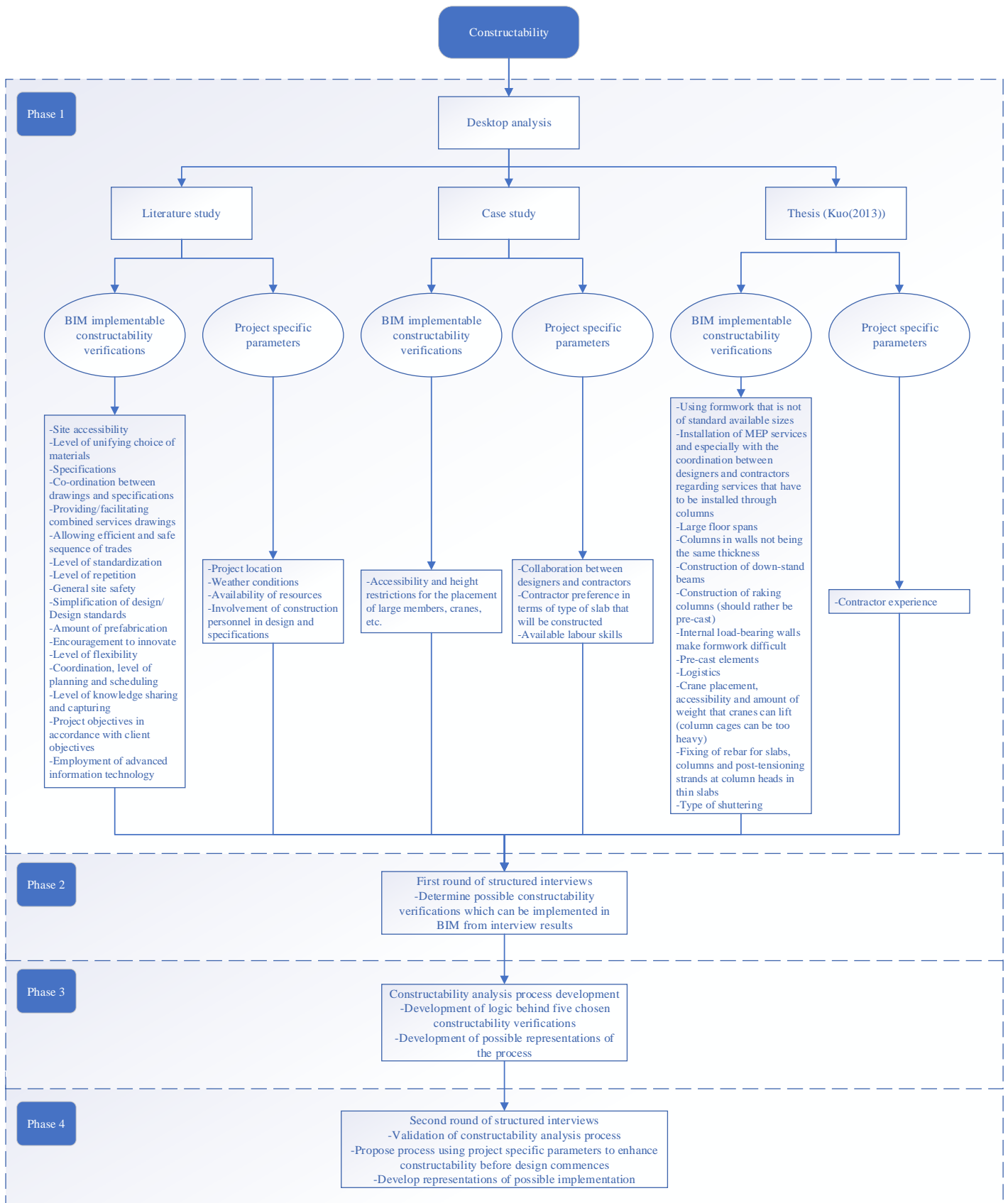


Figure 4.2: Research methodology overview

In phase 4, the five constructability verifications developed were validated through a second round of interviews with six experienced consultants. The consultants' preferences in terms of the implementation of the proposed constructability analysis process was also obtained. The project-specific parameters identified during phase 1 were used to also propose an added process to the consultants in which project-specific parameters were considered before a design commenced. The added process aimed to increase the consideration of project-specific parameters before a design is undertaken. Their opinion of such a process was obtained.

The preferences of the consultants were used to further develop the constructability analysis process, along with the process which considered project-specific parameters.

4.3 METHODOLOGY CLASSIFICATION

4.3.1 Overview

Kothari (2004) defined research as using a scientific and systematic approach towards searching for pertinent information regarding a specific topic. Research methodology refers to the way, or route, a researcher will follow in order to achieve a certain goal (Jonker & Pennink, 2010). Research Methodologies can be classified into different types. Kothari (2004) classified research types into groups which each contain two opposing research methods. These groups are the following:

- Descriptive versus Analytical Research
- Applied versus Fundamental Research
- Quantitative versus Qualitative Research
- Conceptual versus Empirical Research

These groups will now be investigated further whereafter the methodology types used will be determined.

4.3.1.1 Descriptive versus Analytical Research

Descriptive research can be described as a process that consists of fact-finding enquiries of various kinds, with the major purpose of descriptive research being the identification of the current state of matters. The main characteristic of descriptive research is the fact that the researcher has no control over the associated variables and can only report on what has happened or what is currently happening. The methods most commonly used in descriptive

research are surveys or questionnaires (Kothari, 2004). Analytical research, on the other hand, includes the use of existing facts and information, and the analysis thereof, in order to make a critical assessment of the available material (Vermeulen, 2014).

In this study, both a descriptive and analytical research approach was used. The research done with regards to constructability improvement through the use of BIM needed to be investigated. Existing facts and information was also used to make an assessment of the available material.

4.3.1.2 Applied versus Fundamental Research

Applied (or action) research is aimed at identifying or finding a solution, in order to resolve an immediate pressing problem facing a society, industrial organisation or business organisation. Fundamental research, however, is primarily concerned with generalisations and formulation of theory (Kothari, 2004).

An example of fundamental research is those concerned with a natural phenomenon, research that relates to pure mathematics, or research studies that concern human behaviour. Examples of applied research would be research which is aimed at making certain conclusions that apply to a concrete business or social issue, and also research that identifies social, political or economic trends that could affect a specific institution.

The principle aim of applied research is thus to develop a solution to an immediate practical problem, whereas fundamental research (also known as basic research) is directed towards discovering information that has a broad range of applications that adds to the existing scientific body of knowledge (Vermeulen, 2014).

In this study a solution was sought for the current poor integration of constructability information during the design phase of construction projects (Tatum *et al.*, 1986) and this led to an applied research approach being used.

4.3.1.3 Quantitative versus Qualitative Research

Quantitative research aims to collect and analyse numerical data of phenomena through the measuring of scales, frequencies, ranges, etc. It is based on measuring quantity or amount and is thus only applicable to phenomena expressible in terms of quantity (Kothari, 2004).

Qualitative research, however, is concerned with phenomena that are of a qualitative nature, meaning phenomena that involve quality or kind. It aims at identifying underlying desires or motives, often through the use of in-depth interviews, word association tests, sentence completion tests and other similar projective techniques (Kothari, 2004). Qualitative research examines and reflects on the less tangible aspects associated with a research project. These are aspects such as values, perceptions, attitudes, etc. The results from a qualitative research study can often be difficult to interpret and are easily challenged (Vermeulen, 2014).

This study aimed to determine the underlying reasons for poor constructability of suspended floor slabs and their supports, thus resulting in a qualitative research approach being followed.

4.3.1.4 Conceptual versus Empirical Research

Conceptual research is a process that is related to abstract ideas or theory. It is most often used by philosophers and other thinkers in the development of new concepts or the reinterpretation of existing concepts. Empirical research relies only on observation or experience, and often without regard for theory and system. It is a data-based research method that presents conclusions that can be verified by experiment or observation. Empirical research can also be seen as an experimental type of research (Kothari, 2004).

In this study the experience of contractors and consultants were relied upon for the development of the proposed constructability analysis process, which resulted in the use of an empirical research approach being followed.

4.3.2 Motivation for methodology types chosen

Considering the problem statement and the identified aims and objectives (see Chapter 1), the research methodology types used for this research were chosen. The motivation behind the types chosen is discussed.

The nature of the problem is to find a solution for the poor integration of constructability information within the design phase of construction projects. The solution was sought by determining which factors affect constructability from literature, contractors' experience with the construction of suspended floor slabs and consultants' preferences for the implementation of a constructability analysis process. Therefore a combination of descriptive, analytical,

applied, qualitative and empirical research methods were chosen.

A literature study on constructability, BIM, constructability's compatibility with BIM and previous similar studies was presented in Chapter 2. Chapter 3 could also be classified as a literature study, presenting literature on the different types of suspended floor slabs used in South Africa.

An analytical research method was used in these chapters because existing facts and information needed to be used to make an assessment of the available material. As information needed to be investigated which could assist in resolving a problem facing the construction industry, an applied methodology was also chosen. The problem facing the construction industry refers to the poor coordination between consultants and contractors (Alaloul, Liew & Zawawi, 2016).

In order to determine the factors which affect the constructability of suspended floor slabs, a case study and available literature was used. The factors were used to derive the questions for the first round of interviews. The aim of the interviews was to determine constructability problems encountered with the construction of suspended floor slabs and their supports. In Chapter 5, the process is presented which was used to derive the questions. The case study used is presented, along with the information on constructability problems identified by Kuo (2012). The questions that were formulated are given, along with the results from the interviews.

A descriptive and applied methodology was chosen as the methodology used in Chapter 5 because the current state of matters with regards to the constructability of suspended floor slabs needed to be determined. An applied methodology was chosen because a solution needed to be found for an immediate pressing problem. This problem was the poor integration of constructability information within the design stage (Kuo & Wium, 2014). A qualitative methodology was chosen, as interviews had been identified as an effective research instrument for obtaining tacit knowledge, regarding the constructability of suspended floor slabs, from experienced contractors. The empirical methodology was also chosen because the verifications which formed part of the constructability analysis process would be based on the experience of consultants from the first round of interviews.

In Chapter 6, there is a description of five identified constructability verifications being

developed. The development is done in terms of the logic of the software required for the programming of the proposed constructability analysis process.

An applied research methodology was chosen for the research described in Chapter 6, as the aim was to solve an immediate pressing problem through the development of the proposed constructability analysis process. An empirical methodology was also chosen because the proposed constructability analysis process was based on the experience and observations of consultants with regard to the constructability of suspended floor slabs and their supports.

The validation of the study is discussed in Chapter 7. Inputs were obtained from the consultants in the second round of interviews on how they would prefer the proposed constructability analysis process to be implemented. The responses were analysed and discussed. The input of the consultants was used to develop further possible representations of the implementation of the proposed process.

An applied research approach was chosen for Chapter 7, because Chapter 7 aimed to develop a process to resolve a current problem. The development of the process relied on the experience and observations of consultants, which was done using an empirical research type.

4.4 RESEARCH INSTRUMENTS

Research instruments are devices or methods used to obtain relevant information regarding a specific research project (Wilkinson & Birmingham, 2003). There are numerous alternatives to choose from, but only the following types were chosen for this research project:

- 1) Desktop analysis
- 2) Case Studies
- 3) Structured Interviews

These methods are discussed in the subsections that follow. Each instrument is presented in terms of a description, the objectives associated with its use, and mitigation or contingency plans for its associated disadvantages.

4.4.1 Desktop analysis

4.4.1.1 Description

A desktop analysis involves searching and using existing data for research purposes. A desktop analysis can be seen as a secondary data analysis, as it involves the analysis of data which was collected by someone else for another primary purpose. It is an empirical exercise which involves the application of similar basic research principles to projects that use primary data. It involves following certain steps, just as any research method does. Secondary data analysis is cost-effective and convenient, due to the researcher having to devote no, or a relatively small amount of, financial resources and effort. The use of existing data also allows findings to be produced, and projects to be completed, at a faster rate (Johnston, 2014).

The information gathered by Kuo (2012) is used in this project due to it being specifically aimed at constructability problems encountered by contractors. The aim was to use the information to derive the questions for the first round of interviews, and, if possible, extract BIM-implementable verifications directly from the information.

4.4.1.2 Objectives

A desktop analysis was conducted to identify factors which affect constructability and to determine already defined common constructability problems associated with the construction of suspended floor slabs from literature. From this, along with the use of a case study, the questions for the first round of interviews were also derived.

A desktop analysis was also conducted in order to obtain all necessary background information for the purposes of this study. The background information refers to construction project success criteria, general constructability information, BIM's current implementation, the inter-connectivity of constructability and BIM, previous studies similar to this study and the available decision-making tools. A desktop analysis does, however, have its disadvantages. These disadvantages will now be discussed, along with their respective contingency or mitigation plans.

4.4.1.3 Mitigation or contingency measures for disadvantages

A possibility exists that the data found during the desktop analysis was collected for some other purpose than what it will be used for after the desktop analysis and as part of a new research

project. Since the original data could possibly have been collected for some other purpose, in some other geographic region or during a very different period in time, the data might not be as applicable to the secondary data analysis as initially anticipated (Johnston, 2014). To prevent this from happening, the collected data was compared with the research aim of this study to determine its suitability. Data which was collected recently and in South Africa, will be given preference. If data was used that does not conform to the aforementioned criteria, this will be clearly stated and such data used with caution.

Another disadvantage associated with the use of secondary data is the fact that as the secondary researcher was not involved in the data collection process of the primary data, they do not know how it was conducted. The secondary researcher therefore has no knowledge of how well the data collection was done, if the data was affected by issues such as respondents' misinterpretations of questions or low response rates, or even whether the data was possibly altered by the primary researcher (Johnston, 2014). The secondary researcher refers to the researcher of this study. To mitigate this as best possible, a thorough inspection was done of the data collection procedure that was used. A case study was also used as a research instrument, as will be discussed in the section that follows.

4.4.2 Case studies

4.4.2.1 Description

The use of case study research, which entails studying past studies' reports, facilitates the understanding and exploration of multifaceted complex problems. It is a robust method of research, especially when thorough investigation is needed. It enables researchers to meticulously examine data from specific contexts. Case studies investigate and explore modern-day phenomena through the use of in-depth contextual analysis of conditions or events, along with their relationships (Zainal, 2007).

A single case study undertaken by Wium (2013) was used because the case study involved the constructability of a suspended floor slab, making it directly applicable to the aim of this study. It was chosen on grounds of its applicability and because it was a relatively recent undertaking.

4.4.2.2 Objectives

The case study which was used involved the construction of a suspended floor slab, and its

supports. Common constructability errors that occurred in the case study were identified, along with the literature found in the desktop analysis, to derive the questions that were asked during the interviews. The use of case studies could, however, have disadvantages that have to be accounted for. Only a single case study was used, as it was the only one case study found which involved the construction of a suspended floor slab.

4.4.2.3 Mitigation or contingency measures for disadvantages

Case studies have been accused of lacking rigour (Zainal, 2007). This was avoided by using only a case study which was done in-depth and which provided sufficient information on what was done.

Although only a single case study was used, the case study was backed up with an extensive literature study and the research done for a previous thesis (Kuo, 2012).

4.4.3 Structured interviews

4.4.3.1 Description

Interviews are often used where other instruments seem inappropriate. Interviews are used rather than questionnaires, when a more in-depth analysis is required or the possibility exists that further questioning, not yet known at the time of constructing the questions, could be required. A research interview is significantly more resource-intensive than the distribution and analysis of questionnaires. An interview requires the researcher, or interviewer, to obtain information from a respondent, or interviewee, on a one-on-one basis. A one-on-one and face-to-face interview basis was chosen due to interviews allowing the in-depth exploration of a matter to obtain a thorough understanding of a topic.

Interviews can be time-consuming due to the vast amounts of data that they can produce. Interviews can often provide a better insight into the significance and meaning of what is taking place than do other instruments, which can often only focus on the superficial elements regarding a research topic (Wilkinson & Birmingham, 2003).

Three basic models exist for interviews and they are unstructured, semi-structured and structured interviews. During unstructured interviews, the researcher establishes the areas of interest, but the respondent guides the discussion of issues. Unstructured interviews can,

however, be difficult to plan, and to steer when the discussion drifts from the key subject matter. Their analysis can also be especially difficult (Wilkinson & Birmingham, 2003).

Semi-structured interviews have less flexibility and the interview is more closely directed by the researcher. More predetermined questions are used, but sufficient flexibility still exists to allow the researcher to shape the direction of the discussion (Wilkinson & Birmingham, 2003).

During structured interviews, all the questions are predetermined, and the researcher has complete control over question ordering. Structured interviews have some predictability which allows the interviews to be timetabled to some extent. Structured interviews are easier to analyse than the other two models. During structured interviews the discussions are also less likely to drift from the key subject matters and this ensures that key questions on important issues are answered (Wilkinson & Birmingham, 2003).

Structured interviews were chosen as the model to be used for this study, as certain predetermined conversation themes were used during the interviews. All the themes involved certain questions which were aimed at acquiring the necessary information.

4.4.3.2 Objectives

Interviews were chosen as a research instrument to aid in this research project as they have the capability of gathering data and information that are not easily obtained elsewhere. Interviews can also result in obtaining a better understanding of a research topic. The collection of tacit knowledge from experienced individuals within the civil engineering and construction industry was important for reaching the aim of this study. In order to reach the study aim, the process would have to perform certain verifications to analyse the constructability of a suspended floor slab designed in BIM. In order to determine and develop these verifications, the first round of interviews was chosen as an instrument to aid in determining where constructability problems arise, or to determine efficient construction practice, in the construction of suspended floor slabs.

Interviews were also chosen as a research instrument for the validation of the study and to obtain user preferences in terms of the implementation of the study. The validation of the study was done through the second round of interviews.

More specifically, structured interviews were chosen as the interview model used during both rounds of interviews, and this was done as structured interviews were more likely to result in the answering of specific key questions. All the respondents were asked the same set of logically ordered questions. The questions for the first round of interviews were based on a case study and past knowledge from previous researchers. The questions asked during the second round of interviews were constructed with the aim of validating the study and to obtain consultants' preferences in terms of the implementation of the proposed process. Implementation of a process during which project-specific parameters were considered was also recommended to the consultants, to validate its practicality and the need for such a process. Before a design is undertaken, the process requests the user to state the condition of certain project-specific parameters. It aims to let users consider certain project characteristics which could prove to be important, before designs are undertaken.

Leniency was given to interviewees during both rounds of interviews. This was done to create an opportunity for the interviewees to elaborate on certain constructability matters which could possibly result in the acquiring of knowledge that had not initially been identified as required.

Two rounds of structured interviews were thus conducted during this research. The first round was conducted with participants from the local construction industry, in an attempt to identify commonly encountered constructability problems and other constructability information regarding suspended floor slabs and their supports.

The second round was conducted to validate the study, with participants from the local consulting industry asked to give their inputs on how they felt the proposed process should be implemented and also on the process which considers project-specific parameters.

Interviews, and more specifically, structured interviews, do, however, have disadvantages and these disadvantages will now be discussed and contingency measures for these will also be given.

4.4.3.3 Mitigation or contingency measures for disadvantages

Due to the potentially vast amounts of information that can be obtained in a short period of time during an interview, the likelihood of losing some information (potentially important) is

high, as the researcher cannot write everything down and thus misses some of the relevant information given (Wilkinson & Birmingham, 2003). This can be avoided by recording the interviews and transcribing the information afterwards.

It is possible that some of the questions that were initially planned to be asked during the interviews could later prove to be unrealistic, ambiguous or unnecessary. To prevent this from happening, a pilot test was done on three separate respondents, and thereafter the questions were evaluated and adjusted accordingly. The official interviews commenced thereafter.

4.5 DATA COLLECTION PROCESS

4.5.1 Interview participants

The aim of the first round of interviews was to obtain information regarding the constructability of suspended floor slabs and ultimately to use this information to develop BIM-implementable constructability verifications. A total of eight participants were interviewed during the first round of interviews. The participants were from construction companies ranging from small to large-sized construction companies in the South African construction industry. Most of the participants were from medium-sized companies, with only two from a small construction company and one from a large company which operates throughout South Africa. The other companies typically operate only within the Western Cape of South Africa. The experience of the interview participants also varied across a wide range, and this is discussed in further detail in Section 5.3 along with their tertiary qualifications.

The aim of the second round of interviews was to validate the proposed constructability analysis process, to obtain consultants' preferences in terms of how the process should be implemented and to obtain consultants' opinions on a process which considered project-specific parameters to further enhance constructability. Six participants participated in the second round of interviews. Participants from the second round of interviews were from businesses that ranged from small local consulting companies to large national and international consulting companies. Three of the participants were from local consulting companies. Their experience and tertiary qualifications are discussed further in Section 7.2.

Before any interview could be conducted, ethical approval had to be obtained from Stellenbosch University's Human Research Ethics Committee. This process will be described first, followed by a discussion of the interview process

4.5.2 Ethics approval and interviewee anonymity

Ethical approval was obtained from Stellenbosch University's Human Research Ethics Committee. The reference number for the ethical approval process was ING-2018-6457. Consent forms were signed by the interviewees and no issues arose around institutional permission from the interviewees' respective companies. The consent forms can be found in Appendices A and K. Before any interview was conducted, the interviewee had the opportunity to inspect the full lists of questions that were to be asked. Interviewees stayed anonymous throughout the entire process and pseudonyms were used instead of their names. The signed consent forms are available on request.

4.5.3 Pilot tests

It was important to conduct a pilot test prior to the commencement of the interviews to ensure that all the questions that would be asked were applicable, relevant and also logical. Pilot tests assisted the research by determining all the limitations, flaws and other weaknesses within the design of the interview and then allowed the researcher to make the necessary and important revisions and alterations prior to the commencement of the interviews (Kvale, 2007).

Pilot tests were conducted with three of the interviewees from each round of interviews. The three interviewees with whom the pilot tests were performed were Contractors A, B and C for the first round of interviews, and Consultants A, B and C for the second round of interviews. After the pilot tests, alterations were required to only the questions for the first round of interviews.

While most of the original questions for the first round of interviews could be retained, the following alterations were made:

- A range of questions was given more detail to reduce ambiguity
- More questions regarding precast construction were added
- Questions were added to obtain more information regarding formwork
- A question was added which requested the interviewee to state any constructability problems that they commonly encountered, in order for the researcher to obtain knowledge of constructability problems which had not been identified by the other questions
- More questions were added with regard to labour

- The order of the questions was changed slightly to better group the questions under more relevant topics

The additional questions were sent to Contractors A, B and C, and they were given sufficient time to answer the questions to the best of their knowledge. The final interview questions can be found in Appendices B and L.

4.5.4 Interview protocol

The structured interviews were administered on a one-on-one basis at a place and at a time of the interviewee's choosing. The majority of interviewees were interviewed on their own companies' properties.. The interviews followed the predetermined questions, but some leniency was allowed regarding the flow of the conversation topic, to increase the possibility of gaining more knowledge and possibly new ideas, in a conversational atmosphere. The derivation of the questions is discussed in further detail in Sections 5.2 and 7.3

The first round of interviews was recorded by means of note-taking and also by using a recording application on a cell phone. The recording techniques were used only with consent from the interviewees. The recordings on the cell phone were used after the interviews to review what had been said and to ensure that all the information provided was transcribed. This was done immediately after completion of the interview, as recommended by McNamara (2009). In the first round, interviews lasted between 70 and 100 minutes and were all performed between the 6th of April and the 18th of May 2018.

The second round of interviews was recorded by note-taking only. It was decided not to record on a cell phone, as done in the first round of interviews, with most questions requiring only short answers and the whole process being much shorter in duration. The second round of interviews each lasted between 35 and 55 minutes and were performed between the 20th of June and 13th of July 2018. The transcripts for both rounds of interviews are available on request. Summaries of the responses can be found in Appendices D and M.

4.5.5 Interview preparations and effective interviewing

McNamara (2009) wrote that the preparations prior to an interview are important in guaranteeing that the interview process is unambiguous and ensuring that the optimal value of

the interviews is attained. It was deemed important to obtain guidelines in obtaining the best possible value from the interviews and it was found that the preparation of an effective and successful interview comprises certain aspects. The following eight aspects were implemented in both rounds of the interview process (McNamara, 2009) (Harrell & Bradley, 2009):

- 1) The venues where the interviews were conducted had as few distractions, and were as private, as possible
- 2) The purpose of the interview was explained
- 3) The format that was used was explained
- 4) Confidentiality terms were addressed
- 5) An indication of the usual duration of the interview was given
- 6) The interviewee was given the contact details of the interviewer
- 7) The interviewee was asked if they had any questions before commencement of the interview
- 8) The interview was recorded in an effective manner and there was no reliance on the memory of the interviewer alone

McNamara (2009) also set out guidelines for conducting effective interviews. These guidelines, which include the following, were followed as best possible:

- 1) Wording was open-ended to allow interviewees to respond using their own words in order for them to contribute as much as possible
- 2) Questions were kept as neutral as possible and wording which could lead the interviewee into giving a biased response was avoided
- 3) Questions were asked one at a time, allowing sufficient time for interviewees to respond
- 4) The wording of questions was aimed to be clear, and familiar to the interviewee
- 5) Care was taken in asking 'why' questions, as this might infer a cause-effect relationship which may not have existed and could possibly have caused interviewees to feel defensive and that they needed to justify their responses.

Using the aforementioned five guidelines, the interviews were conducted as described in the subsection that follows.

4.5.6 Conducting the interviews

A protocol was established to ensure that the interviews were effective and that the maximum

information, experiences and knowledge were gathered during the interviews. The protocol was based on research done by McNamara (2009) and also by Harrel and Bradley (2009). The protocol included the following aspects:

- 1) Occasional verification that the interview was still being recorded was important
- 2) One question was asked at a time
- 3) Focus was kept on remaining as neutral as possible
- 4) Responses were encouraged
- 5) The interviewer's appearance during note-taking was considered carefully, so as not to influence the answers of the questions that followed
- 6) Transition between major topics was provided by stating the topic that was under discussion and the topic that was to be discussed next
- 7) Control was kept over the interview by not allowing interviewees to stray completely off topic. Interviewees were, however, allowed to stray off topic to an extent where valuable information could still be gathered.
- 8) The interviewer understood all the questions, in order to be able to respond to any inquiries from interviewees
- 9) Questions could be asked out of order if deemed necessary, but the interviewer had to ensure that all the material was covered
- 10) The interviewer practiced 'active listening' during each response by listening carefully to the given responses and also evaluating whether the question had been fully answered

4.5.7 Saturation points

The number of interviews for both rounds of interviews were undertaken up to the point where data saturation was attained for each. Data saturation refers to the point where no new data elements are found and no additional new information is necessary, as it will not alter comprehension of the researched phenomenon (Nascimento, de Souza, Oliveira, de Moraes, de Aguiar & da Silva, 2018).

For each round of interviews, data saturation was attained at earlier stages for certain questions, while responses to other questions remained different, which had the potential to provide important new information. When data saturation had been obtained for all the topics used in each interview, no further interviews were conducted

4.6 CHAPTER SUMMARY

This chapter has presented the research methodologies and instruments used to reach the aim of this study. A brief overview of the research methodology used has been given in Section 4.2, whereafter the motivation for the methodology chosen was discussed. The different research methodologies used in this project were analytical, descriptive, applied, qualitative and empirical research methodologies. The research instruments that were used were a case study, a desktop analysis and structured interviews. These methods were found to be required to reach the aim of the study. It was important to identify the research methodologies and instruments used in order to identify and plan for the disadvantages associated with each.

The interview process used during both rounds of structured interviews has also been discussed. The derivation of the interview questions from the case study and desktop analysis, used during the first round of interviews, will be presented in Chapter 5, along with the results of the first round of interviews. The derivation of the questions used during the second round of interviews, along with the results, is given in Chapter 7.

CHAPTER 5

First round of interviews and results

Figure 5.1 shows the content and the research stage relative to the other chapters.

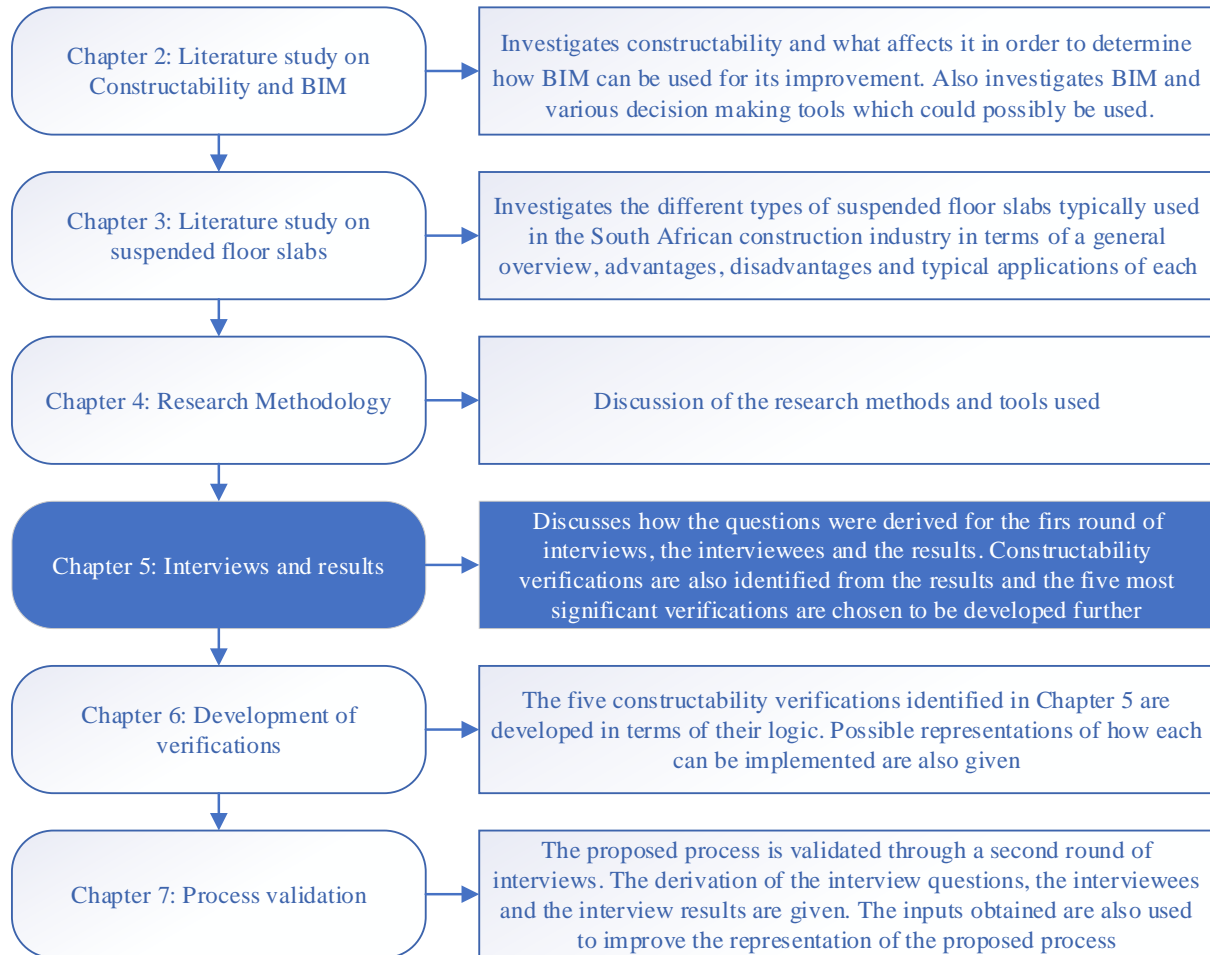


Figure 5.1: The content and research stage of Chapter 5 compared to the other chapters

5.1 INTRODUCTION

The previous chapter described the research methods that were used in this research. This chapter describes and discusses the results from the first round of interviews that contributed to the collection of the data needed to solve the research problem statement.

This research study aims to develop a process with which BIM can be used to verify the constructability of a design for suspended floor slabs and their supports. To accomplish the aim, structured interviews were used for the collection of the data during the first round of interviews. This chapter provides details of the participants in the first round of interviews and

of the derivation of the questions asked during the interviews. To conclude the chapter, the results from the interviews were analysed with the aim of identifying five constructability problems and the verifications for these that would be necessary to implement them in BIM.

5.2 DERIVATION OF QUESTIONS

The aim of this subsection is to describe how the questions asked during the first round of interviews were derived. The process used for the derivation of the questions is shown in Figure 5.2. The process can be divided into four basic steps, each of which will be discussed later.

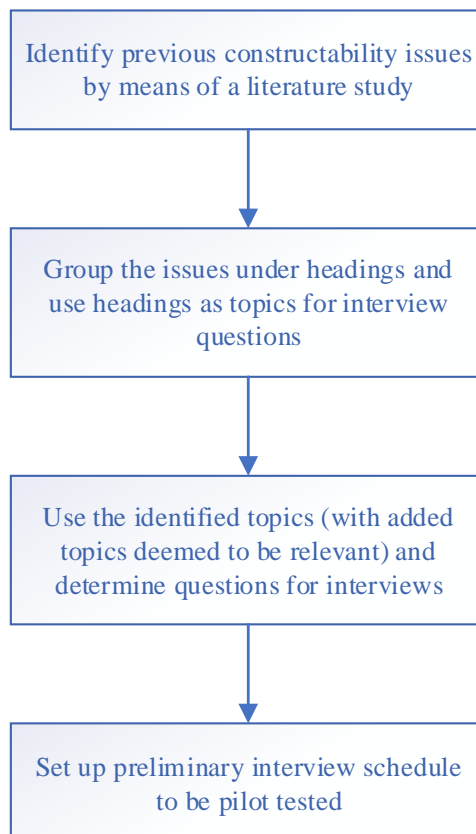


Figure 5.2: Question derivation process

The questions asked during the interviews were based primarily on a case study done by Wium (2013) and the research done for a MEng thesis by Kuo (2012). The questions are also supported by the literature study that was undertaken (see Section 2.4.3).

The case study that was used, involved the construction of a 21 m x 65 m (21 m clear span) concrete roof structure for a modern wine cellar outside Stellenbosch in South Africa. From the description in this conference paper, the relevant areas of possible aspects of constructability regarding suspended floor slabs and their supports, which could be

implemented in a BIM process, were identified. These included the following (Wium, 2013):

- Collaboration between designers and contractors from the design stage onward
- Accessibility and height restrictions for the placement of large members, cranes, etc.
- Contractor preference in terms of the type of slab that is to be constructed
- Available labour skills

A previous investigation conducted by Kuo (2012), was also used to derive questions for the interviews. Kuo (2012) identified common constructability problems by asking contractors and consultants to provide up to five specific problems with regard to constructability that they had encountered in one of the last five projects they had undertaken. The problems identified can be found in Appendix C. The problems that were identified as being relevant to suspended floor slabs and their supports are printed in red.

As with the case study undertaken by Wium (2013), the significant areas of possible constructability concerns that were relevant to the present study were identified and they included the following (Kuo, 2012):

- Using formwork that is not of the standard available sizes
- Installation of mechanical, electrical and plumbing (MEP) services, and especially regarding the necessary coordination between designers and contractors and the services that need to be installed through columns
- Large floor spans
- Columns which are in walls that are not of the same thickness as the walls
- Construction of down-stand beams
- Construction of raking columns (which should rather be precast)
- Internal load-bearing walls make construction of formwork difficult
- Precast elements
- Logistics
- Crane placement, accessibility and weightlifting capacity (column cages can be too heavy)
- Contractors' experience
- The fixing of reinforcement for slabs, columns and post-tensioning strands at column heads in thin slabs
- Type of shuttering used

Using the two aforementioned lists of possible areas, or project characteristics, certain themes were identified for discussion during the interviews. The themes were identified as possible areas where constructability concerns arise or where constructability has the potential to be improved. The themes can also be seen as conversational topics, under which certain relevant questions were asked. These themes included the following:

- Span-length ranges
- Precast slabs
- Concrete pouring
- Width of columns and walls
- Slab thickness
- Down-stand beams
- Raking columns
- Internal load-bearing walls
- Cranes
- MEP services installation
- Connections
- Formwork
- Labour
- Transportation
- Curing

Some of the themes required more in-depth analysis and thus were divided into sub-themes. Relevant questions under each theme were constructed with the aim of either:

- 1) Directly identifying constructability problems
- 2) Obtaining information which could assist in enhancing constructability
- 3) Obtaining information which could illustrate the impact of enhanced constructability

The questions were all seen as relevant to the constructability of suspended floor slabs and their supports. The questions could be directly or indirectly applicable to the aim of this study.

It was deemed important to also add a general section, questions regarding standard costs, questions regarding contractor/site managers' experience, and a concluding section. The reasons why these four themes were added will now be discussed.

For the general section, it was deemed important to obtain information regarding the interviewee's employment, tertiary education and experience. This information would not only give an indication of how experienced the interviewees were with what was being investigated, but also be helpful in distinguishing the constructability concerns likely to be more relevant in the case of contradicting opinions.

It was also considered important to obtain indications of the standard costs of concrete, reinforcement and formwork. At the time of the derivation of the questions, this was seen as possibly being helpful later in the research. The cost impact of resizing certain structural elements to maximise repetition could be determined using these standard cost rates.

In the section of the contractor or site manager's experience, the interviewee was asked to provide all common constructability problems that they had encountered. This section was added as a safety measure, to account for possible constructability information or concerns that had not arisen from the other conversational topics.

To conclude the interviews, a question was added to determine the opinion of the interviewee regarding the impact of the enhanced constructability of suspended floor slabs and their supports on a project. This question was added to determine the possible impact of the research, and it served as a start to the validation of the study.

The final interview questions can be found in Appendix B. A total of 75 questions was used and a number of the questions had subdivisions which could be asked specifically for each common slab type. This was done in an attempt to obtain more specific constructability concerns associated with each type of slab.

After the derivation of the questions, the interviews were undertaken, as has been discussed in Section 4.5. The experience and tertiary qualifications of the interviewees will now be discussed.

5.3 PARTICIPANTS

The aim of this subsection is to describe and analyse the experience and tertiary qualifications of the participants in the first round of interviews. Their experience is described in terms of

their experience within the construction industry and also specifically with the construction of suspended floor slabs. All their significant tertiary qualifications and professional registrations are also given. The information is important for future studies to do comparisons on the sources from where the information originates and to possibly make decisions when opinions are contradicting.

5.3.1 Experience

Eight contractors were interviewed. One of the interviewees, Contractor H, also had experience as an designer in the consulting industry. All eight interviewees had experience with the construction of suspended floor slabs. The experience of each contractor is shown in Figure 5.3. The average experience of the interviewees in the construction industry is 20.5 years and the average experience with the construction of suspended floor slabs are almost 17 years.

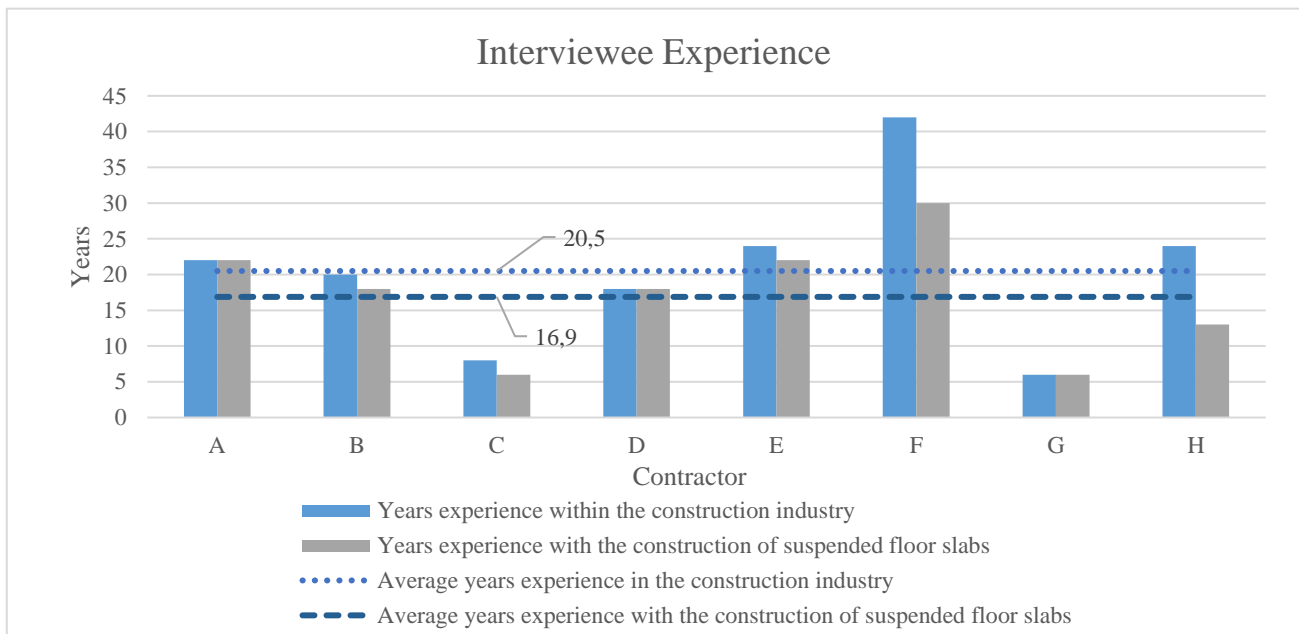


Figure 5.3: Interviewees' experience in the construction of suspended floor slabs

From this, it can be concluded that the pool of participants can be seen as experienced, not only within the construction industry, but also with the construction of suspended floor slabs.

Figure 5.4 shows the distribution of the interviewees' experience in the construction of suspended floor slabs. As there can be seen, all the participants have more than five years of experience and less than 30 years of experience with the construction of suspended floor slabs. The distribution of experience can also be seen as wide, with a maximum of two interviewees falling within the same 5 year experience bracket.

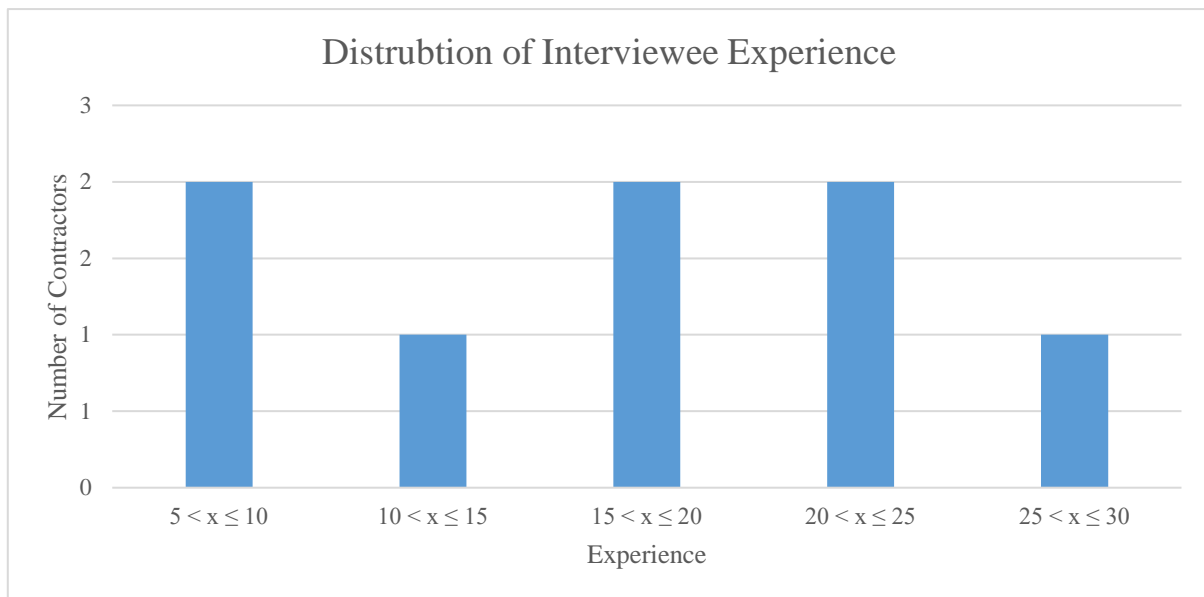


Figure 5.4: Distribution of interviewee experience with suspended floor slab construction

5.3.2 Tertiary qualification

Seven of the eight interviewees had some form of tertiary qualification and the tertiary qualification(s) obtained by each interviewee are summarised in Table 5.1, which also gives the position of each interviewee within their company. The table also shows that five of the interviewees had either Bachelor or Masters degrees. Three of the interviewees were professionally registered by various bodies. Contractor A was registered with the South African Qualifications Authority (SAQA), Contractor C with the South African Council for Project and Construction Management Professions (SACPCMP) and Contractor H was registered with the Engineering Council of South Africa (ECSA). The table also shows that seven of the employees were in management positions at their individual companies, one of them (Contractor H) being the Managing Director.

From this it can be concluded that the interviewee pool was relatively highly educated, with only one interviewee having no tertiary qualification. The inputs from the interviewees are thus mostly based on their extended knowledge and experience obtained, making the interviewees' inputs invaluable for this research and for future research.

It could also be concluded that almost all the interviewees had advanced within their fields, as this can be seen from the management roles they fill. This serves as an indication of their reputation and work ethic, which further enhances the importance and substance of their inputs. The results from the interviews are discussed in the subsection that follows.

Table 5-1: Summary of interviewees' tertiary educations and positions within respective companies (Round 1)

Contractor	Tertiary Education Obtained	Position in Company
A	BSc Quantity Surveying and registered with SAQA	Professional Quantity Surveyor
B	BEcon and Project Management Diploma	Project Manager
C	BEng (Civil) and registered with SACPCMP. Enrolled for MEng (Civil)	Site Agent
D	Civil Engineering Diploma	Business Unit Manager
E	None	Construction/Site Manager
F	Higher National Diploma in Civil Engineering	Director
G	MEng (Civil)	Site Agent
H	BEng (Civil)	Managing Director and Professional Engineer

5.4 RESULTS ANALYSIS

5.4.1 Results summary

After the transcription of all the interviews, all the responses from the interviewees for each theme, or sub-theme, were summarised. The important and relevant information obtained from the responses to each question, and from each interviewee, was populated into a summary table. The summary table can be found in Appendix D.

5.4.2 Extraction and identification of constructability verifications to be developed

Using the summarised responses, the possible necessity for verifications of constructability concerns were identified under each theme (or sub-theme). The initially identified verifications may not have a very significant impact on the constructability of suspended floors slabs and their supports, but the first step was to identify every possible verification. The aim was to identify all the possible constructability verifications, regardless of the size of their possible impact. All the identified verifications under each theme, or sub-theme, can be found in Table 5.2. Table 5.2 also gives a score for each verification and its calculation is discussed hereafter.

Table 5-2: Identified possible constructability verifications with final scores received

Theme	Sub-Theme	Verifi- cation No.	Possible process verifications extracted	Score
Span length ranges		1.1	Compare with economic span lengths given by C. H. Goodchild (excludes Rib and block slabs).	6
		1.2	If column heads are present, state that column heads should be avoided if possible, because of the difficulty in constructing the required formwork systems.	5
		1.3	If post-tensioned slab, then recommend that services layout must be finalised before construction commences, because changes occurring afterward can cause structural problems.	6
		1.4	If coffer slab, recommend changing type of slab (rather use post-tensioned) as coffer slabs are very expensive in terms of formwork and labour.	5
Precast slabs	Available lengths	2.1	Compare lengths, widths and thicknesses with the available precast sizes (obtained from manufacturer).	5
		2.2	For rib and block slab, measure width and, if side panels do not fit in, state that extra formwork and concrete would be required and a re-design must be considered.	3
		2.3	If precast slab, state that truck accessibility and distance to supplier must be carefully considered.	7
	Application	2.4	If in-situ cast slab, consider whether sufficient space for formwork exists underneath slab.	2
		2.5	If more than four storeys, then recommend use of in-situ slabs, which will allow more control on dimensions.	5
	Constructability concerns with supports (Temporary and Permanent)	2.6	For hollow-core slabs longer than 8 m, state that propping will be required, and position of propping must be considered.	2
		2.7	For rib and block slab, state that propping will be required, and position of propping must be considered.	2
		2.8	Measure lintel depths into walls and compare to National Home Builders Registration Council (NHBRC) requirements.	2
		2.9	State that sizing and orders of precast panels must be verified. Delivery of incorrect sizes are a common occurrence.	6
Monolithic concrete pouring				
Standard costs				
Columns, beams and wall widths		5.1	If beams and/or columns are in/on top of walls (non load-bearing) then they must be measured and recommended to be 220/230/270 (cavity)/280 (cavity)/330/350 mm for easier formwork and better aesthetics. More efficient construction will take place if walls that are adjacent to columns and/or beams have the same widths.	7
		5.2	If no walls present, but only columns and beams are connected, then recommend them being the same width for easier formwork and better aesthetics.	7
Slab thickness		6.1	Process should ask for brick height and also thickness of mortar between bricks. Compare slab height with multiple of these heights (different options in terms of where mortar layer can be) if the outside brick face is vertically continuous.	5
		6.2	Process should ask for brick height and also thickness of mortar between bricks, should then compare it to the height of the internal walls (plus or minus an increment of the mortar layer between bricks).	8
		6.3	If slab thickness is more than 300 mm, state that power floating and curing can be problematic for thicknesses greater than 300 mm.	6
		6.4	Measure weather step and compare to 25 mm increments to ease with formwork	4
Down-stand beams		7.1	If down-stand beams are present, point out and state that this must be reconsidered, due to common concerns such as formwork being difficult to construct and costing more, compaction, honeycombing, rework due to rubble accumulation at bottom of formwork giving undesirable finish, reinforcement cover, reinforcement 'kicking', joint preparation. All of these take time and thus also increases the cost.	7
Raking columns	Construction of raking columns	8.1	Measure angle of beams and columns, if not 0, 90 or 180 degrees then point out and state that possible problems such as formwork being more complex to construct, compaction problems, honeycombing, loss off quality, additional machinery will be needed, and accuracy can be difficult.	7
	Precast raking columns	8.2	If raking columns present, point out and recommend raking columns to be precast and point out their connections must be revised.	4

Internal load-bearing walls	Construction of internal load-bearing walls	9.1	If there are walls in the model, they would be structural elements and thus load-bearing. Recommend that the total length of load-bearing walls should be made as little as possible because load-bearing walls' formwork is cumbersome and accuracy can be difficult. Minimising the total load-bearing wall length can be done through longer spans (consider post-tensioned slabs).	7
		9.2	Recommend that the presence of slip-joints between slabs and walls must be verified.	4
	Precast load-bearing elements			
Cranes	Project size for type of crane	10.1	Crane placement and size need to be considered. Implement previous studies on crane selection such and placement optimisation.	7
	Crane usage			
	Concerns with crane usage			
MEP Services		11.1	Verify if final service layout exists, if not, recommend that it should be finalised and completed before construction commences.	8
		11.2	If services run horizontally through columns, point this out and state that contractors prefer not to have this due to difficulties in formwork.	6
		11.3	Verify whether sleeves for services are tied to the bottom layer of reinforcing. If tied to top layer, then recommend not to due to increased possibility of cracking.	7
		11.4	If hollow-core slab, verify whether services are placed within the tubes. If so, recommend not to, due to difficulties in alignment and cutting of slabs would be required that could result in significant structural implications.	7
		11.5	If hollow-core slab, verify that services do not cut through slabs. If cutting occurs, then recommend that this must be clearly specified beforehand to supplier, or re-designed with either ceiling-and-soffit-mounted services or with services in the walls.	7
		11.6	If Rib and block slab, verify that services go through as few blocks as possible and recommend to rather use ceilings with soffit-mounting. Blocks have to be removed and then holes have to be filled with cement, requiring extra formwork and concrete.	3
		11.7	If columns are present, recommend vertical services be placed in centre of columns.	5
		11.8	If services in 110 mm walls, recommend that services be kept to a minimum.	3
		11.9	If two or more services cross, then point this out and state that it could cause a significant loss in the slabs' structural integrity.	7
Connections	Slab and column connections	12.1	Measure slab thickness, if thinner than an average of 150, 240, 200, 250 or 200 mm, then state that compaction could be difficult for this thickness.	7
		12.2	Measure spacing, if smaller than 50 mm, state that compaction could be difficult because 'poker' would be hard to fit between reinforcing. 'Poker' refers to tool used for compacting cement between reinforcement.	5
		12.3	Measure cover, if less than 50 mm, state that a tolerance needs to be incorporated according to South African National Standard (SANS) 10120-G.	8
		12.4	Measure column sizes, if smaller than 250 x 250 mm, state that cover and spacing needs to be considered, it becomes problematic for these dimensions and smaller.	4
	Slab and lift shaft/stair wall connections	12.5	Recommend that anchorage lengths must be verified as soon as the widths of beams and/or columns are changed. A length of four times the diameter of the reinforcement must still be able to fit from the centre of the beam/column towards the edge, with additional allowance for cover.	7
Formwork	Wood versus steel formwork	13.1	If columns are curved, round or have curved edges, then it should be stated that steel formwork would be needed, and that repetition of the same curves would save cost and time. Also verify all the different column and beam cross-sections that are used separately, if more than one cross-section is used for beams and/or columns, then recommend that the number of different cross-sections be minimised to enhance efficiency and the learning curve of the labourers involved.	8
		Cutting and erecting own formwork		
	Standard formwork sizes	13.2	Compare columns and beam widths and heights to the locally available panels.	7
		13.3	Compare slab area underneath to available sizes/formwork table sizes. Allow a tolerance of 10 mm for recommendation.	5
Experience	Common constructability concerns	14.1	Determine the number of different types of concrete used and if more than two, recommend to use only two as it makes the ordering process easier, which could result in saving time and costs. -40 MPa for bottom floor and foundations and the rest 25/30 MPa.	8

		14.2	Analyse site accessibility by verification of access for vehicles in terms of material drop-off zones, etc.	6
		14.3	Measure span lengths and try to keep to 5 cm increments	5
		14.4	Ask user for contractor preference in terms of construction with either masonry, concrete or steel. Recommend load-bearing walls for masonry preference, concrete beams and/or columns for concrete preference and steel beams and/or columns for steel preference. If not, then recommend either a re-design towards the contractor's preference or the selection of a new contractor.	5
		14.5	If post-tensioned slab, point out corners and state that potential congestion of the reinforcement and post-tensioning strands could occur and must be verified.	4
		14.6	Verification of all floor types used: if more than one, recommend that this be kept to a single type. This would result in more efficient construction by increasing repetition and enhancing the learning curve.	7
		14.7	Verification of safe working area in terms of edges, confined spaces and heights.	6
		14.8	Verification of orientation and heights of overhead power lines to ensure safe passage and use of cranes, trucks and ladders.	5
Labour	Use of local labour			
	Labour for skilled construction activities			
Transportation		16.1	If precast, measure size and weight of largest members with the help of the precast function in Revit and compare to regulations issued by SANRAL for trucks. If an abnormal load permit would be needed, flag the particular member and recommend a re-design to smaller weight/size that fits within the regulations. Also compare weight to available crane sizes.	7
Curing				
Influence of enhanced constructability				

From the table above, it can be seen that a total of 51 possible constructability concerns that required verification were identified. To demonstrate the potential of Autodesk Revit as a tool to improve the constructability of suspended floor slabs and their supports, it was decided to illustrate only how the most significant verifications could be implemented. It is important to note that the scores given for criteria were assigned at the discretion of the researcher.

The most significant verifications thus had to be identified, using the following two criteria:

- 1) Their potential impact on the cost, time or quality of the suspended floor slabs and their supports
- 2) The relative emphasis placed by interviewees on the importance of each concern needing verification

The first criteria were evaluated using Table 5.3. The verifications were graded on a scale of one to five. A verification can have a significant impact on either the cost, time or quality of a project and receive a relatively high impact. A verification could also have a less significant impact on a combination of the cost, time and quality of a project and yet receive a relatively high grading. Due to the verification having an impact on a combination of cost, time and/or quality, and not only one of the three, it was seen as still possibly having a significant impact

on a project's success. If, however, a verification was deemed to have a small impact on improving constructability it would receive a relatively low grading. All the gradings of the verifications were done relative to each other. The chosen levels of impact were based on the opinion of the researcher. The information found in the literature study, the case study done by Wium(2013) and the research done by Kuo (2012) also assisted in the grading of the verifications for these criteria.

Table 5-3: Impact of verification on time, cost or quality criterion

Level	1	2	3	4	5
Impact on time, cost or quality (or a combination of these)	Minimum	Low	Moderate	High	Major

The second criterion considers the relative level of emphasis placed on the importance of such a verification by the interviewees. This criterion was based on Table 5.4, which also grades verifications on a scale of one to five. If an interviewee stated that a verification would have a significant impact on constructability, then the corresponding verification would be given a higher level of significance. If several interviewees identified an item, then that consideration would also receive a high rating. This criterion thus depended upon the emphasis that the interviewees had placed on it during the interviews. Interviewees emphasized the importance of improving certain areas, elements or processes involved with design or construction.

Table 5-4: Relative interviewee emphasis on significance criterion

Level	1	2	3	4	5
Relative interviewee emphasis on possible significance of a verification	Minimum	Low	Moderate	High	Major

The final score for each identified constructability verification required was calculated as the sum of the scores obtained for each tabled criterion. Each of the two criteria thus had the same weight in the final score. The final score obtained for each identified verification can also be found in Table 5.2. A breakdown of the scores given for both criteria for the verifications can be found in Appendix E.

5.4.3 Identified verifications to be developed

During the assessment, five verifications received the joint highest scores and were chosen.

Each of the chosen verifications is given and described in Table 5.5.

The first verification, i.e. the floor-to-floor height verification, obtained its high combined score because the cutting of bricks which it necessitated resulted in unnecessary time wastage and the costs of the extra machinery and labour needed. Six of the eight interviewees also stated the importance of designing walls so that the height would be at multiples of the brick heights to be used (see Appendix D).

The second identified verification, i.e. the MEP services coordination verification, was identified as a result of a combination of the literature study undertaken, the research done by Kuo (2012) and the information obtained during the interviews. During the literature study, the importance of coordination among project participants had already been emphasized (see Section 2.4.2.6). Kuo (2012) also identified numerous problems with regard to the installation of MEP services, resulting in problems having to be resolved later, which incurs unnecessary extra costs (see Appendix C). Interviewees also stated either that poor coordination between designer and contractors often occurs, or emphasized the importance of proper planning with regard to the layout of services.

A third verification, the concrete cover verification, was chosen after four of the interviewees had emphasized that obtaining the specified concrete cover was often a concern in the construction of suspended floor slabs (see Appendix D). The extra time required to correct problems pertaining to the unavailability of sufficient concrete cover can also result in significant costs.

The column cross-section verification obtained its high score from a combination of what was found in both the literature study and the opinions of the interviewees. In section 2.4.2.3, the importance of repetition in enhancing constructability was highlighted, and four of the interviewees also emphasized how increased repetition could enhance constructability.

The final verification, the concrete types verification, also obtained its high score as a result of the information found in the literature study and that gained from the interviewees. In section 2.4.2.1 the impact on constructability of a unified selection of materials were discussed and this was backed up by the opinions of the interviewees. Three interviewees emphasized that using only two types of concrete in a project involving suspended floor slabs would result in

easier planning and ordering and also in cost-saving (see Appendix D).

The verifications identified are developed in terms of the logic required for their implementation within Autodesk Revit, and this is discussed in Chapter 6.

Table 5-5: Description of the five most significant verifications identified as necessary

No.	Original verification no.	Name	Description
1	6.2	Floor-to-floor height verification	BIM process should ask for brick height that will be used and also thickness of mortar between bricks, and should then compare it to the height of the different walls within the model (plus or minus an increment of the mortar layer between bricks).
2	11.1	MEP services coordination verification	Checks whether a service layer exists and is finalised, whether clash detection has been done and if final services layout has been completed; if not, recommends that it must be finalised and completed before construction commences.
3	12.3	Concrete cover verification	Reminds the designer to increase amount of cover required, to incorporate tolerances as set out in SANS 10120-G.
4	13.1	Column cross-section verification	Verification of all the different column cross-sections used separately: if more than one type is used, then recommend that the number of different cross-sections be minimised to enhance both efficiency and the learning curve of the labourers.
5	14.1	Concrete types verification	Determine number of different types of concrete used and if more than two, recommend using fewer types, which will result in easing the ordering process, which in turn could result in saving both time and money.

5.5 SUMMARY

Interviews were conducted with site agents, managers, directors, and quantity surveyors with a wide range of experience and different kinds and levels of tertiary education. These

interviews were conducted following a list of predetermined questions. How these questions were derived has been discussed in this chapter. The questions are based on a case study done by Wium (2013), research done for a thesis by Kuo (2012) and the literature study done in Chapter 2. The interviews were conducted primarily to identify correctable constructability concerns associated with suspended floor slabs and their supports.

The constructability concerns identified, and all relevant information regarding all the questions and constructability gathered during the interviews, were extracted, organised and analysed. Fifty one possible constructability analysis verifications were identified from the gathered information. The five most significant verifications of all those identified were then determined, based on selected criteria. The criteria used were a) the possible impact on time, cost and quality of a construction project and b) the emphasis which the interviewees placed on the importance of certain concerns. The verifications were all graded using scores of one to five. The verifications identified as having the greatest impact on constructability were the following:

- 1) Floor-to-floor height verification
- 2) MEP services coordination verification
- 3) Concrete cover verification
- 4) Column cross-section verification
- 5) Concrete type(s) required verification

The aim of the study was to develop and show a process to be implemented in BIM, which analyses the constructability of suspended floor slabs and their supports. The verifications identified will be used to show the capacity of BIM to fulfill the aim of the study. The verifications will be used as examples to illustrate how such a process can be implemented and represented within Autodesk Revit.

The aim of this chapter was to identify the verifications that would be used to illustrate the constructability analysis process. The logic behind how each of these verifications can be implemented, how they can be represented, and where the relevant information required for each can be found, within Autodesk Revit, is represented and discussed in Chapter 6.

CHAPTER 6

Development of constructability verifications

Figure 6.1 shows the content for Chapter 6 along with the research stage compared to the other chapters.

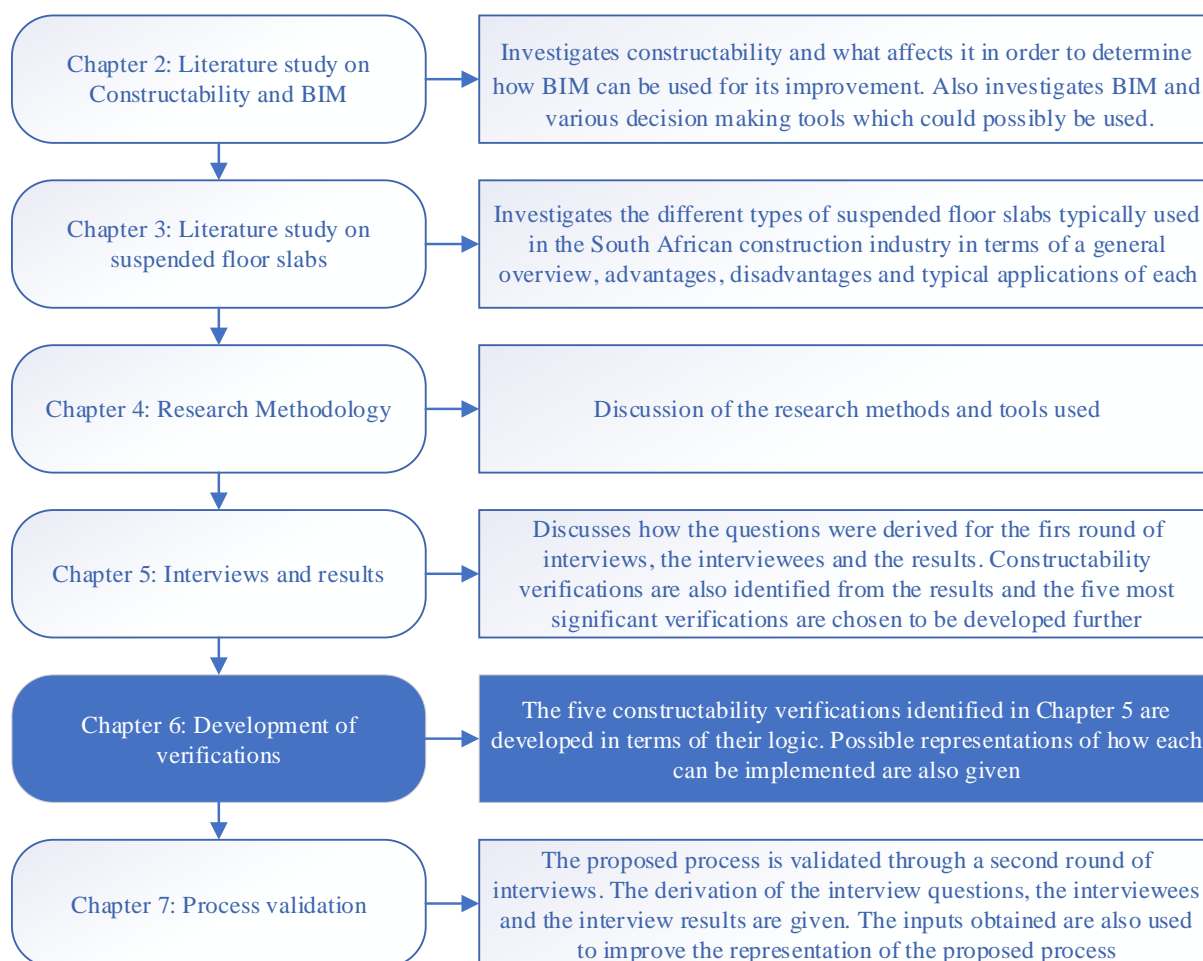


Figure 6.1: The content and research stage of Chapter 6 compared to the other chapters

6.1 INTRODUCTION

In Chapter 5, five constructability verifications were identified to be developed in terms of the logic required for their implementation within Autodesk Revit. In this chapter, the use by the author of Autodesk Revit as a tool to demonstrate how the constructability of suspended floor slabs and their supports could be improved by identifying constructability concerns, is discussed. Whilst any BIM platform can be used, Autodesk Revit was chosen because of its availability at Stellenbosch University. The logic behind the five verifications identified is developed and illustrated with flow diagrams, illustrations and examples. Proposals will also

be given for how each of the five verifications can be implemented through a Graphical User Interface (GUI) on Autodesk Revit. The aim and process of each verification is also described.

Where the specific information required for a proposed process can be found on Autodesk Revit is also shown. Besides the development of the process, it was considered important to know what information and parameters were available in the software that was used.

The aim of this chapter is to demonstrate the logic behind the identified verifications, to a point where the flow diagrams, which is developed in this chapter, could easily be used to program the proposed process for implementation in BIM. After completion of this chapter, the validation of the proposed verifications and the process will be represented, and the results of the validation will be given.

6.2 DEVELOPMENT OF VERIFICATIONS

Each verification is first discussed in terms of an overview of the need for it, how it works and its aim. Thereafter, the execution and implementation process for that specific verification is discussed and described. The input required from the user is described. Where the required information can be found within Autodesk Revit is also explained.

Flow diagrams are used to show the logic and process needed for each verification to reach its aim. The description of each process is further aided by the use of illustrations and examples from Autodesk Revit to give more clarity regarding what will be done. Screenshots are used to illustrate and assist in the descriptions of where the required information can be found. GUIs are also given to illustrate how the process will be implemented within Autodesk Revit. The development of each of the five verifications identified will now be described.

6.3 BRICK HEIGHT INCREMENT VERIFICATION

The first aspect to be considered, is the verification of brick height increments. The aim of the verification is to test whether the designed structural or architectural wall heights, which can be loadbearing or non-loadbearing, are at increments of the brick height used. Most of the interviewees indicated that this verification could result in significant savings of time and cost. If walls are not at increments of brick heights, the consequent extra cutting of bricks that is required results in additional machinery and labour costs.

6.3.1 Process

A description of the process is provided in the following paragraphs and is supported by Figure 6.2.

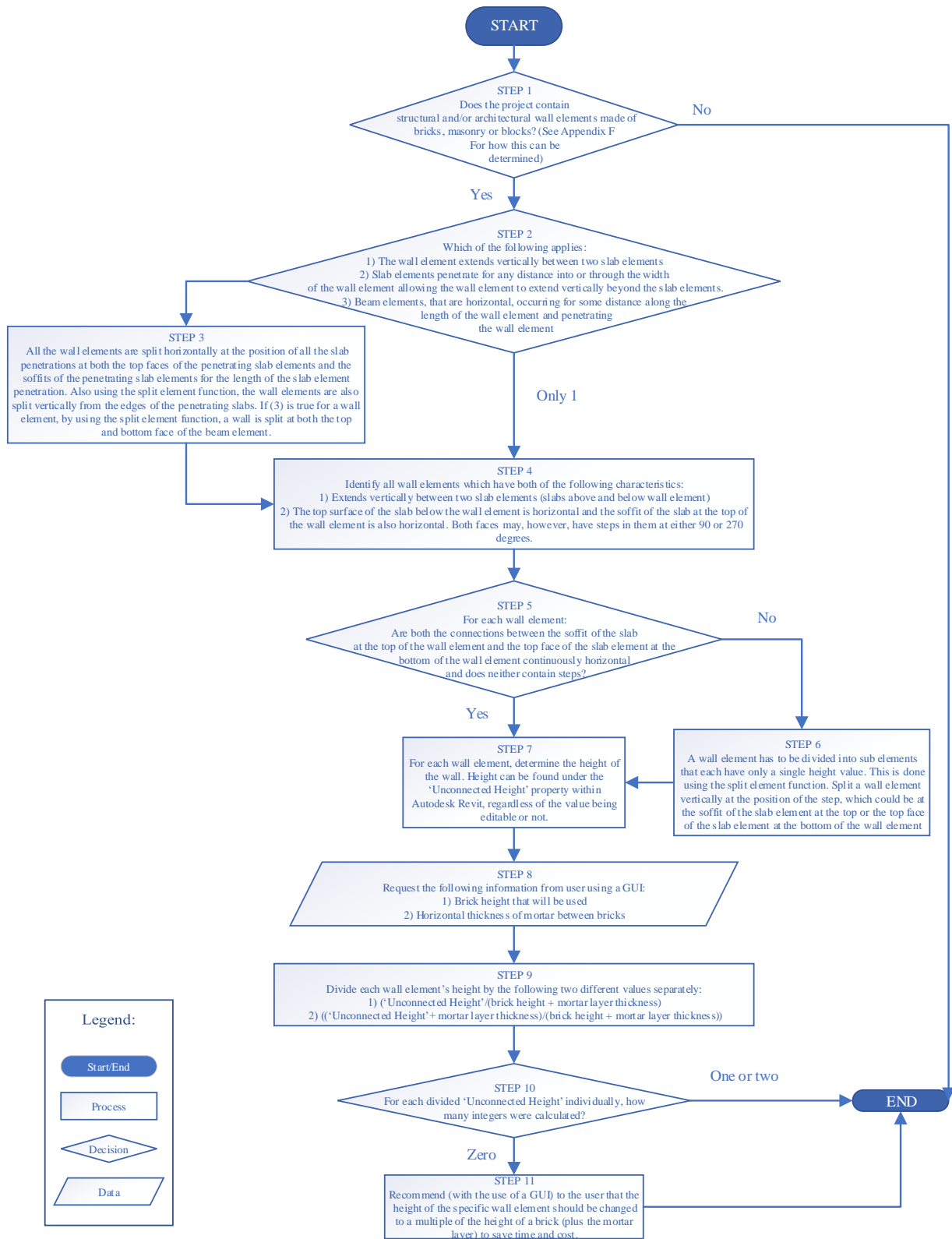


Figure 6.2: Brick height increment verification logic

For this verification to be successful, the following information needs to be provided within the process by users:

- The materials of which the wall elements are made

Step 1 aims to identify whether the project includes structural and/or architectural wall elements (see Appendix F).

In step 2, if the project does contain these elements, each of the wall elements will be analysed and tested to see whether the following violations apply to it:

- 1) The wall element extends vertically between two slab elements (slabs on top and under the wall element)
- 2) Slab elements penetrate for any distance into or through the width of the wall element (See point 2 on Figure 6.3) allowing the wall element to extend vertically beyond the slab elements.
- 3) Beam elements, that are horizontal, occur for some distance along the length of the wall element and penetrate the wall element (See point 1 on Figure 6.3)

If none of these violations apply to an element, the element is discarded from the process.

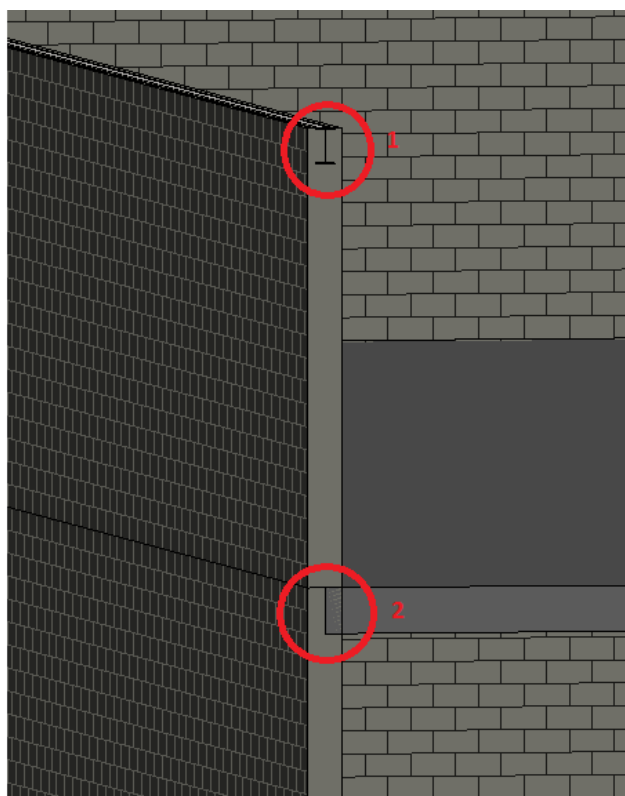


Figure 6.3: Wall element penetrations points 1 and 2

For step 3, if any rule, or combination of rules, apply to an element, with the exception of a case in which only the first rule applies, the wall element should then be divided into sub-elements which each has only a single height value. If only rule one applies to a wall element, then step 3 is skipped.

The splitting of wall elements is done using the split element function within Autodesk Revit. The division into sub-elements is done according to the following guidelines:

- All the wall elements are split horizontally at the position of all the slab penetrations at both the top faces of the penetrating slab elements and the soffits of the penetrating slab elements for the length of the slab element penetration
- Also using the split element function, the wall elements are also split vertically from the edges of the penetrating slabs
- If rule number 3 is true for an element, by using the split element function, a wall is split at both the top and bottom face of the beam element. See Figure 6.4 for examples on how the split element function is applied when there are slab and beam penetrations.

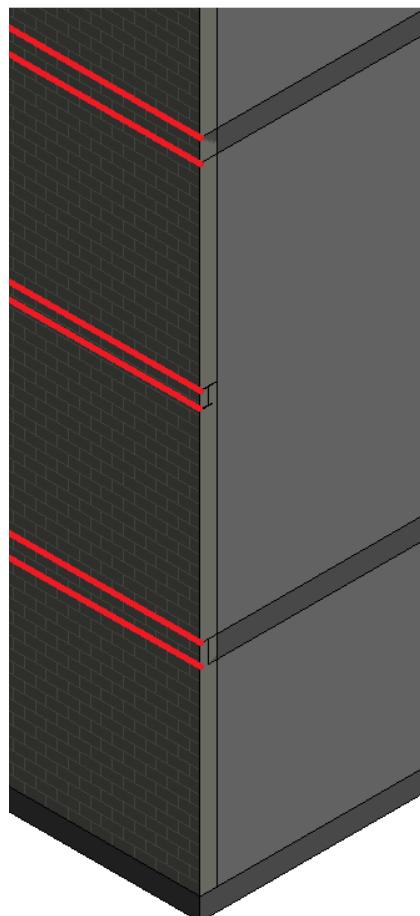


Figure 6.4: Examples of the splitting of wall elements with beam and slab penetrations

For step 4, after the wall elements, to which rules 2 and/or 3 applied, have been sub-divided into elements, along with the wall elements for which only rule number 1 applied, the following is done:

Identify all structural and/or architectural wall elements which have both of the following characteristics:

- 1) Extends vertically between two slab elements (slabs above and below wall element)
- 2) The top surface of the slab below the wall element is perfectly horizontal (0 or 180 degrees) and the soffit of the slab at the top of the wall element is also perfectly horizontal. Both faces may, however, have steps in them at either 90 or 270 degrees.

For step 5, the wall elements which have both the aforementioned characteristics, are grouped together and each element is tested according to the following criteria:

- Are both the connections between the soffit of the slab at the top of the wall element and the top face of the slab element at the bottom of the wall element continuously horizontal (0 or 180 degrees) and does neither contain steps?

If a wall element fails to meet the criteria, step 6 should be completed before proceeding. Step 6 involves the following:

A wall element must be divided into sub elements that each have only a single height value. This is done using the split element function. Split a wall element vertically at the position of the step, which could be at the soffit of the slab element at the top or the top face of the slab element at the bottom of the wall element. See Figures 6.5 and 6.6 for examples of how wall elements are split vertically, using the split element function.

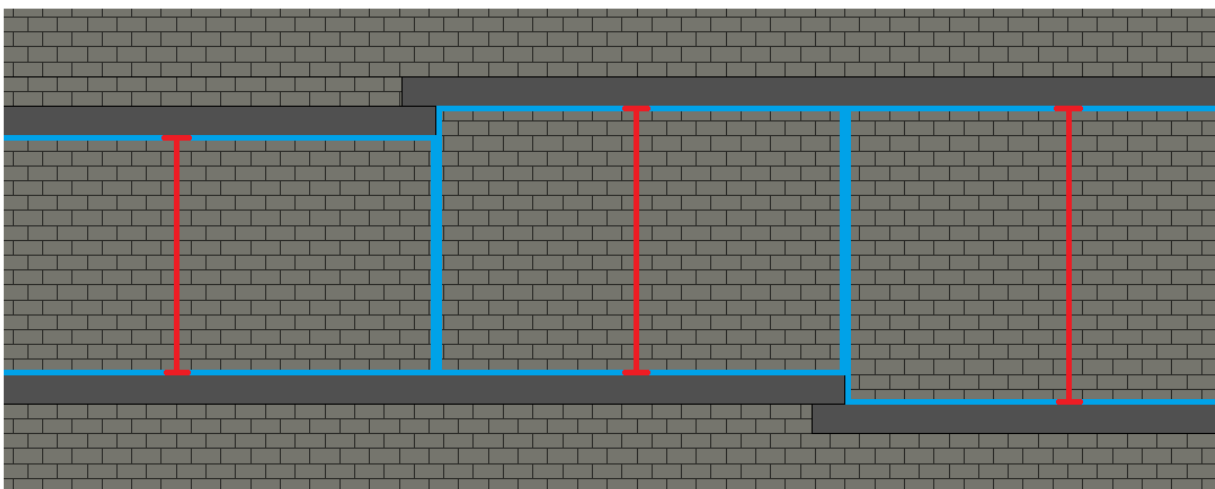


Figure 6.5: First example of vertical splitting of a wall element in an elevation view

For step 7, the height of each of the wall elements is determined. The height of a wall element can be found under the value in the ‘Unconnected Height’ property within Autodesk Revit (See Figure 6.7). Figures 6.5 and 6.6 show examples of the heights referred to in red.

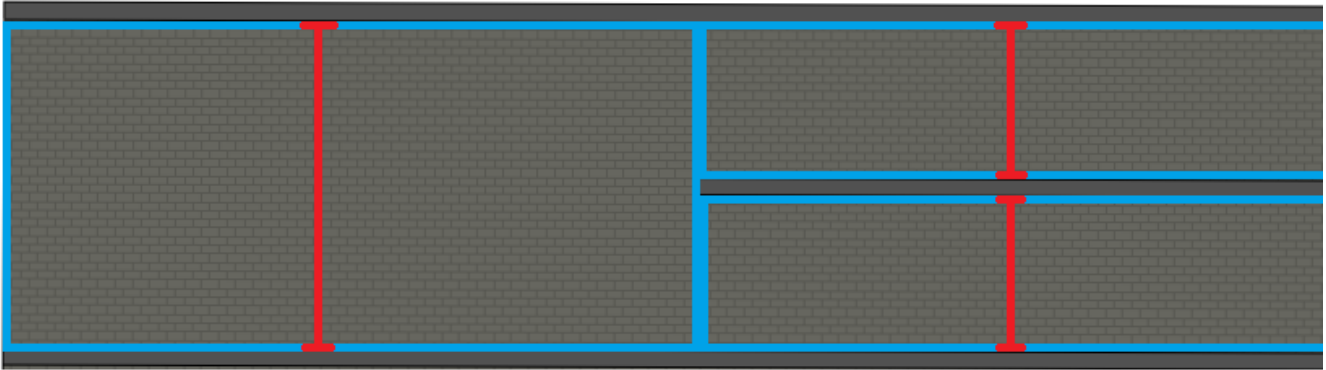


Figure 6.6: Second example of vertical splitting of a wall element in an elevation view

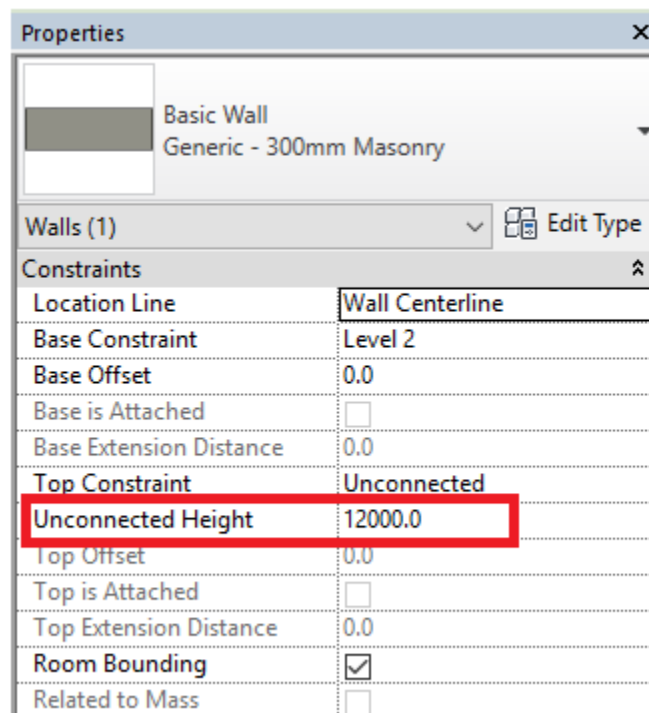


Figure 6.7: Unconnected height property

For step 8, a GUI needs to be developed which requests the following information from the user:

- 1) Brick height that will be used
- 2) Horizontal thickness of mortar between bricks

Figure 6.8 shows an example of the GUI which must be completed by the user.

Figure 6.8: Example of GUI to be completed by user

For step 9, make certain that each individual wall element is at a height which is an increment of the brick height used. This is done by dividing the height of each wall element by the following two values separately:

- 1) ('Unconnected Height' / (brick height + mortar layer thickness))
- 2) (('Unconnected Height' + mortar layer thickness) / (brick height + mortar layer thickness))

For steps 10 and 11, if the results of both of the above two calculations' is not an integer, recommend (with the use of a GUI and highlighting the wall element concerned) to the user that the height of the specific wall element should be changed to a multiple of the height of a brick (plus the mortar layer) to save time and cost. See Figure 6.9 for an example of how this recommendation can be made within Autodesk Revit.

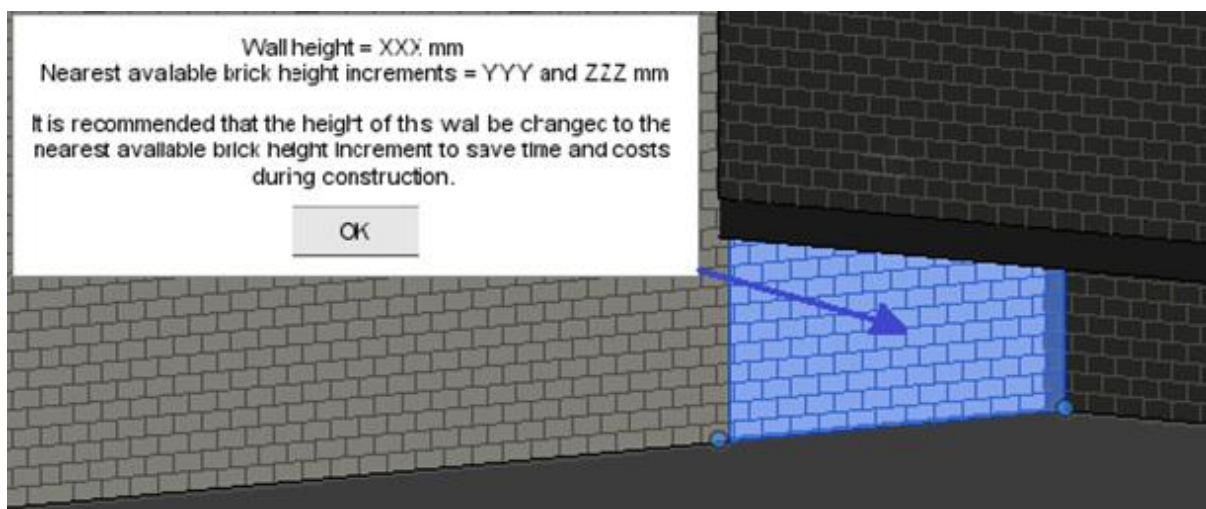


Figure 6.9: Example of GUI implementation of brick height increment recommendation

6.4 MEP SERVICES COORDINATION VERIFICATION

The second aspect identified as having a serious impact on the constructability of suspended floor slabs and their supports, is the coordination regarding MEP services. The interviewees emphasized that the installation of MEP services is a substantial source of concerns in the construction industry. The aim of the verification is to ensure that the MEP services layout has been finalised before construction commences. Most of the interviewees indicated that the lack of coordination between engineers and MEP services designers, and insufficient planning coordination, are the most common sources of problems associated with the installation of MEP services. The interviewees stated the MEP services designs have often not been completed by the time construction commences, which then later results in alterations being required to already built structural elements. It can be concluded that if the whole MEP services design process can be made more effective, it could result in fewer change orders being issued, which would effectively result in time and cost savings.

It should, however, be noted that in the modern construction industry, it is rarely possible for MEP services design to be finalized before construction commences, as indicated by the majority of interviewees. This is due to client requirements, consultant design schedules, changes, regulatory requirements, mistakes, etc. Practicalities such as this, and issues such as contractors not wishing to divulge construction methods that could give a competitive advantage, can severely hinder the flow of information between parties. Any attempt in making the process more effective should, however, be sought.

6.4.1 Process

A description of the process is provided in the following paragraphs, supported by Figure 6.10.

Step 1 is to ensure that all the services are set to be visible within Autodesk Revit. Figure 6.11 shows where in the software this can be checked. It is possible that certain services are not set to be visible to the user and ensuring that they are is important for the remainder of the process to proceed smoothly.

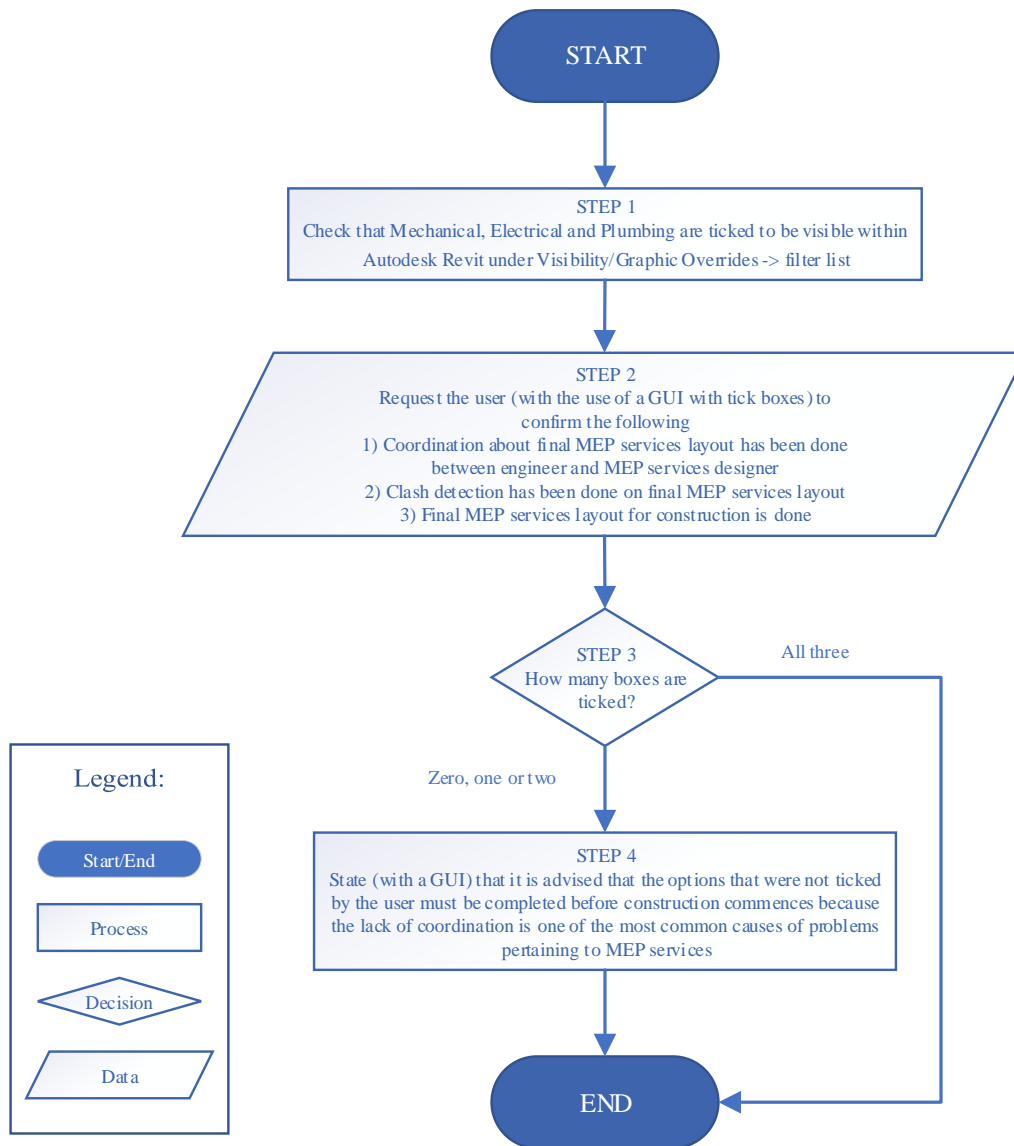


Figure 6.10: MEP services coordination verification logic

Step 2 involves requesting information from the user regarding the current state of affairs pertaining to the MEP services design. A GUI must be developed which requests the user to confirm the following

- 1) Coordination on the final MEP services layout has been done between the engineer or architect, and the MEP services designer
- 2) A check for clash detection has been done on the final MEP services layout
- 3) The final MEP services layout for construction has been completed

Figure 6.12 shows an example of the GUI which needs to be completed by the user.

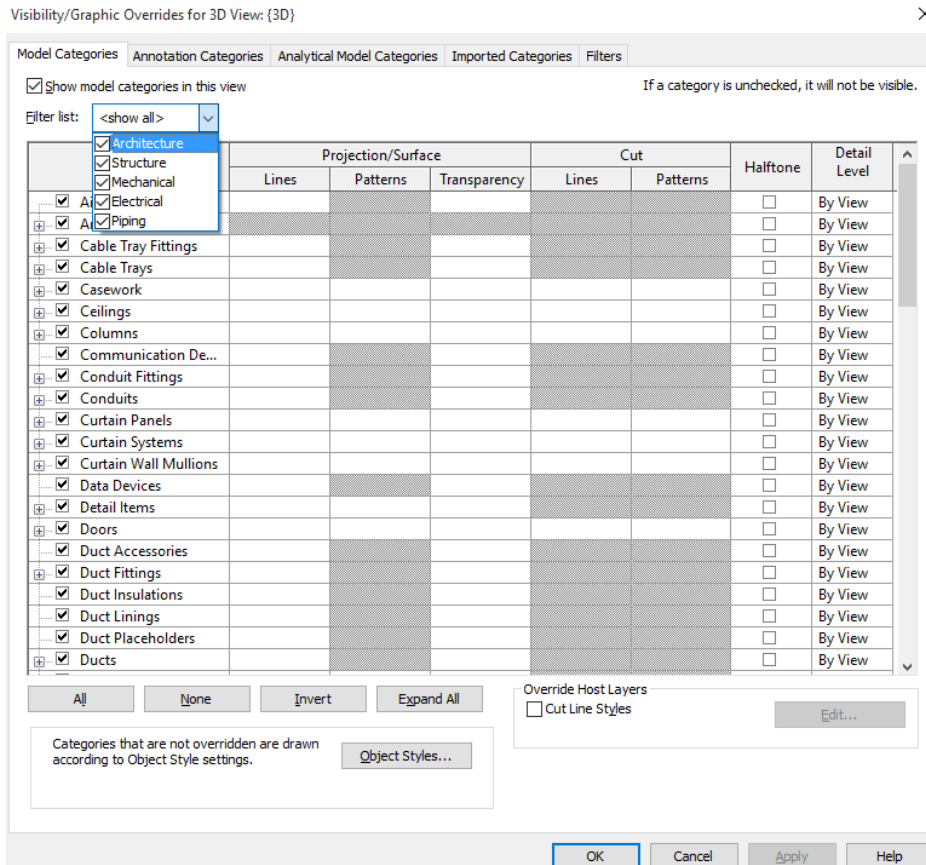


Figure 6.11: Ensuring visibility of services

Step 3 checks whether all the boxes have been ticked by the user. If all the boxes have not been ticked, then Step 4 is needed. Step 4 involves the development of a GUI which recommends to the user that the options which have not been checked should be completed before construction commences. Figure 6.13 shows an example of how the recommendation can be implemented in a GUI. The objective is to ensure that the MEP services layout is finalised before construction commences and emphasize this by reminding the user thereof and of its importance.

Please confirm if the following has been done:

Coordination about final mechanical, electrical and plumbing services layout has been done between engineer and mechanical, electrical and plumbing services designer

Clash detection has been done on final mechanical, electrical and plumbing services layout

Final mechanical, electrical and plumbing services layout for construction is completed

Figure 6.12: GUI developed to check whether coordination on MEP services is complete

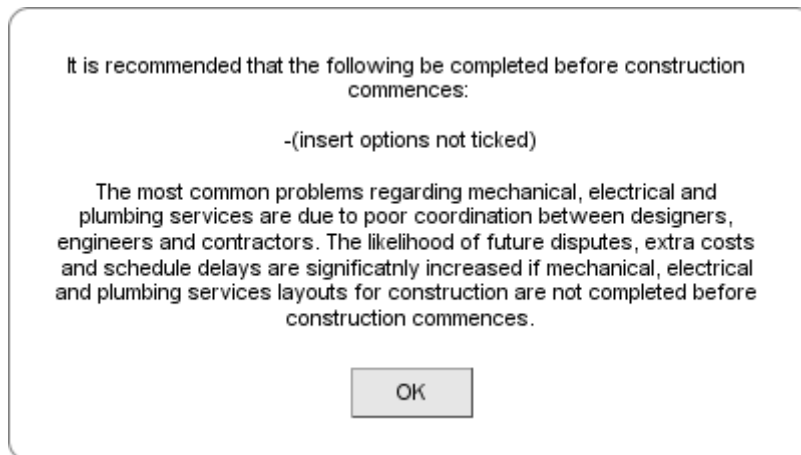


Figure 6.13: Recommendation for services coordination GUI

6.5 CONCRETE COVER VERIFICATION

The third identified aspect to be considered is the concrete cover. The aim is to reduce problems during construction which result from insufficient cover. Most of the interviewees indicated that the common specified cover, usually 30 mm, is often difficult to obtain due to the manufacturing tolerances on the reinforcement bars, which can be up to 4 mm per bar, and to human error. The interviewees recommended that a tolerance of approximately 10 mm be added to the cover if a relatively small cover is specified. Interviewees stated they preferred a specified cover in the region of 50 mm. Interviewees also stated that the connections between slabs and columns are often the most difficult areas in which to reach the specified cover.

In support of the verification, the Eurocode provides a tolerance of at least ± 10 mm for the cover of reinforcement bars. The Eurocode first determines a minimum cover required and then adds around 10 mm for tolerance (*Eurocode 2, 2004*). It should, however, be noted that larger diameter bars could be required due to the decreased effective depths.

6.5.1 Process

A description of the process is provided in the subsection which follows and is supported by Figure 6.14.

For this verification to be successful, the following information needs to be provided by users within the process:

- The materials of which the elements are made

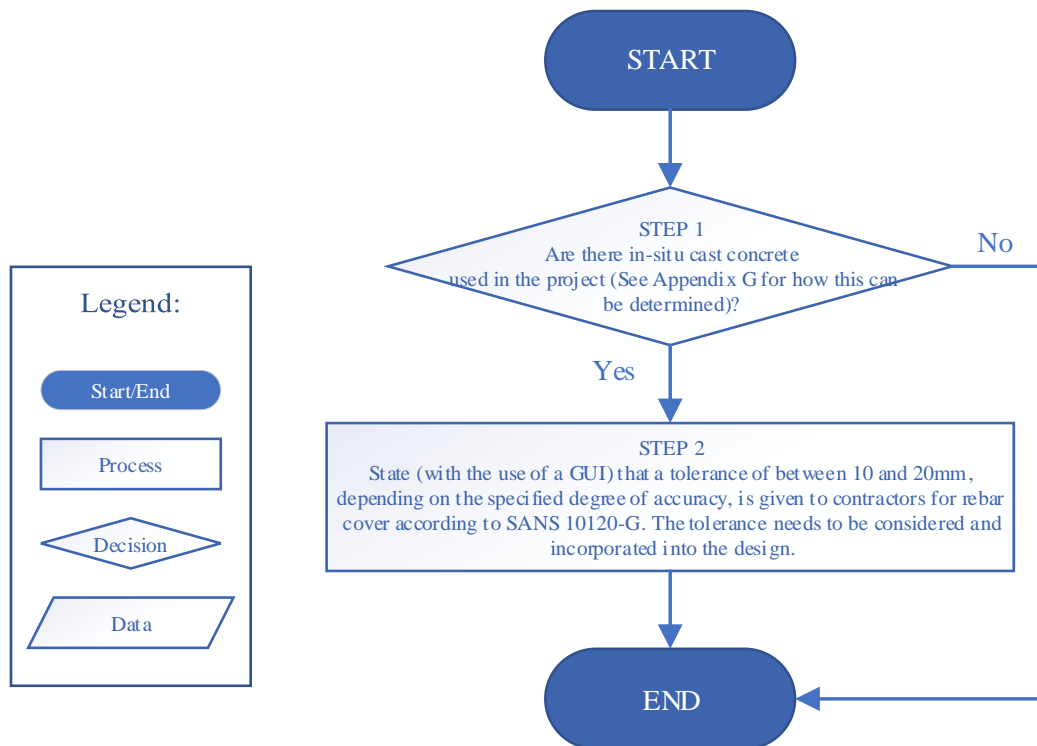


Figure 6.12: Concrete cover verification logic

Step 1 is to determine whether in-situ-cast concrete will be used in the project. The process for determining whether in-situ-cast concrete is used is illustrated in Appendix G. If in-situ concrete is used in the project, it implies that steel reinforcement will be fixed on site which will have a certain specified concrete cover chosen by the designer.

If in-situ concrete is used in the project, step 2 occurs. Step 2 involves reminding the user that a tolerance of between 10 and 20 mm, depending on the specified degree of accuracy, is given to contractors for reinforcement cover, according to SANS 10120-G (South African Bureau of Standards, 1982). The tolerance needs to be considered and incorporated into the design. This recommendation can be done with a GUI. Figure 6.15 shows an example of the recommendation GUI. The objective is only to inform the user of this tolerance and to let the user then use his/her own discretion.

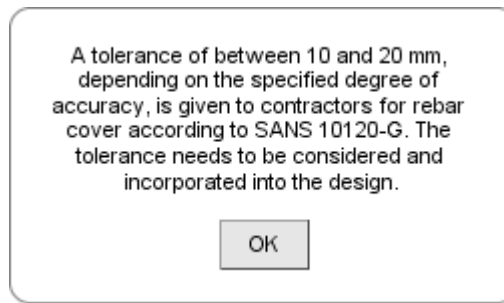


Figure 6.13: GUI reminder to check concrete cover tolerance specification

6.6 CONCRETE COLUMN CROSS-SECTIONS VERIFICATION

Another aspect identified as needing consideration, is the repetition of concrete column cross-sections. The aim of this verification is to reduce the number of different types, in terms of dimensions, of cross-section used. The aim is to enhance repetition, and thereby the learning curve of the labourers involved. Minimising the number of different cross-sections can increase the construction efficiency by reducing the time and cost needed for construction of the different formwork assemblies required for each type. The ability to employ repetition instead of unnecessary variation can prove to be critical to efficiency, especially in projects where numerous elements of the same type are used.

6.6.1 Process

The logic behind the verification is discussed in the subsection which follows and is supported by Figure 6.16.

For this verification to be successful, the following information needs to be provided by users within the process:

- The materials of which the column elements are made

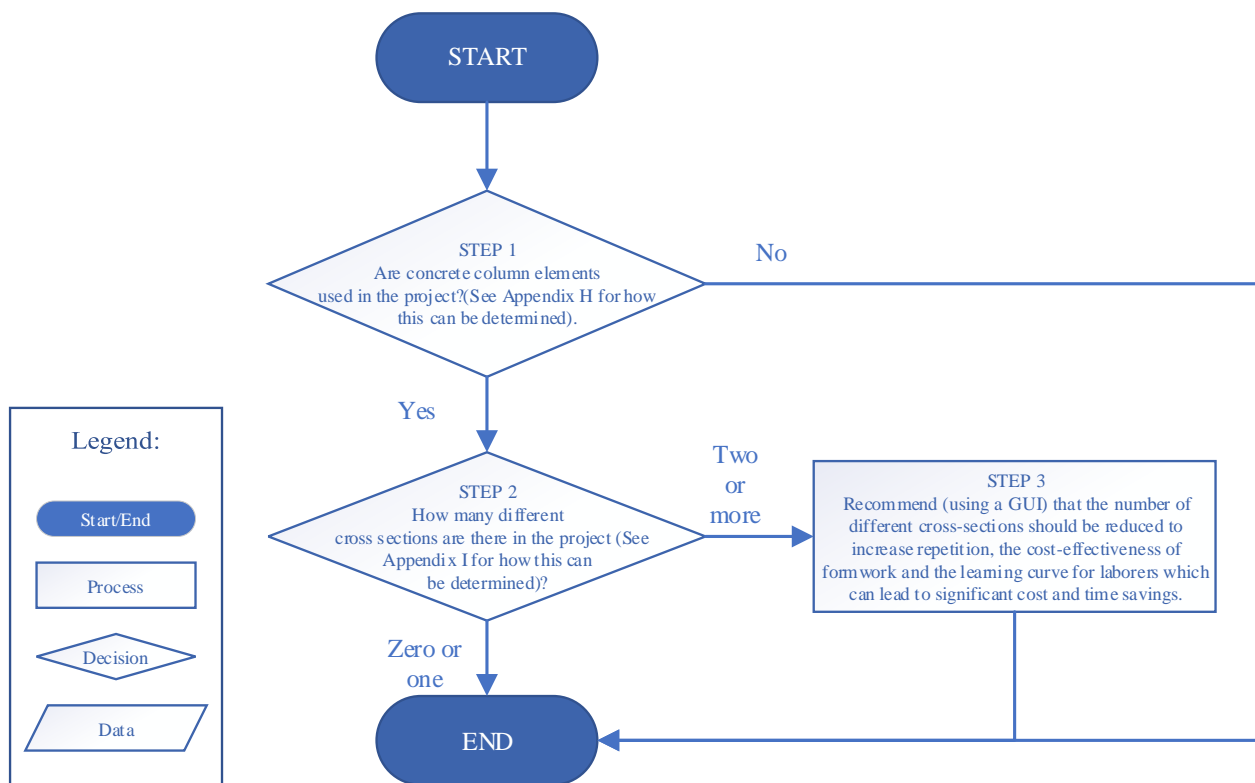


Figure 6.14: Verification of cross-sections of concrete columns

Step 1 is to determine whether concrete column elements are used in the project. Appendix H shows how this can be done. If there are items within the list, proceed to step 2.

Step 2 inspects the list made in step 1 which shows all the different column cross-sections used in a project (See Appendix I). If two or more different cross-sections are used in a project, proceed to step 3. Step 3 involves the development of a GUI which recommends that the user reduce the number of different types of cross-sections used. The GUI will also state to the user why it is recommended that fewer cross-section types are used. Figure 6.17 shows an example of such a recommendation. The objective is to reduce the number of different cross-section used within a project.

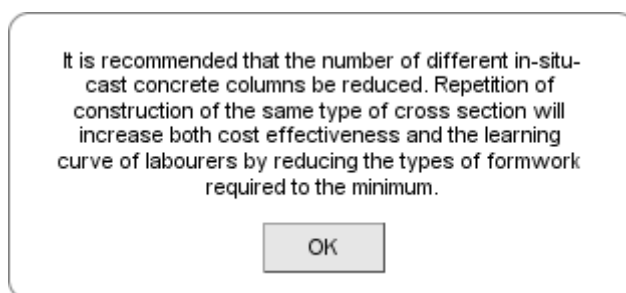


Figure 6.15: GUI recommending cross-section repetition

6.7 CONCRETE TYPES VERIFICATION

The final aspect developed regards the number of types of concrete used in a project. The aim of the verification is to reduce the number of different types of structural concrete (in terms of concrete strength) that will be used in a project. Several interviewees indicated that it often occurs that too many different types of concrete are used in a project. This makes the ordering of concrete unnecessarily difficult and complex. Several interviewees stated that there was no difference between, for example, using 25 and 30 MPa concrete. Interviewees stated that using only two types of concrete would be sufficient and that typically using only a relatively stronger concrete, such as 40 MPa concrete, and a 25/30 MPa concrete were sufficient.

6.7.1 Process

The logic used in this verification is discussed in the paragraphs which follow and is supported by Figure 6.18.

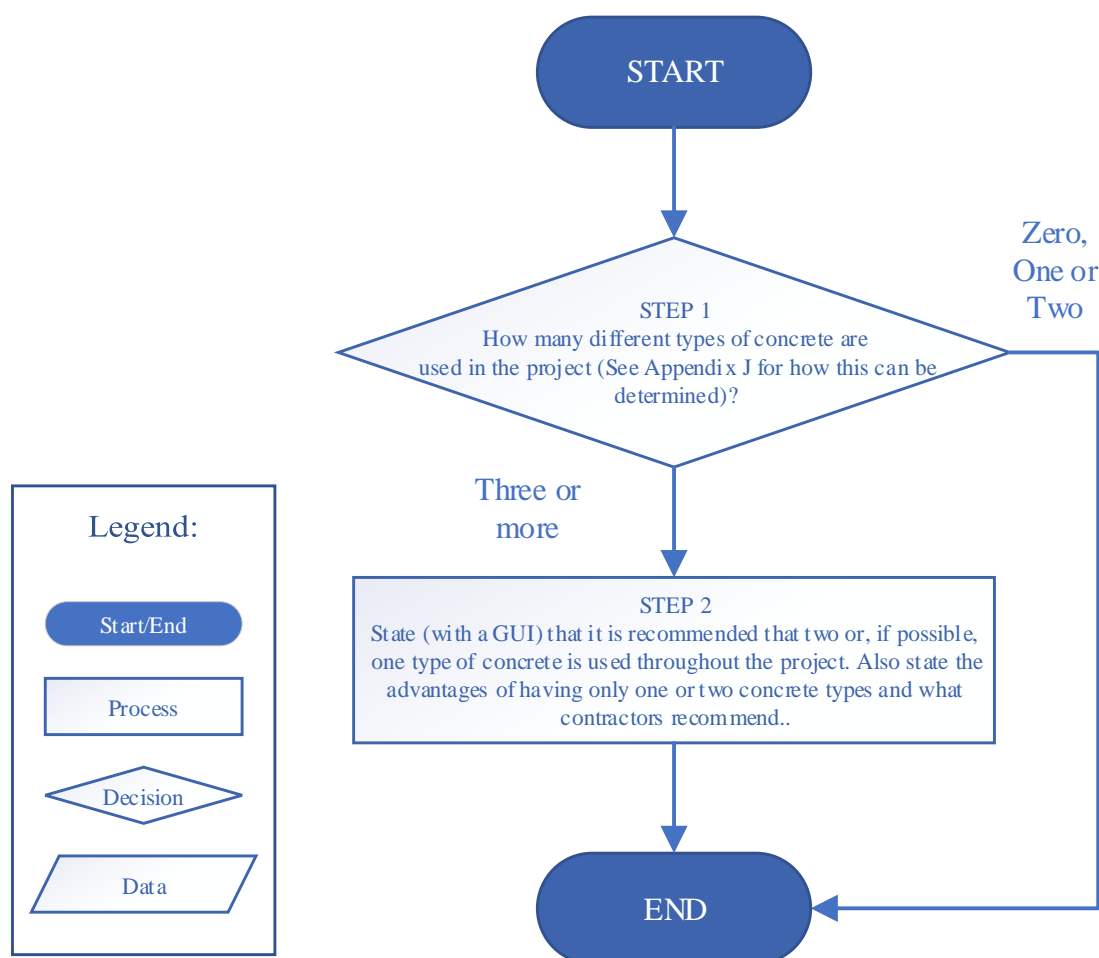


Figure 6.16: Verification of concrete types

For this verification to be successful, the following information needs to be provided by users in the process:

- The concrete compressive strength property of all concrete elements

Step 1 is to determine how many different types of concrete are used within the project. Appendix J shows how this can be determined within Autodesk Revit.

If more than two types are used for all structural members, excluding the concrete used for non-structural members or zones, proceed to step 2. In step 2, a GUI must be developed which recommends that the user should decrease the number of different types of concrete used. Figure 6.19 shows an example of the GUI. It is deemed important to simply remind the user that this type of impracticality that can occur in a design and to then let the user decide if the proposed solution (fewer types) can be incorporated or not.

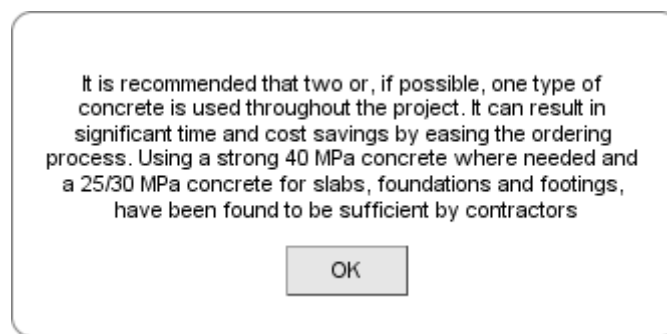


Figure 6.17: GUI recommendation for using minimum number of types of concrete

6.8 CHAPTER SUMMARY

Five verifications of constructability, identified in Chapter 5, were developed to be implemented in Autodesk Revit. The flow of logic behind each verification was developed and illustrated. The information which need to be captured in Autodesk Revit in order to perform the different verifications, was determined, and how and where the needed information could be obtained was also given.

It is important to note that the verifications were developed to show that Autodesk Revit can facilitate a constructability improvement process and has the required capacity for its implementation. The verifications identify potential concerns and then remind the user of their presence. A user will then be able to decide how such a concern is to be addressed.

Autodesk Revit has many functions incorporated which can be used in a process which improves constructability. After the development of the five verifications, the researcher came to realise the potential of Autodesk Revit to be used as a tool for the improvement of constructability.

The development of the proposed software required to perform the verifications will, however, be much more complicated than what had originally supposed. The aim was to develop the logic behind each verification and to determine whether Autodesk Revit had the capacity to capture the required information.

It is, however, also important to make the proposed process user-friendly for future users. How designers, engineers, or any other users, would want the process to be implemented is determined in Chapter 7. Chapter 7 will also serve as a validation of the proposed process.

CHAPTER 7

Process Validation

Figure 7.1 shows the content and research stage of Chapter 7 compared to the other chapters

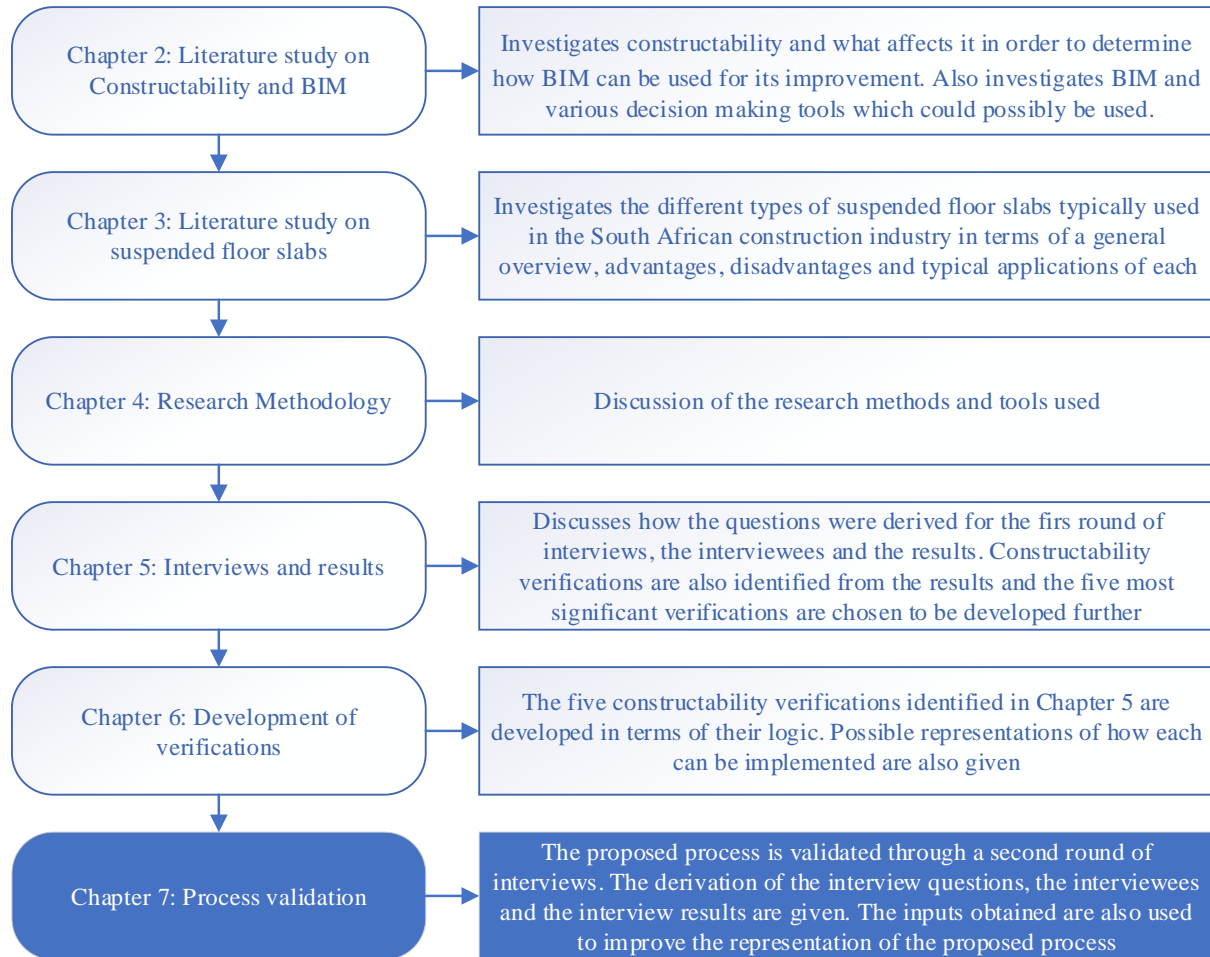


Figure 7.1: The content and research stage of Chapter 7 compared to the other chapters

7.1 INTRODUCTION

This chapter reports on the validation of the constructability analysis process proposed in Chapter 6 through interviews with experienced civil engineering consultants and designers. Relevant questions to determine whether consultants or designers could benefit from the proposed constructability analysis process, how they would prefer it to be implemented, how their design procedure generally works and the level of adaptation of BIM, were determined. The results of the interviews were discussed, analysed and entered into the software used, to develop further representations of how the constructability analysis process should be implemented. The experience of the participants interviewed is also presented and discussed.

A process which would encourage all team members to consider project-specific parameters before design commences is also proposed to the interviewees and their opinions of and recommendations for it were used to develop a representation of how the process should be implemented.

The aim of the research reported in this chapter was to validate the proposed processes and to determine the preferences of consultants in terms of the implementation of the proposed technique.

7.2 PARTICIPANTS

7.2.1 Experience

Six consultants were interviewed for the purpose of validation of the development of the proposed process. All six of the interviewees had experience in the use of civil engineering design software, of which three had experience with Autodesk Revit. The experience of each consultant in the consulting industry, with civil engineering design software, and with Autodesk Revit in particular, is shown in Figure 7.2. The average experience of the interviewees in the consulting industry was 11.7 years, the average experience with the use of civil engineering design software was 10.6 and the average experience with the use of Autodesk Revit was 3.83 years.

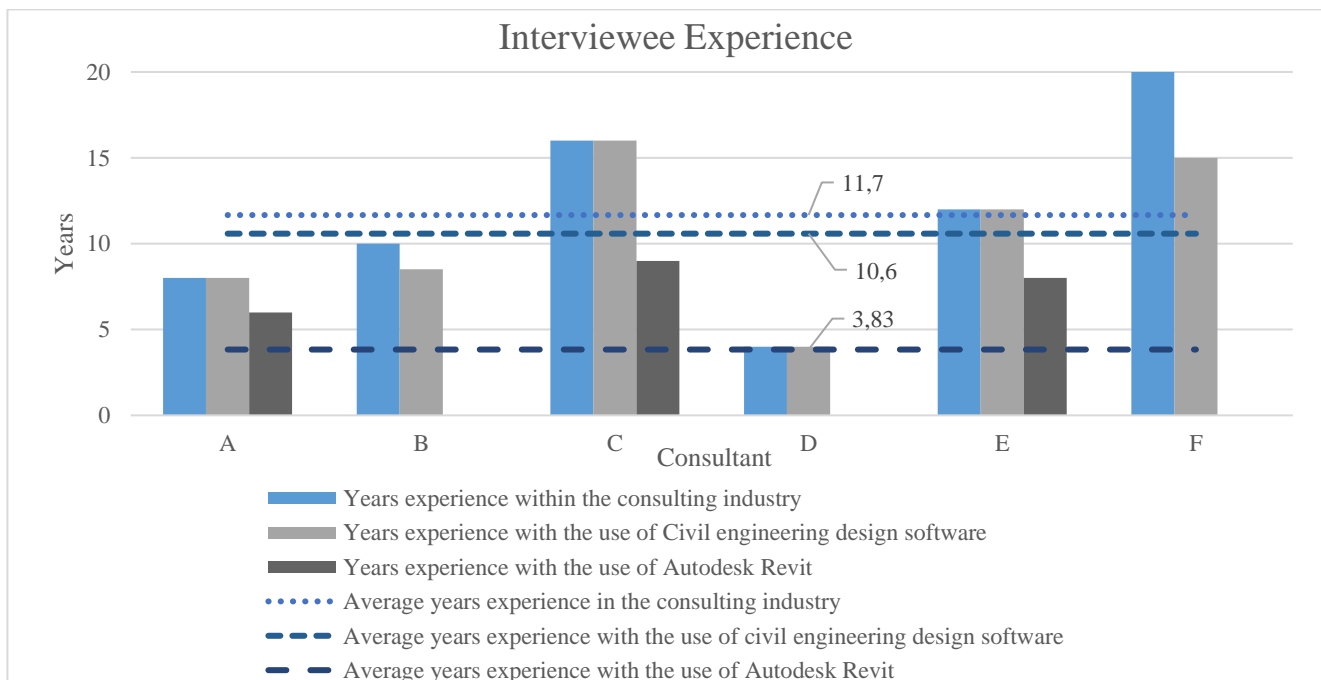


Figure 7.2: Experience of interviewees (Round 2)

The experience of the interviewees within the consulting industry, and those with the use of civil engineering design software, can be seen as high. The interviewee pool's experience with the use of Autodesk Revit, however, is much lower. Autodesk Revit, however, is a relatively new software used within the South African consulting industry, as indicated by Goldswain (2016). It was seen as an advantage for this study that the interviewee pool had any experience with its use.

The distribution of the interviewee pool's experience with the use of civil engineering design software is shown in Figure 7.3. The distribution can be seen as being relatively wide, with the experience ranging from four to sixteen years. Five of the six interviewees had more than five years' experience with the use of civil engineering design software. Civil engineering design software refers to any software which is used for design within the civil engineering consulting industry.

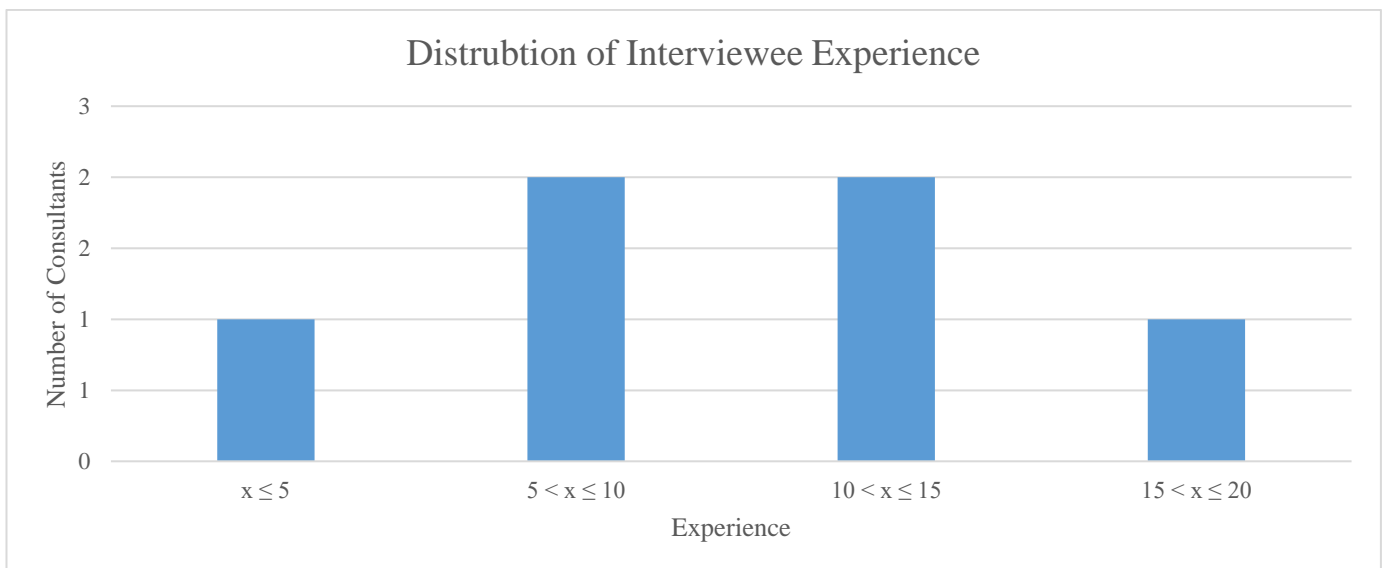


Figure 7.3: Distribution of interviewee pool experience of using of civil engineering design software (Round 2)

7.2.2 Tertiary qualification

All six of the interviewees had obtained some form of tertiary qualification. The interviewees' tertiary qualifications and their positions in their respective companies are summarised in Table 7.1. All the interviewees had obtained a bachelor's degree in civil engineering and three of the interviewees had obtained either master's or doctorate degrees in Structural Engineering. Two of the interviewees are registered professional engineers and three others are in the process of becoming registered professional engineers. Five of the six interviewees work as full-time consultants and one does part time consultation work as a university lecturer.

Table 7-1: Summary of interviewees' tertiary education and position within respective companies (Round 2)

Contractor	Tertiary Education Obtained	Position in Company
A	BEng. (Civil)	Structural Engineer
B	PhD (Structures) and Graduate Diploma in Engineering (Geotechnics and Materials)	University Lecturer
C	MEng. (Structures)	District Practice Area lead (Structures)
D	MEng. (Structures)	Structural Engineer
E	BEng. (Civil)	Managing Director and Professional Engineer
F	National Higher Diploma in Civil Engineering and BEng. (Civil)	Director and Professional Engineer

From Table 7.1 it can be concluded that the interviewee pool can be seen as highly educated, with all the interviewees having obtained at least a bachelor's degree in civil engineering. The inputs from the interviewees are thus all based on both obtained knowledge and experience.

7.3 DERIVATION OF QUESTIONS

The interview schedule used can be found in Appendix L. This section describes the derivation of the questions that were asked of the interviewees. The aim of the second round of interviews can be divided into three parts. The first was to determine whether consultants would benefit from the proposed constructability analysis process, consisting of verifications, which aimed to identify possible concerns in constructability of which they needed to be aware. The second was to determine how consultants would want the proposed constructability analysis process to be implemented. The third, and final part, was to determine the opinions of consultants regarding the process which would allow consultants to consider using project-specific parameters at some stage during a design.

To satisfy the aim of the second round of interviews, it was deemed important to obtain the following information from the process:

- 1) The current level of popularity of BIM
- 2) Whether consultants could benefit from the proposed constructability analysis process
- 3) Consultants' preferences in terms of the representation and design of the proposed

process, to make the process user-friendly and easy to use

- 4) Whether the choice and implementation of project-specific parameters during some stage in the project lifecycle would be beneficial and at which stage
- 5) The general design procedure used by consultants
- 6) Further comments from consultants on the study and the proposed process

Each aspect is discussed individually below.

1) The current level of BIM adoption was deemed important in order to obtain an indication of the popularity of BIM within the local consulting industry and to determine whether the interviewees had any experience with BIM.

2) The validation of the proposed constructability analysis process was done by determining whether consultants thought that they would benefit from the proposed process. The proposed process was explained, and the interviewees then had the opportunity to state whether they could benefit from such a process, and also if they thought that less experienced engineers could benefit from it as well. The aim was to determine consultants' thoughts on the process and its possible benefits for all participants in a construction project.

3) Establishing the preference of the contractors in terms of the implementation of the proposed process was also an aim. The consultants' preferred implementation was determined by giving the interviewees options in terms of how the process could work, be represented and the level of detail they would want to receive as feedback.

4) Another process aimed at improving constructability was proposed to the interviewees. The interviewees' opinions were obtained on a process which could incorporate project-specific parameters during some stage of the design process. The project-specific parameters included, but were not limited to:

- Project location
- Distance from suppliers (precast, concrete, etc.)
- Contractors' preference in the area
- Weather

The proposal was to request the user to give the details of the abovementioned project-specifics

(interviewees could add further parameters) and to ensure that these project-specifics were considered in the planning, as they could possibly play an important role in a number of decisions. The process was developed based on the constructability-affecting factors identified in Section 2.4. By investigating and determining consultants' views on the matter, the need for such a process, and whether consultants could benefit therefrom, could be determined.

5) The design procedure generally used was determined, in order to identify the possible future users of the proposed process and where it was likely to be used during the design process. Due to the different types of software available for use for different functions and needs of a project, it was necessary to determine the current use of BIM within the modern design procedure.

6) In conclusion, the interviewees had the opportunity to make any further comments regarding the proposed process.

7.3.1 Layout of interview questions

The questions asked during the interviews were divided into the following sections:

- General
- Initial process
- Investigation of possible constructability concerns
- Viewing constructability concerns
- Frequency of constructability concern messages
- Detail level provided in constructability concern messages
- Implementation of the constructability analysis process
- Implementation of project-specific parameters
- Design procedure
- Concluding remarks

General

In the General section, the local popularity of BIM was determined through asking if the interviewees' companies make use of BIM. The study was also validated by asking the interviewees if consultants could benefit from the proposed process.

Initial process

In the initial process section, the aim was to determine how consultants would prefer the initial stage of the constructability analysis process to be implemented, i.e. the first step of the process. Interviewees were asked if they would prefer to be able to select which constructability verifications they want to be done or if they would prefer to be able to do only all the available verifications. The interviewees were given GUIs which show examples of the two options. The interviewees also had the opportunity to give recommendations on the initial process.

Investigation of possible constructability concerns

For the concern investigation section, the aim was to determine how consultants would want to investigate the identified constructability concerns. The section refers to the part of the process occurring immediately after the constructability verifications had been applied. Interviewees were asked if they want to be able to choose which verification's identified constructability concerns they would want to inspect, or if they would want the process to show each concern separately, one at a time. Examples of GUIs for both options were shown and the interviewees had the opportunity to give recommendations.

Viewing constructability concerns

In terms of the representation of constructability concerns, a section was added to determine how each consultant would want to view concerns. The section aimed to determine how the consultants would want to handle the concerns identified. Consultants were asked if they would prefer to be able to choose to ignore or rectify a concern themselves, in which case, after they had investigated all the identified concerns, their choice for each concern would be shown in either a 'Rectify later' or 'Ignore' list. This would act as a reminder to a user of the remaining concerns they still had to rectify. Consultants could choose between the aforementioned process and, alternatively, to view an identified concern and then be able to just select 'okay'. Consultants would then be depending on their own memory in terms of which concerns needed to be rectified. Examples of GUIs for each option were shown to the consultants and they also had the opportunity to give further recommendations.

Frequency of constructability concern messages

For the next section, the number of messages per constructability concern consultants would prefer was determined. Interviewees were asked if they would prefer a single concern message per verification and have all the areas with the associated concern shown, or a concern message

at each area where an concern would occur. Interviewees also had the opportunity to provide further recommendations.

Detail level provided in constructability concern messages

In the detail level section, the amount and types of detail which consultants would want to be given in a concern message was determined. Consultants were asked which of the following options they would prefer to be shown when viewing a concern message:

- 1) What the potential problem is
- 2) Origin of concern (what contractors have encountered on construction sites regarding a certain concern)
- 3) Recommendation on how to rectify the concern
- 4) Possible advantages if the concern is rectified

Interviewees also had the opportunity to give further recommendations.

Implementation of the constructability analysis process

For the implementation section, consultants were asked when, during the design stage, they would prefer to be able to perform the constructability analysis process. This was done to determine at what stage during a design the process should be aimed.

Implementation of project-specific parameters

The feasibility of the process which aims to make consultants consider the usefulness of entering project-specific parameters for a design, was considered next. Consultants were asked if they would want project-specific parameters to be considered during some stage of the design. Examples of project-specific parameters were given. Consultants were able to add parameters which they deemed important. Consultants were also asked to state at what stage during the design process they would want such a process to be implemented.

Design procedure

The general design procedure used by consultants was determined next. This was done to obtain an indication of how the proposed process could be implemented in order to make it as practical and easy to use as possible.

Concluding remarks

To conclude the interviews, consultants were given the opportunity to provide any further recommendations or comments they had regarding the proposed processes. The final question was added to extract any information that had not already been obtained and which could prove helpful for the aim of this study. Any additional constructability verifications and process features could prove to be helpful.

The results obtained from the interviews are given and analysed in the subsection that follows.

7.4 RESULTS

7.4.1 Summary of results

A summary of the responses obtained from the respective interviewees for each question can be found in Appendix M. Table 7.2 shows a summary of the combined responses for each question.

Table 7-2: Summary of responses per question

Section	Responses Summary
General	The companies of all the interviewees use some form of BIM, with Autodesk Revit and Tekla BIMsight being the most popular.
	All the interviewees stated that the proposed constructability analysis process would help designers and consultants a lot. Some also stated that the process should be fast and easy to use.
Initial process	Five of the six interviewees preferred to be able to select which verifications they would want to perform. Some also stated that the verifications should be divided into categories and sub-categories. Two interviewees also stated that a 'check all' tick box should be added.
Investigation of possible constructability concerns	All the interviewees preferred to be able to choose which identified concerns to investigate from a list. One interviewee stated that the verifications of conditions that had been satisfied should also be given.
Viewing constructability concerns	All the interviewees preferred to be able to choose between selecting either to ignore or to rectify a concern themselves, with a list of their choices being shown after all concerns had been investigated. Two interviewees would add an option which asks the user to state why he or she made their choice in order to keep a record of the decisions made. Two interviewees would also use better descriptive wording than 'Rectify later' (either 'Accept' or 'User Correction'). An interviewee also stated it is important that the user must be notified repeatedly of the concerns until they are resolved.
Frequency of constructability concern messages	All the interviewees preferred only a single message per concern, with all the relevant areas being shown. One interviewee stated that a user would want a list of all the concerns and their relevant element IDs, and to see graphically where the concern was. Another interviewee stated that a user would want a separate window next to the viewport in Autodesk Revit, with a list of all the concerns,

	and any concern selected in it should be highlighted in the model.
Detail level provided in constructability concern messages	All the interviewees would want to know what the potential problem was. Three interviewees would want to know the origin of the concern(s). Four of the interviewees would want a recommendation on how to rectify the concern. Three interviewees would want to know the possible advantages if the concern is rectified. One interviewee stated only the potential problem should be given, and nothing else, in order not to influence the engineering judgement of the user.
Implementation of the constructability analysis process	All the interviewees stated that the process should be available at any stage in order to minimise the amount of re-design that would need to take place after the constructability analysis process had been done.
Implementation of project-specific parameters	Five of the six interviewees would want a process to be implemented which considered project-specific parameters. They stated that the process should be easy to use and able to be bypassed. The general quality of construction done in the area, formwork stripping time, crane heights, the possibility of using cranes, site boundaries and geotechnical considerations can be added to the parameters. One interviewee stated that the team leader must fill in the parameters. All the interviewees stated that the process of considering or adding project-specific parameters should be considered as early as possible, which is at the conceptual stage.
Design procedure	Most of the interviewees stated that the general procedure included the architect making provisional drawings, the engineer then analyses the drawings, some coordination between the architect and the engineer then occurs until the client is satisfied, at which stage the drawings are finalised. All this also depends on the type of contract or project.
Concluding remarks	Interviewees stated that the following could be added: a cost per kilogram for different steel sections, the cube test results of the project, it should be able to have a view showing the differences between old and new drawings, a headroom check for stairs, and the user should be able to provide the tolerances for the verifications which involve measurements. One interviewee also stated that BIM models might not yet have been set up when certain verifications were needed, this should become part of the design procedure.

7.4.2 Illustrations of results, conclusions and proposed implementation

Using Table 7.2, the results of the validation and implementation interviews were analysed for the advantages, possible disadvantages and general conclusions that could be drawn from them. Specific recommendations were discussed further, if deemed to be practical for the aim of the developed process. The results were discussed per section of the interview guide, and proposed illustrations, incorporating the inputs from the interviewees, are given for the implementation of the process.

7.4.2.1 General section

Results show that BIM was already popular in use within the South African consulting industry.

The extent of its implementation, and the type of BIM software used did, however, differ. The industry is, however, not yet at the level of implementation of the United Kingdom, although it could be seen as positives that its popularity was increasing and the local industry was adapting to the modern era.

All the interviewees stated that consultants could benefit from the proposed process, which could be seen as a validation of the study. The fact that all the interviewees stated that they could benefit from the proposed process was an indication of the need for such a process and also of its practicality. The interviewee pool could be seen as being relatively experienced, and even the most experienced among them also stated they could benefit from it.

7.4.2.2 Initial process

Most interviewees stated they would prefer to be able to choose which constructability verifications they would want to be performed, as opposed to letting the process perform all the available verifications. This is because certain verifications could possibly be irrelevant in certain cases. Consultants advised that the verifications should be categorised under the relevant headings, in order to make the selection of verifications easier. Consultants also advised that a ‘check all’ tick box should be added which could be used to automatically select all the verifications available. This feature could be helpful in saving time when a user wanted to perform all the verifications. Figure 7.4 is an example of how the initial process could be implemented and illustrated

Please select which of the following verifications you wish to be performed:

Category	Verification name	Description	Additional information required:
<input type="checkbox"/> Walls	<input type="checkbox"/> Floor-to-floor brick height increment	Measures floor-to-floor height and compares it to increments of brick heights depending on the specific brick height used	Brick height that will be used (mm): <input type="text"/> Height of mortar between bricks (mm): <input type="text"/>
<input type="checkbox"/> Services	<input type="checkbox"/> MEP services coordination	Aims to determine if MEP services layout has been finalized after coordination between the engineer and MEP services designer has taken place	Please confirm which of the following has been done: <input type="checkbox"/> Coordination between engineer and MEP services designer regarding final layout <input type="checkbox"/> Clash detection on final layout <input type="checkbox"/> Final MEP services layout is completed
<input type="checkbox"/> Columns	<input type="checkbox"/> Cross section repetition	Advises a designer to use less cross section types to enhance repetition	
<input type="checkbox"/> Concrete	<input type="checkbox"/> Concrete cover	Reminds the designer to increase cover to incorporate manufacturing tolerances and human error on the construction site	
	<input type="checkbox"/> Concrete types	Advises the designer to use less different types of concrete if more than two types are used	
<input type="checkbox"/> Select All			
<input type="button" value="Analyze Constructability"/>			

Figure 7.4: Proposed screen showing choice of constructability verifications to perform

7.4.2.3 Investigation of possible constructability concerns

All the interviewees preferred to be able to investigate each identified constructability concern individually, and in an order of their choosing. Interviewees preferred not to investigate concerns all at once or in a process which showed the concerns one-by-one. This was because users possibly wanted to investigate and address certain more important concerns first, if only a limited time schedule was available. One interviewee recommended that the verifications which have been satisfied should also be shown. This could be done in order to give the user a sense of reassurance regarding the design. Figure 7.5 shows an example of how the GUI could be illustrated, showing which verifications were successful and which should be investigated.

The following verifications identified areas where constructability improvement is possible:

Verification Name:	Status
Floor-to-floor brick height increment	Successful
MEP services coordination	Successful
Cross section repetition	Investigate
Concrete cover	Investigate
Concrete types	Investigate

Cancel

Figure 7.5: Proposed GUI for investigation of identified constructability concerns

7.4.2.4 Viewing constructability concerns

All the interviewees wanted to be able to choose either to ignore or decide that they would fix ('Rectify later') an identified concern as opposed to just being shown the concern message. Interviewees also stated they would prefer to have two lists populated with their respective choice for each concern identified. When users have done the investigating of all the possible problems identified, these two lists should be shown, giving the concerns which were chosen to be ignored and those chosen to be rectified later by the user. The lists serve as a reminder and as a summary of the user's choices.

Interviewees explained that users would want to be able to choose to ignore a concern if it were either unavoidable, and had to be accepted as it was, or was insignificant enough to be ignored. Users could also select an option to 'Rectify later' (or 'User correction' or 'Accept' as recommended by two interviewees) which implies that the user would correct the concern after

the constructability analysis process has been completed. Figure 7.6 shows a proposed representation of the lists of choices made for each constructability verification.

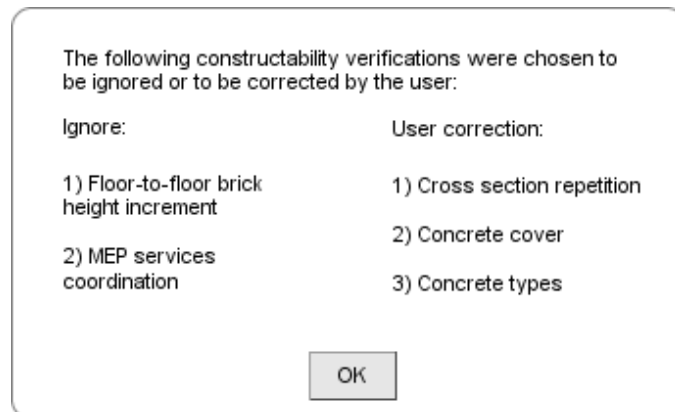


Figure 7.6: Proposed GUI showing choice for each identified constructability concern

Two interviewees advised that a user should be able to state why a concern has been ignored and that the given information should then be saved with the project, in order to keep a record of the decisions made. This can be helpful in projects which span long durations, or are postponed, or in cases where the designer assigned to the project changes, to remind the user why certain decisions were made. Figure 7.8 shows how the GUI of an identified possible constructability problem can be illustrated.

One interviewee stated that it was important for the user to be reminded of the identified concerns which had been chosen as to be rectified. This could be done with an added feature in the project browser which showed a list of the concerns chosen to be fixed by the user. Figure 7.7 shows an example of the added window, reminding the user of the potential constructability problems yet to be rectified.

7.4.2.5 Frequency of constructability concern messages

All the interviewees preferred to be shown only a single message which described the potential problem and to have (if relevant) the elements or zones highlighted where the potential problem could occur. This option was preferred above the option of having a message shown at each potential area where a concern can occur, because of the possibly unnecessarily large number of GUIs that might be shown, when a single message already satisfactorily described the potential problem.

Two interviewees stated a user would also want to have a list in the project browser which shows all the identified concerns and also shows the relevant element IDs (Autodesk Revit

generates a unique six-digit ID number for each element in a project model) of the elements where the potential problem could occur. Interviewees also stated a user would want to be able to select a potential problem in the browser and the relevant elements and/or zones must be highlighted. These recommendations would streamline the process and make it much simpler and easier to use. Figure 7.7 shows an example of the added constructability window which shows the pending constructability concerns, which still need to be resolved, with their relevant element IDs.

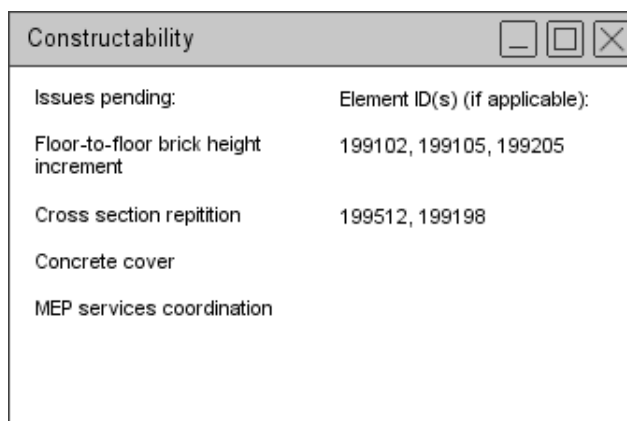


Figure 7.7: Proposed window showing pending constructability concerns with IDs of the relevant elements

7.4.2.6 Detail level provided in constructability concern messages

A relatively wide distribution, and somewhat opposing views and comments, were obtained in terms of the level and type of detail interviewees would prefer to be given by the process for the identified potential constructability concerns. All the interviewees did, however, state they would prefer to be informed of what the potential problem is. A majority of the interviewees also stated they would want to be informed on how a potential problem could be rectified. This could especially prove to be an important part of the notification in cases where inexperienced users are using the process, or the user has limited knowledge of constructability. Figure 7.8 shows an example of the level of detail a user would prefer to receive.

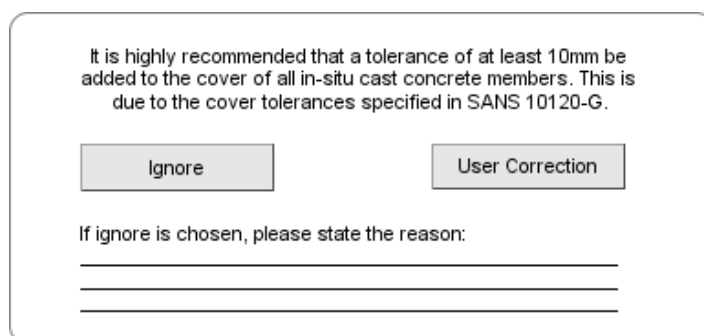


Figure 7.8: Proposed GUI for choosing how to handle a constructability concern

7.4.2.7 Implementation of the constructability analysis process

All the interviewees stated they would want the process to be available at any given time due to a user possibly wanting to perform different verifications at different stages during the design. From this, it was concluded that the process should be an added feature in Autodesk Revit, which can be performed at any time and as many times as desired.

7.4.2.8 Implementation of project-specific parameters

A majority of interviewees stated that they would want project-specific parameters to be implemented as part of the design process at the earliest possible stage (conceptual stage). The idea is to have the user consider adding any project-specific parameters which could affect the design and construction of a project if not considered at an early stage, or possibly just forgotten. This could be done through the use of a GUI which requested the user to state the conditions for certain identified project-specific parameters.

The project-specific parameters identified as possibly being significant prior to the interviews were project location, distance from suppliers (for precast members, concrete, etc.), construction preference of contractors in the area and the weather in the area. During the interviews, interviewees stated that the general quality of construction in the area, formwork stripping time, crane heights, the possibility of using cranes, site boundaries and geotechnical considerations (such as having to provide supports for slopes) should be added to the list of parameters. All of these can be added to the list of project-specific parameters, and the user should be requested upon creating a new project, in Autodesk Revit, to state the properties for these parameters. The process must be simple to use and able to be bypassed, as recommended by a number of those interviewed. Figure 7.9 shows a proposal for how the GUI could be implemented.

Please select the most relevant criteria characteristic for each of the following project parameters:

Distance from suppliers (concrete, precast):	Construction quality in the area:
<input checked="" type="radio"/> < 100 km	<input checked="" type="radio"/> Good
<input type="radio"/> < 500 km	<input type="radio"/> Acceptable
<input type="radio"/> > 500 km	<input type="radio"/> Poor
Construction preference of contractors in the area:	Formwork stripping time required:
<input checked="" type="radio"/> Concrete	<input checked="" type="radio"/> < 2 days
<input type="radio"/> Steel	<input type="radio"/> < 7 days
<input type="radio"/> All	<input type="radio"/> > 7 days
Possibility of crane usage:	Height available for crane(s)
<input checked="" type="radio"/> No limitations	<input type="radio"/> < 15 m
<input type="radio"/> Possible, but with some limitations	<input type="radio"/> < 25 m
<input type="radio"/> Impossible	<input checked="" type="radio"/> > 25 m
Expected weather conditions:	Supporting of slopes
<input checked="" type="radio"/> Average daily temperature above 25 °C	<input checked="" type="radio"/> Will not be required
<input type="radio"/> Average daily temperature between 10 °C and 25 °C	<input type="radio"/> Required in certain areas
<input type="radio"/> Average daily temperature below 10 °C	<input type="radio"/> Will be required intensively

Figure 7.9: Proposed project parameter GUI

7.4.2.9 Design procedure

From the interviewees' description of a general design procedure, it is evident the proposed process of constructability analysis must be available during the entire design and coordination period for the user to gain the most from its application. The proposed process of incorporating project-specific parameters can possibly only be available at a stage where several important design decisions has already been made, such as opting for the use of precast members, but could still prove to be helpful if implemented upon the creation of a new project within Autodesk Revit.

7.4.2.10 Concluding remarks

Interviewees advised a range of features and/or constructability verifications that can be added to the constructability analysis process. From this, it is evident that a large number of verifications are still to be identified, and added to the list of verifications identified, after the first round of interviews, for this study. The extent to which a constructability analysis process

could improve constructability could prove to be efficient and helpful, but further study is needed in the area.

7.5 GUIDELINES FOR PROCESS IMPLEMENTATION

Using the results from the validation interviews, a set of guidelines were developed for the implementation of a constructability analysis process. This section summarises how consultants would prefer a constructability analysis process, which is applicable to any type of structure and structural elements, be implemented in BIM. Table 7.3 shows the guidelines developed.

Table 7-3: Guidelines developed for the implementation of a constructability analysis process

Process stage	Consultants' preferences
Start	Consultants prefer to be able to select the constructability verifications to be performed. The verifications should be grouped under relevant headings, along with short descriptions of each verification. If further information is required from users, it can be requested during the start of the process. Consultants would also prefer to have a 'select all' option for the verifications.
Identified concerns	After the verifications have been performed, consultants prefer to be shown which verifications identified constructability concerns and which were satisfied.
Investigation of concerns	Consultants prefer to be able to choose which identified concerns they want to investigate.
Viewing of constructability concerns	Consultants prefer to have a choice of how a concern is handled. Consultants would want to choose to either ignore a concern or to state they will address it after the investigation of the concern. Consultants also prefer to be able to give their reason(s) for their choice(s) and that the reason(s) should be saved for future use.
Constructability concerns message frequency	Consultants prefer to view a single message per identified concern and to have all the relevant areas or members shown together.
Detail level of identified concerns	Consultants prefer to be only informed of what potential problems could occur and to be given recommendations on how a concern could be rectified.
Implementation of constructability analysis process	Consultants prefer to have a constructability analysis process at their disposal at any stage whilst using BIM.

7.6 SUMMARY

A second round of interviews was conducted with experienced consultants using a predetermined interview schedule. The aim of the interviews was to validate the proposed constructability analysis process and obtain the preferences of consultants in terms of the

implementation of the proposed process. Furthermore, it was necessary to determine whether a feature which encouraged a user to consider the addition of project-specific parameters could be practical and useful. Consequently, it was also an aim to determine the applicability of the proposed processes and where each should fit into the design process of a project.

A range of useful responses was obtained from the consultants. Their responses were summarised and analysed. All the interviewees stated that the proposed constructability analysis process, consisting of constructability verifications, could be helpful, and they could benefit therefrom.

The preferences of contractors in terms of the implementation of the proposed constructability analysis process was obtained. Their preferences were used to develop proposed representations of the GUIs, as well as windows, that could be used during the constructability analysis process.

Interviewees were also asked if they could benefit from a process which made a designer consider project-specific parameters. A majority of interviewees stated they could benefit therefrom, even if a user was only reminded of these project-specific parameters.

This chapter attained its aim of validating the proposed process. Although the proposed process has only been developed to a small extent, the potential of the process for becoming a method of saving time and costs in the future, if further developed, was realised through the interviews discussed in this chapter. Conclusions and recommendations regarding the entire research project will be discussed in the chapter which follows.

CHAPTER 8

Conclusions and recommendations

8.1 INTRODUCTION

The aim of this research was to develop a process with which BIM can be used to verify the constructability of a design for suspended floor slabs and their supports. The aim was achieved through a study of the available literature, together with the knowledge gained from interviews conducted with experienced contractors and consultants.

This chapter concludes the research study with conclusions and recommendations for future studies.

8.2 SUMMARY OF STUDY

The focus of this study was on enhancing the constructability of suspended floor slabs and their supports through the use of BIM, more specifically, Autodesk Revit, as a tool.

Chapter 2 reports on a literature study that was undertaken to investigate constructability in terms of its definition, barriers and benefits. In parallel, this study determined factors affecting constructability. A range of factors was found, and these factors were analysed in terms of their compatibility with BIM. BIM was described in terms of its current implementation in the construction industry and the IFC classes associated with it. The compatibility of constructability in BIM was addressed. The current application of BIM in the construction industry was addressed and previous similar studies were investigated. This investigation emphasised the need for a constructability enhancement process implemented on BIM.

The different types of suspended floor slabs used in the South African construction industry is presented in Chapter 3. The slab types are described in terms of an overview, associated advantages and disadvantages and typical applications.

The research methodology was described in Chapter 4. Only qualitative research methods were used in this study. Two rounds of interviews were conducted, each for different purposes. The first round of interviews was conducted to determine the constructability issues encountered

with suspended floor slabs, and their supports, by contractors. The questions asked during the second round of interviews were developed for validation of the study and for determining consultants' preferences in terms of the implementation of the constructability analysis process.

In Chapter 5 there is a report on a range of constructability problems that had been encountered with suspended floor slabs and their supports, which had been identified through the interviews. Verifications of possible concerns over constructability which could be implemented in BIM, were identified from the problems. The highest-ranking verifications were selected for development through the use of two sets of criteria.

Chapter 6 describes how the selected verifications were developed in terms of the logic behind the verifications and how they can be used to identify potential constructability concerns. The logic developed is represented by the use of flow diagrams. The aim was to develop the logic to an extent where the diagrams could easily be used to program the proposed process for implementation in BIM.

In Chapter 7, the discussion concerned the method by which the proposed process was validated through interviews with consultants in the industry. The aim was to determine whether consultants could benefit from the process, their opinion thereof, and how they would prefer the process to be implemented.

8.3 CONCLUSIONS

To achieve the aim of this study, several objectives were defined and achieved.

The first objective was to determine the factors which affect constructability. An in-depth literature study was undertaken and interviews were conducted to achieve the objective.

From the first round of interviews with experienced contractors, it was evident that the contractors all agreed that the enhancement of the consideration of constructability during the design phase would result in significant advantages for all project participants.

It was also realised that numerous problems regarding the constructability of suspended floor slabs and their supports are regularly encountered. The areas, or project characteristics, from

which the most problems originated were MEP services, down-stand beams, raking columns, load-bearing walls and concrete cover. There are also numerous design preferences of contractors which could make construction easier and more efficient.

The next objective was to determine possibly useful verifications of constructability. From the information gathered through the interviews with contractors, a long list of constructability problems was identified. Possible constructability verifications were also determined.

From the list of verifications identified, a number of verifications were selected to serve as examples of how a constructability analysis process could be implemented. This was achieved through the use of two sets of criteria, using the impact on time, cost or quality (based on the researcher's opinion), and the relative emphasis on their significance highlighted during interviews. Using the two sets of criteria, the highest-ranking verifications were identified to use as examples.

The next objective was to provide visual representations of the end-product. The inputs from the consultants from the second round of interviews were used to develop visual representations of how the process could be implemented. Examples were used to demonstrate the application of the proposed constructability analysis process.

The final objective of the study was to develop general guidelines for the implementation of a constructability analysis process. This was achieved by using the inputs of consultants from the second round of interviews to develop guidelines based on the preferences of consultants. The guidelines were developed to be applicable to any similar constructability analysis process.

The development of the guidelines (See Section 7.5) of a constructability analysis process can be seen as the final answer of this research. The guidelines describe how a constructability analysis should be implemented and used.

In accordance with the aim of the study, it can be concluded that BIM, and more specifically Autodesk Revit, has the capacity for implementing a process which aims to improve constructability. Because of the wide range and large amount information which can be stored in BIM, the process can be developed to incorporate a wide range of different verifications. Based on the opinions of all the participants for both rounds of interviews conducted for this

research, the development of the proposed process could prove capable of saving significant amounts of both costs and time. Further research and development of the proposed process is, however, necessary, but its potential impact and the need for it have been identified.

8.4 RECOMMENDATIONS

The recommendations from this study are discussed in this section.

8.4.1 Research methods

It is recommended that more structured one-on-one interviews be undertaken to identify more constructability problems associated with other relevant structural components.

The case study used also proved to be helpful in terms of establishing a background for the author and also to develop the questions to be asked in the interviews. It is recommended that for future studies, where available, more case studies be used for the same purposes and to identify commonly encountered constructability problems.

8.4.2 Constructability analysis process

The possibility of developing a process which generated a ‘constructability score’ for a given design was initially considered as part of this research. However, a score can be misleading, and the focus should rather be on identifying potential constructability problems in a design. The user should be allowed to assess the importance of the problem, which might vary according to the project concerned. It is recommended that the same method used in this study be retained for future studies.

It is recommended that the constructability analysis process be developed to analyse the constructability of other structural components such as roofs, foundations, retaining walls and steel structures. The ultimate aim is that a user should be able to perform a constructability analysis process on any type of structure.

8.4.3 Validation of process

It is recommended that all further developments undertaken regarding this research study be validated by experienced consultants. It should also be determined, as in this study, how consultants would prefer a constructability analysis process to be implemented. This is done to

make the process as user-friendly, and easy to use, as possible.

One-on-one structured interviews were used to validate this research and it was found that the method used was effective. It is recommended that the same process be followed for future validations, and more participants with a wider range of experience, and fields in which they operate, should be interviewed.

8.4.4 Verifications

Recommendations regarding the further development of each of the five example verifications developed in Chapter 6 are made in this subsection.

8.4.4.1 Brick height increment verification

The verification can be further developed to incorporate all the elements which are made from bricks within a BIM model.

8.4.4.2 MEP Services coordination verification

A further development of the verification would be to recommend how MEP services should be installed for certain wall and slab thicknesses.

8.4.4.3 Concrete cover verification

The further development of the verification can involve cover recommendations according to the SANS codes for specific structural elements such as slabs, columns and beams.

8.4.4.4 Concrete column cross-sections verification

The verification can be further developed to a point where the user is able to choose the level of repetition. A user might, for example, be able to analyse repetition per a selected number of floors.

The verification could also be developed to a point where it can differentiate between columns which have curved sides and square/rectangular columns. Because curved sides are most likely to require specially made steel formwork, the process can be developed to highlight 'curved sides' and recommend to the user that curved sides should either be avoided or repeated as

much as possible. The recommendation aims to maximise the cost efficiency of the specially made steel formwork required.

Another development of the verification could be to incorporate steel member sections and let the process make recommendations on repetition of columns, girders, purlins, truss elements, etc.

8.4.4.5 Concrete types verification

The verification can be further refined to incorporate contractors' recommendations on the types of concrete used for specific structural elements.

8.4.5 Conclusion of recommendations

The proposed process is not restricted to what was done in this research and undertaking further developments thereof from other perspectives could prove to be beneficial. The enhancement of the constructability of construction projects for the benefit of all project participants, by using BIM software as a tool, is a field of research which requires further investigation and development.

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Appendices

Appendix A: Consent form for first round of interviews



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STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

You are invited to take part in a study conducted by Dirk Jacobus Kotzé, from the Department of Civil Engineering at Stellenbosch University. You were approached as a possible participant because you fit into our research category of construction site manager, experienced construction worker or construction company owner/manager.

1. PURPOSE OF THE STUDY

The aim of the research is to determine the logic behind a process that analyses the constructability of suspended floor slabs and also to give a representation of how the proposed process could be implemented on Autodesk Revit. The process will be aimed at analysing the common suspended floor slab types used in the South African construction industry. The process will analyse aspects of floor slabs from the perspective of the contractor to help improve the constructability of floor slabs. The process will give possible constructability concerns, advantages and important constructability characteristics as a reminder to the user (the designer) to help them user in the process of making a decision on which type of floor slab will be most efficient for the specific situation.

2. WHAT WILL BE ASKED OF ME?

If you agree to take part in this study, you will be asked to answer questions administered during one-on-one interviews. The questions to be asked are all based on the construction of suspended floor slabs. The interviews will aim to identify constructability problems that might possibly occur, the level of labour skill required, relative (relativity of costs of each type to each other) cost and construction time, as well as mechanical, electrical and plumbing installation issues for each type of suspended floor slab used in South Africa. The experience of each participant with the installation of floor slabs will also be investigated. Crane placement and truck accessibility issues on site will also be determined.

3. POSSIBLE RISKS AND DISCOMFORTS

The time required for one-on-one interviews could possibly disturb the interviewees' daily routine, therefore the interviews will be kept as short as possible.

4. POSSIBLE BENEFITS TO PARTICIPANTS AND/OR TO THE SOCIETY

The possible benefits for the participants will be that the process would improve the constructability of floor slabs by analysing the constructability at the design stage which would result in fewer constructability issues occurring during the construction phase. This would make projects more cost and time efficient.

5. PAYMENT FOR PARTICIPATION

Participants will be interviewed on a voluntary basis and no compensation will be given for participation.

6. PROTECTION OF YOUR INFORMATION, CONFIDENTIALITY AND IDENTITY

You have the option of being completely anonymous at the interview. If you choose to stay anonymous then any information you share with me during this study and could possibly identify you as a participant will be protected by using pseudonyms and not the actual names of the participants. This will be done by making sure that the one-on-one interviews are kept confidential.

The information will be shared only for academic purposes.

If the results obtained are to be published the real names of the participants will not be published but pseudonyms will be used instead to retain confidentiality.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to participate in this study or not. If you agree to take part in this study, you may withdraw at any time without any consequence. You may not remain part of the study if you are unable to answer key questions that will lead to the successful completion of the study. The researcher may withdraw you from this study if you violate the terms and conditions under which the research is to be conducted. If you choose to withdraw from the study, then all the information that you have given up to that point will be disposed of.

8. RESEARCHERS' CONTACT INFORMATION

If you have any questions or concerns about this study, please feel free to contact Dirk Jacobus Kotzé (16960548@sun.ac.za) and/or the supervisor Prof Jan Wium (janw@sun.ac.za) from the Department of Civil Engineering at Stellenbosch University.

9. RIGHTS OF RESEARCH PARTICIPANTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

DECLARATION OF CONSENT BY THE PARTICIPANT

.....

As the participant I confirm that:

- I have read the above information and agree that it is written in a language that I am comfortable with.
- I have had a chance to ask questions and all my questions have been answered.
- All concerns related to privacy, and the confidentiality and use of the information I provide, have been explained.

By signing below, I _____ agree to take part in this research study, as conducted by Dirk Jacobus Kotzé.

Signature of Participant

Date

DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the principal investigator, I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition, I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator (who has signed a non-disclosure agreement), and this "Consent Form" is available to the participant in a language in which the participant is fluent.

Signature of Principal Investigator

Date

Appendix B: Interview schedule for first round of interviews



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Identifying regular or potential constructability problems related to suspended floor slabs and the related site efficiency problems in terms of crane placement and truck accessibility in the South African construction industry.

Introduction

With the increase in the complexity of modern day construction projects, the issue of constructability has become increasingly important. It is recognised that the integration of construction information in the early stages of a project provides a good opportunity for significant time-and cost-savings (Hanlon & Sanvido, 1995). It is important that design professionals need to be alert to the possible problems and claims that can result from a design's constructability profile. When a project has inherent constructability problems, the results of litigation can involve change order disputes and issues, delay claims and owner dissatisfaction. In more extreme cases, direct claims could be made against the company responsible for the design. The claims could be for poor plans, estimates, specifications or schedules that either made the project difficult to build, more time consuming or more costly than had been planned.

To integrate information regarding constructability efficiently and effectively into the design phase, it should be organised and be accessible in a format that is desirable to its users (mostly designers). An even further, and more effective, improvement, would be possible if the software that designers use for their designs were able to identify possible future constructability problems whilst the designer was using the software.

Building Information Modelling is becoming increasingly popular internationally and the benefits of its use have proven to be immense. Using Building Information Modelling to increase the constructability of projects could possibly have significant advantages in saving time and cost.

**Note: Questionnaire is to be administered using one-on-one Interviews*

Interview guide for construction site managers/experienced construction workers/construction company owners or managers

Interviewee details:

1. Name (optional)
2. Pseudonym to use if choosing to stay anonymous
3. Interviewee's position in company
4. Interviewee's tertiary education and details of qualifications
5. Number of years the interviewee has been working in the construction industry
6. Number of years the interviewee has been involved with the construction of suspended floor slabs

Span length ranges:

7. State the length between permanent supports (i.e. beams, columns, load-bearing walls) to which you are comfortable to construct the following types of suspended floor slabs, and what problems start to occur at that length?

One-way slabs

.....
.....
.....

Two-way spanning slabs

.....
.....
.....

Flat slabs (without column heads)

.....
.....
.....

Coffer slabs

.....
.....
.....

Coffer slabs (with integral beams)

.....
.....
.....

One-way post tensioned

.....
.....
.....

Flat post-tensioned

.....
.....
.....

Hollow-core

.....
.....
.....

Hollow-core pre-stressed

.....
.....
.....

Rib and block

.....
.....
.....

Precast slabs:

8. What standard lengths are available for each of the following precast slab types:

Hollow core

.....
.....

Hollow core pre-stressed

.....
.....

Rib and block

.....
.....

9. For what size (number of floors, floor area, etc.) or type of project would a contractor install precast slabs and why?

.....
.....
.....

10. What other decisive project factors would make a contractor rather install precast slabs than use in-situ-cast slabs?

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.....
.....

11. What constructability problems occur as a results of permanent support conditions of precast slabs and/or lintels?

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.....
.....

12. What constructability problems could occur as a result of the temporary support conditions of precast slabs and/or lintels?

.....
.....
.....

Concrete pouring:

13. Do you prefer to monolithically cast the beams and slabs for a given storey, and why?

Yes / No

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.....
.....

14. If not, what problems can occur as a result of beams and slabs not being cast monolithically?

.....
.....
.....

Standard costs:

15. What are the standard concrete costs?

.....
.....

16. What are the standard reinforcement costs?

.....
.....

17. What are the standard formwork costs?

.....
.....

Columns and wall widths:

18. Do you prefer that columns and/or beams in walls are the same width as the walls?

Yes / No

19. If yes, what are the advantages?

.....
.....
.....

20. For which widths or width range is this possible?

.....
.....

Slab thickness for in-situ or precast slabs:

21. Do you prefer to cast slabs that have a thickness which is a multiple of the brick height used?

Yes / No

22. If yes, what would these preferred thicknesses be?

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23. What other constructability problems have you come across with regards to slab thickness and what were the reasons for the problems?

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.....
.....

24. If a slab has to be designed thicker than what it needs to be in order for the slab to be at a multiple of the brick height used, what would the implications be? (the researcher wants to know whether making a slab thicker to fit in with a wall and having to cut fewer bricks, or using less concrete and saving time, would increase the cost of the project or result in other significant issues).

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.....
.....
.....

Down-stand beams:

25. Do you prefer to construct slabs without down-stand beams?

Yes / No

26. What problems occur with the construction of down-stand beams?

.....
.....
.....

Raking columns:

27. Do you prefer having to construct regular in-situ columns rather than in-situ raking columns (columns at an angle)?

Yes / No

28. What problems occur with the construction of in-situ raking columns?

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.....
.....

29. If a column must be at an angle, would you prefer the column to be precast?

Yes / No

30. What are your reasons for the previous answer?

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.....

Internal load-bearing walls:

31. What constructability problems occur as a result of having to construct internal load-bearing walls (masonry, concrete or precast)?

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.....

32. Would using precast load-bearing elements make any difference in terms of construction efficiency?

Yes / No

33. What are your reasons for the previous answer?

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.....
.....

34. Would having fewer internal load-bearing walls result in faster and more efficient construction?

Yes / No

35. If yes, how can this be done?

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.....
.....
.....

Cranes:

36. For what size of project (number of floors, floor area, etc.,) or to cope with which specific project factors, would a contractor typically acquire a mobile crane to assist in its construction?

.....
.....

37. For what size of project (number of floors, floor area, etc.,) or to cope with which specific project factors, would a contractor typically acquire a tower crane to assist in its construction?

.....
.....

38. Are cranes used to lift formwork from floor to floor?

Yes / No

39. If yes, do you prefer to lift column cages as a whole from floor to floor with the use of cranes?

Yes / No

40. Can the column cages be too heavy for the cranes to lift?

Yes / No

41. If yes, what is the typical maximum size that column cages can be (not considering special cases where abnormally large cages are needed)?

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.....

42. How disruptive, in terms of construction efficiency, is the process of dismantling column cages to the extent where they can be lifted by a crane?

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.....

43. Is the formwork used for slabs lifted from floor to floor with a crane?

Yes / No

44. If yes, how is this done?

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.....

45. What problems do you encounter with the use of cranes for construction?

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.....
.....
.....

Mechanical, electrical and plumbing (MEP) services installation:

46. Do you prefer not to have to install MEP services through steel and/or concrete columns?

Yes / No

47. What constructability problems have you encountered with the installation of services in the following slab types:

One-way slabs

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.....
.....

Two-way spanning slabs

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.....
.....

Flat slabs (without column heads)

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.....
.....

Coffer slabs

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.....
.....

Coffer slabs (with integral beams)

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.....
.....

One-way post tensioned

.....
.....
.....

Flat post-tensioned

.....
.....
.....

Hollow-core

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.....
.....

Hollow-core pre-stressed

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.....
.....

Rib and block

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48. What other constructability problems have you encountered in terms of the installation of MEP services in slabs or in and around columns or walls?

.....
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.....
.....

Connections:

49. Is the fixing of the reinforcement from slabs, columns and possibly post tensioning strands at column heads a problem when using thin slabs?

Yes / No

50. What problems occur due to this?

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.....
.....

51. If yes, what should the minimum thickness be for this to not be a concern?

.....

52. What constructability problems occur due to the tying of floor slabs to lift shafts and stair walls?

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.....

53. What other constructability problems do you encounter that are due to the connections between slabs and other elements?

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.....

Formwork:

54. What advantages does using wooden formwork have over using steel formwork?

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55. What advantages does using steel formwork have over using wooden formwork?

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56. Please state when (what types or size of projects) you would choose to rather cut and erect your own formwork and not hire a subcontractor?

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57. What problems occur due to cutting your own formwork?

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.....

58. When using a subcontractor for formwork, is there any extra costs due to beams, columns and slabs not being in standard formwork sizes?

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.....

59. When not cutting your formwork (i.e. using steel formwork and/or standard wooden formwork panels) would you prefer the beams, columns and slabs to be designed in such a way that standard available formwork sizes can be used, and no cutting or special ordering of formwork is needed?

Yes / No

60. Is it cheaper to construct using standard formwork sizes than having to cut your own special panel sizes or order special formwork panels?

.....
.....

61. What standard sizes are available for the formwork needed for the beams, columns and slabs?

.....
.....

62. What implications (cost, time, quality, etc.) would it have on a project if the beams and/or slabs are made slightly larger/smaller during design for contractors to be able to use standard formwork sizes?

.....
.....
.....

Contractor/site manager's experience:

63. What constructability problems have you encountered with construction of the following slab types (wish to know what a contractor would want a designer to know during the design phase in order to avoid certain common constructability issues):

One-way slabs

.....
.....
.....

Two-way spanning slabs

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.....
.....

Flat slabs (without column heads)

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.....
.....

Coffer slabs

.....
.....
.....

Coffer slabs (with integral beams)

.....
.....
.....

One-way post tensioned

.....
.....
.....

Flat post-tensioned

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Hollow-core

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Hollow-core pre-stressed

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Rib and block

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64. With regards to the number of the same type of slabs that a contractor should have previously constructed for there to be concluded that the contractor is experienced with the construction of a specific type of slab (includes flat, one-way, two-way, post-tensioned, coffer, hollow core and rib and block slabs). Does this number differ for the different types of slabs (i.e. includes flat, one-way, two-way, post-tensioned, coffer, hollow core and rib and block slabs)?

Yes / No

65. If yes, please state the number that a contractor should have previously constructed for each type of slab for there to be concluded that the contractor is experienced in constructing that specific type of slab?

One-way slabs

.....

Two-way spanning slabs

.....

Flat slabs (without column heads)

.....

Coffer slabs

.....

Coffer slabs (with integral beams)

.....

One-way post tensioned

.....

Flat post-tensioned

.....

Hollow-core

.....

Hollow-core pre-stressed

.....

Rib and block

.....

66. If no, what number of the same type of slabs should a contractor have previously constructed for there to be concluded that the contractor is experienced with the construction of a specific type of slab (includes flat, one-way, two-way, post-tensioned, coffer, hollow core and rib and block slabs)?

1	
2-3	
4-6	
7-10	
11+	
Other:	

Notes:

.....

Labour:

67. Do you ever appoint labourers from the surrounding area or community for a specific project?

Yes / No

68. If yes, for what types (e.g. projects in isolated areas, provincial projects etc.) of projects is this done?

.....

69. If yes, how hard is it to find these labourers?

.....

70. For construction activities requiring some level of skill/experience, do you always use your own employees or not?

Yes / No

71. If no, what level of labour skill/experience is required for each of the following slab types and state the scarcity of the specific level of labour skill:

One-way slabs

.....

Two-way spanning slabs

.....
.....
.....

Flat slabs (without column heads)

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.....
.....

Coffer slabs

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Coffer slabs (with integral beams)

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One-way post tensioned

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Flat post-tensioned

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Hollow-core

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Hollow-core pre-stressed

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Rib and block

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Transportation:

72. Is transportation ever a limitation in terms of the sizes of precast slabs, formwork, reinforcement, etc.?

Yes / No

73. If yes, how and what are these sizes/lengths?

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Curing:

74. How does the curing differ for the different types of slabs (i.e. the level of effort and time it takes)?

One-way slabs

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Two-way spanning slabs

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Flat slabs (without column heads)

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Coffer slabs

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Coffer slabs (with integral beams)

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.....

One-way post tensioned

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Flat post-tensioned

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Hollow-core

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Hollow-core pre-stressed

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Rib and block

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Conclusion:

75. What influence (good and bad) will it have on the rest of a project if suspended floor slabs and its supports are made more constructible?

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Thank you for your cooperation

Appendix C: Vincent Kuo identified constructability problems

Note:

Each contractor and consultant respondent were asked to provide up to 5 specific ‘constructability problems’ they experienced in one of the last 5 projects undertaken, or any that is vivid in his/her memory. Below is presented all the constructability cases exactly as given by the respondents. The cases are separated by single lines. The analysis in the thesis was primarily done on the contractors’ cases. However, both the contractors’ and consultants’ cases are presented below.

Contractor’s cases

Generally, the method of construction can be changed to a faster and more cost-effective solution. The problem is normally that the construction drawings are issued to the contractor just in time, hence not leaving enough time to change the design.

Normally if the contractor wants to change the conforming details, he/she will have to do the design of the alternate proposal and also supply guarantees for the life of the structure. This is not the core business of a typical contractor, and hence don’t pursue these issues further.

All formwork suppliers have certain standard dimensions for their formwork systems. By for example making a beam 450 mm wide and not 425 mm it makes no significant difference on the design but makes the construction faster and cheaper. In the majority designs these issues are not being considered.

Structures will be designed in a manner that doesn’t make it possible to achieve scheduled milestone dates. For example, suspended slabs will be designed not to support the suspended slab above during construction and curing. This then requires back propping of the bottom slab, hence delaying the follow-on activities on the bottom slab. The problem is that the project schedule will not allow for this. If, for example, the schedule was the most important item, the suspended slabs could be constructed using precast beams and planks with composite in situ concrete on top.

On the majority of projects, the information flow to the contractor is late, resulting in delays to the project. The design company are normally not at fault, because they are waiting for details from vendors which must first be employed by the client, before they will supply details required by the designer to do the foundation designs. The overall design is not done timeously, allowing as little interference to the construction works as possible.

Durban Harbour Quay Wall

The precast yard and launching facilities were designed under the supervision of the contractor. Had this not being the case, a great deal of re-work would have been required to ensure an effective system.

Toyota Paint Plant

The changing of the precast tilt up walls to an in-situ slide wall and column combination proved to be a vital change in completing the project on time.

Sappi Saicor Upgrade

Changed the sequencing of the works, which required the columns to be cast with shear and moment reinforcement at deck level, prior to casting the deck. This was a contractor suggestion.

GFIP Package F

Changed the shape and size of precast bridge beams. This was a contractor suggestion.

Warwick Triangle Outbound Viaduct

Project was required for the 2010 Fifa World Cup. Normal procurement processes would have derailed the project. Client was advised to procure as a design and construct option with a high-quality score for innovation and construction methodology. A combination of precast and cast in situ construction was adopted so that activities could run in parallel. Contract was completed 1 month ahead of schedule.

Mondi Paper Machine Rebuild

‘Sound’ design was in place, but the tight turnaround schedule could not be met. An alternative design to precast some of the elements was adopted which could be done while demolition of the existing line was being carried out. This ensured that the schedule was met but using innovation and the contractor's input.

Sappi Amakhulu Expansion

Engineer had scheduled an unrealistic construction period which could not be met. Contractor had to innovate construction methods and ultimately a schedule was agreed with client that was 50% longer than the original.

In-situ beams changed to precast.

Better finish, consistent colouration.

Precast moulds more consistent.

Change concrete design, e.g. self-compacting, flow for work ability etc.

Small bathrooms - insitu build (bricks, mortar, plaster, etc).

Changed to pods on site. Plumbing executed in jigs. No chasing. (No waste, dust - health and safety improvement). Plumbing executed to a manufactured standard. Testing done off site to a working pressure double that of the required standard.

Power floating. Not an option in residential buildings. (Too many services, e.g. conduits, ducts etc.)

Allowances must be made for screeds.

If vinyl finish. screeds must be class 1 with pumpable self-levelling screeds to achieve flatness.

Electrical boxes - Back to back on 110 mm masonry walls.

After chasing, wall destroyed. Wall stability compromised.

Solution – Electric services fixed first. Place shutter over piping. Cast up stand with electrical services boxes in shutter. No chasing results in wall being more stable.

Kitchen walls (230 mm or 280 mm).

Chasing of plumbing, water supply, water waste, electrical services, etc.

Moving kitchen cupboard away from wall by 60 mm. Surface mount fixtures. Testing of services. Easy to fix leaks.

No chasing equals no waste. Negative is that cupboard requires a backing.

Continuously reinforced floors to be constructed to degree of accuracy 1.
Soft roof (timber roof construction) very time consuming, risky access.

Fast track project ring-beams designed as concrete.
Engineer should have specified boxed steel beams for speed.

Very complicated structural steel design on a fast track project.

Numerous concrete shear walls.

Safe execution of work. Designers often do not consider how activities take place on site, and prepare a design to safely allow activities to take place. An example is the application of polystyrene copings on high parapet walls where materials must be hoisted into position, and then rendered.

Poorly specified materials that are impractical when it comes to serviceability, in particular the lack of attention to design on a glass roof, where workers are again put at risk during the installation. Cleaners may also be at risk once the building is handed over as the glass could fail with people on it.

Service co-ordination, this is always a problem, systems are designed in isolation and are poorly co-ordinated. This complicates the installation process, delays construction due to clashes having to be resolved, and also incurs costs.

Facade design can have a huge impact on constructability, and designers often only consider the effect of the aesthetics of a design, rather than the practicality of implementing it, and have an expectation of fast-track construction on difficult systems which take time.

Specifying products that are new to our market. On a recent project, our Architect has specified a large number of products that have never been used in our market, or installed by our contractors. This causes delays, training that is required, re-work costs, and frustrates people due to their lack of knowledge of the systems, maintenance etc.

(Shopping centre) Platform was supplied by others and were constructed out of sand (building foot print of 750x250 m) - this made the access for both supply of material and equipment very difficult. This type of platform is also extremely vulnerable to rain. This ended up costing the contractor a lot of money in rework and specialised plant to move material and equipment. The contractor was aware of this and allowed for this in his price - if a basic 150 mm layer of G5 was provided the final value of the project would have been lower and ease and speed of construction would have been better.

Extremely light structural steel roof structure. This forced the contractor to assemble whole portions of the roof on the ground and then hoist it into position. If the structure was heavier the contractor could have used normal erection methods to erect the roof. The contractor allowed for bigger lifting equipment in his bid and this escalated the costs.

6 m high composite retaining walls constructed of 2 x 115 mm brick skins and reinforced concrete filled cavity were specified. Concrete retaining walls would have been much easier and faster to construct.

On Michelangelo Tower, the Facades were very cumbersome to build. It was composite brickwork plastered and rendered with lots of windows and mouldings surrounding and large architectural copings. This had to follow the structure over 36 stories and be fully scaffolded over the height because of the different trades which required access to complete the works.

On the Cape Town international Airport extensions, the concrete structure was very heavy because of huge floor spans, generally 15 metres, with 700 m long road bridge structure and complex free spanning gauto volume structural steel roof.

The parking garage at Cape Town international airport was a very long post-tensioned slab building with very heavy and numerous concrete facades and internal shear walls. It was designed to match an existing garage which present the aesthetics of the building.

The hotel on top of a parkade was a flat slab concrete structure traditionally reinforced on top of a 8 floor post-tensioned slab parkade building with brick and plastered facades. The bathrooms were prefabricated and hoisted and built in position to save time. The rendered facades had to be scaffolded and took time with structural challenges.

A shopping centre was single storey with very high intermediate firewalls and the 500m long mall had s framed structure with up to 8 m high brick walls. The entire roof structure was in structural steel with large spans in one direction and too small spans in the other directions, which made the steel design very heavy.

Reinforcement sizes can be too big or spacing too little for concrete to be vibrated in beams and columns.

Drilling and epoxy of bolts in columns/walls for steel brackets needs to be installed and takes time.

Holes clashing with reinforcement . Struggles to get all the holes drilled when reinforcement in column/wall is a Y32 or Y20.

Columns in walls should be the same width as the wall for shuttering and better finishing purposes.

Steel designers not considering the yield length of the steel after the steel was bended.

Steel can too long and must be cut.

Design drawings not showing enough details, i.e. sectional details. Especially for structural drawings.

The pipeline material used in a design was very expensive and unpractical. Also, the proposed alternative material was in line with the core expertise of the contractor. The alternative not only offered a financial saving, but also a reduced project risk in terms of schedule, quality and safety. The alternative was, however, not considered.

The method of construction specified (incremental launching), governed by the design of the bridge, was very expensive and impractical for the length of the bridge. A precast beam solution was viable and much cheaper but dismissed for aesthetic reasons.

In situ slab with down stand beams was specified. This is always very difficult, time consuming

and equipment intensive, which makes it very expensive. A precast solution or an in-situ solution with permanent soffit formwork would have been possible but was not considered.

Raking columns were designed to be in-situ, with massive cast-in items and very creative shapes. These could easily have been precast, which would have yielded a much higher quality finish as well as a much cheaper concrete mix design. The shape and congestion of the reinforcing made it almost impossible to pour and compact (vibrate) with conventional concrete, thus a self-compacting mix was used, which was not only very expensive in itself, but also pushed up the formwork costs tremendously (pressure much higher and water tightness requirements).

125 reinforced concrete columns (50m high) were designed in such a way that the reinforcing was more than 500kg/m³ (with bar lengths up to 13m long), which not only made it very expensive, but also impossible to slide (slipform), which is not the most efficient way to construct these types of columns. A small increase in diameter of the columns would have dramatically reduced the reinforcing requirements (increased stiffness) as well as the overall cost of these structures.

Containing of ground water during basement construction.

Poor coordination of services, especially in hospitals.

Lack of/insufficient information in construction documentation (drawings, specifications, etc.).
Not enough construction specifications.

Accommodation of all services inside in situ reinforced concrete slabs- no ceiling voids.

The City Lodge hotel floor specification did not include floor screed, and a Class 2 floor was specified. This, in conjunction with the excessive deflection of the floors, resulted in very uneven floors and a lot of remedial work in order to install the floor finishes.

The Lynx Office Park's parking basement design had a section that was lower than the sub-soil drain. With the ground water levels rising in summer, the lower area of the basement was subjected to flooding and damp.

The Coega Warehouse had very tall and narrow concrete columns with corbels and holding down bolts in some parts of the building. This should have been in steel like most of the other columns. These were difficult to construct and had to be braced temporarily until the steel structure was up. The bases and holding down bolts of the Coega Warehouse was heavily reinforced, and this made the very bulky holding-down bolts impossible to install.

The cantilever balconies incorporated into a precast floor system at the Augustus was designed with a kink in the reinforcing to accommodate the difference in level. This, and the fact that there was very little cover on top of the steel, resulted in the balconies snapping and breaking off from the building. They were later supported by a retro-fitted steel bracket.

Constructability issue = No chasing was allowed on internal walls. Major problem with water and electrical reticulation which had a huge cost impact for the client.

Structure = Load bearing brickwork with in situ slabs. Constructability issue = all internal walls

were load bearing. This resulted in a very inefficient formwork process as formwork for each room had to be constructed individually. Very poor design.

Structure = Precast concrete perimeter walls (5 m x 10 m). Constructability issue = Panels had recesses in them. Subcontractor got a lot of the panels wrong. Substantial remedial work required. Lesson = keep precast panels simple.

Structure = Precast concrete perimeter walls (5 m x 10 m). Constructability issue = Precast panels were cast in stacks of 4. Connection to structural steel roof was detailed to be cast in bolts. Impossible to use cast in bolts when panels are cast on top of each other. Post-fix is a better solution.

Flat plate galvanised box gutters were detailed. No allowance made for distortion of metal sheets during galvanising process. Result was ponding of water in gutters.

Complex transfer structures often occur, typically at podium level (above basement & below superstructure).

We focus on precast structures and therefore any constructability issues are thoroughly addressed in the planning phase. Any small issues that may arise thereafter is then used to prevent the same mistakes. Experience and proper consultation with contractor and site personnel, in our opinion, is the only way in which these issues can be prevented.

Constructability needs to be especially considered for earthworks, drainage, outfall sewers and reticulation, pipejacking, pump stations and tunneling;

The constructability of a project is dependent on many factors: Location- is it in open space or restricted built-up area, Climatic conditions- high rainfall/dry area, Geological site conditions-availability of raw materials and skills, this, along with logistics of the construction site and design and choice of construction methods, are all relevant factors.

Drainage; the drainage of a construction site is very important. In construction it is easier to accommodate water than try to beat it. Where waterlogged construction sites need to be developed, the lowering of the water table ahead of construction of the earthworks commencing is necessary. This can be achieved by way of constructing drainage pits that are subjected to continuous pumping or, where possible, the excavation of drains leading the water to a low point off the site. This will result in the lowering of the water table, allowing conventional earthworks to proceed. The lead time for this operation ahead of the commencement of the earthworks should be about two weeks. This method was used some years back in the construction of a prestigious block of apartments along the coast just north of Durban.

Outfall Sewers, reticulation. and storm water drains: Where pipe drainage is concerned, the geology of the terrain, restricted area of construction and depth of excavation are the three big variables affecting the constructability of the project. Reticulating areas of Durban North's soil conditions varied. Some areas were easily excavated mechanically. The standup time of this material, however, permitted the support of the excavated trench with a minimum support of timber and trench jacks. At a three-meter depth average, production of completed sewer laid was 30 meters per day plus where soil conditions changed to a soft sandy pink soil with very low Plasticity Index. Excavations required close timber shoring. Production was 30 meters per week. In addition to the lower production, additional plant by way of a compressor and

additional labour for the driving and extracting of timber shoring were involved. Huge cost difference for identical production. All due to differing soil conditions.

Pipejacking: Indicated where depth of excavation is excessive or working area is restricted. The pipejacking method of construction was used in the construction of portion of the Durban North outfall sewer and specifically for the portion crossing under the main road, adjacent to the Virginia airport. The jacking pit was constructed on a suitable open site adjacent to the highway. The shield and jacking equipment were lowered into place. The first pipe was positioned in the shield and jacking commenced. The project was able to proceed independently from the other activities with no disruption to traffic. Once the pipes were jacked to line and level and grouted, they were connected to the rest of the pipeline by way of manholes. The use of this method clearly indicates the circumstances in which special techniques need to be applied. Thus, avoiding the disadvantages of the conventional trench excavations.

Pump Stations: Two sewer pump stations along Fairway in Durban North were constructed subsequent to the completion of the above-mentioned outfall sewer. To avoid interlocking sheet piling and heavy crane equipment in a relatively restricted space, the pump stations were constructed by way of sinking concrete cassions. The cassions were constructed in lifts of 2 meters and excavation took place inside the cavity and the cassion was lowered by its own weight to line and level. Controlled Excavation of the earth within the pump station structure followed. This procedure of the construction of the cassion walls and excavating, was repeated till the final required level of the structure was obtained. The floor was then cast, and the internal structure completed together with the installation of pumping equipment. In effect, the benefit of the cassion construction of the pump stations are identical to those described above for the pipejacking. They both have their advantages in specific circumstances in the constructability of certain projects. In effect, the final structure is used as a means of support of the excavations whilst it is been installed into its final position. In the case of the jacked pipe, hydraulics is used, in the case of the pump station, gravity is used to finally position the structure.

Consultants:

Cranes in confined city block sites. Often no place for a crane and stockpiling of materials, mainly in city blocks. Tower cranes only option as mobile cranes cannot access the site when columns are in place.

Detailing methods of reinforcing bars. Too heavy column cages for cranes to handle. Also, bars detailed too long to man-handle on site. Also detail beams with open stirrups where site craneage is a problem. Detail cages for pre-assembly off site.

Detailing of reinforcement bars for sliding shutters. Bars preferably of smaller diameter and short enough to be handled by staff on site on high elevations. Detailing structural steel without giving attention to splices during design stage causes unwanted workshop connections. Agree with fabricators up front. Do clear drawings and provide proper details.

Poor soil conditions on site can be a problem. Specify G7 gravel layers as part of tender for access to building sites in areas of soft wet clays.

Parking structure concrete had to be low shrinkage concrete and slabs had to be crack free. Light-weight walls were required in the renovated industrial buildings.

Erection of new steel structure on top of existing building can be difficult because of access.

In situ concrete structures are slower to build than precast buildings, but cheaper.

‘Saamgestelde balke (composite beams) - om die bekisting presies te laat pas teen die staal balke voordat beton gegiet word kan ‘n probleem wees’.

‘Diep uitgrawings vir voetstukke wat lateraal ondersteun moes word - was nie geskik vir heipale nie’.

‘Gate vir voetstukke en fondamentmure wat toespoel tydens swaar reenbuie - kon verhoed of verminder word deur stormwaterbeheer toe te pas op terrein’.

‘Die sweis van struktuurstaal wat nie behoorlik gedoen word nie en oorgedoen moes word op verskeie voetstukke en lasplekke’.

‘Die kontrakteur wat nie geskik is vir die grootte van die projek nie - kies die kontrakteurs beter deur te kyk na vorige werk van dieselfde aard suksesvol afgehandel’.

Change in geotechnical conditions resulting in partial piling of the building- unforeseen and not expected by geotechnical engineer.

A 250 room beach front hotel comprising of five 8 storey blocks. The hotel was designed and built as a flat slab and column structure on spot base foundations designed for a characteristic ground bearing pressure of 250 kPa (soft rock). The contractor was anxious to be awarded the contract on a negotiation basis. Unwisely, he agreed to a very short contract period which in our opinion was unachievable. At the time of the negotiation the architectural drawings were far from completion. The bills of quantities were provisional and suspect in their accuracy. Our structural drawings were in an estimate stage for lack of architectural information. The client pressed for construction to commence. With an enormous team effort on the part of all the consultants and the contractor the project was completed about 12 months beyond the contract completion date. Endless arguments ensued between all parties concerned. Issues of design constructability to be resolved by the consultants and the contractor require the timeous issue of information by the client. Few clients understand the complexity of the co-ordination of professional services on a project of this nature. When a client chooses to change his mind, disputes between the consultants, client, and contractor are inevitable. With on-going changes to the design brief, issues of constructability were not assessed at any stage by the contractor. Delay in completion of the contract should have been obvious to all concerned.

An investigation into the cause of failure of a portion of the timber roof structure at a university library. We were asked by the university to verify the design recommendations prepared by another consulting structural engineer for the rectification of a collapsed portion of a timber roof structure at the university library. The span (distance between supporting columns) of the portion of roof that had collapsed was significantly greater than (in our opinion could) be accommodated by the timber bolted and plate connector system installed. The proposed method of rectification entailed the strengthening of several timber members which were under-designed and the provision of new additional timber members. The analysis was further complicated by the fact that some of the timber used in the roof was ungraded. Our recommendation was to remove the portion of timber roof structure in the vicinity of the large spans and to replace the timber with structural steel trusses. This design recommendation was

implemented at considerable savings to the client. In our opinion, the original designers of the timber roof structure chose to solve the ‘long span’ problem in timber. A more appropriate solution was to design and construct that portion of the roof in structural steel. The engineer appointed to rectify the problem did just that. He should have considered this to be a structural problem, rather than one of timber design. This type of error of judgement is not uncommon in structural engineering.

An investigation into the cause of failure of timber roof trusses at Damlin College, Durban. The building was built by a reputable contractor. In terms of the contract, the timber roof structure was to be installed by a specialist sub-contractor on a design and supply basis. The contractor asked the client to appoint a consultant to verify the installed trusses, but the client refused to do this notwithstanding the fact that the contractor had observed that the timber roof had not been examined by a professional engineer on completion of its installation. The dispute went to arbitration. We acted for the contractor and were asked to verify the design and the roof timbers. Numerous minor errors in design and the timber installation were uncovered by our investigation. These errors would not have caused the roof to collapse had it not been for the fact that a knot in one of the timber rafters was located directly over the supporting wall plate, which was also out of position. What was interesting is that had it not been for the unfortunate presence of the 30 mm knot in the timber rafter situated in that specific position, the roof would not have failed. The timber trusses were standard and relatively simple to install. The problem was that the timber member was not of the specified grade and the contract's agent on site did not have the expertise to verify the grade of timber used in their manufacture. The lesson to be learnt is that professional monitoring and certification of construction is necessary to minimise the incidence of such failures. The reason for the use of non-structural grade timber was simply that it was unobtainable at the time.

Installation of light-weight concrete fenestration panels (1 m wide and 2.8 m in height) to the facade of a sizable office building. The panels were essentially designed by the architect in collaboration with the fabricator and had 4 x 12 mm diameter bolts cast into them, one at each corner. Our task, as structural engineers, were to advise how to fix these panels to the reinforced concrete facade of the building. Neither the architect, nor the panel fabricator, had realised that the very small deflections of the reinforced concrete structure would have very adverse visual implications in the variation of the width of the joint between the panels specified by the architect. Special methods of fixing were devised to obviate this problem. The fixings of traditional and well tested glazing and curtain walling elements to reinforced concrete or steel frames incorporate methods of accommodating differential movement sometimes referred to as ‘compensation channels’. With the very rapid development of new construction products and new materials, some of these considerations are overlooked and fall between the functions of the structural engineer, the architect, and the specialist manufacturer. When things go wrong, they blame the engineer!

29 Storey luxury residential building: Construction of the reinforced concrete end shear wall. The construction of an end-wall to a very attractive beachfront building entailed some careful formwork construction and setting out to meet the visual requirements set out in the bill of quantities and discussed at several design development and site meetings prior to its construction. Regrettably, when the wall was built, other aspects of construction took priority with the result that the entire wall had to be re-worked to achieve an acceptable appearance at considerable cost to the contractor. I think that the expectations of the architect and the builder (who was also part developer) exceeded their appreciation of the difficulty of working 60 meters up on a flimsy scaffold. Such work is possible where/when high-rise building skills are

well established. Regrettably, high-rise building construction is very cyclical.

Raft foundation construction due to dolomite requirements. Very few capable raft contractors and limited availability of powerful trench diggers. Rafts with beams deeper than 900 mm requires more powerful trench diggers if soil in which raft is constructed is hard.

Outlet pipe through steel tapered column to hide outlet in steel column, as per architect's requirements- Very difficult detail to install and difficult to maintain.

Breaking large penetrations through post-tensioned slabs requires detailed back-propping and repair anchor specifications. An experienced contractor is required with support from one of the experienced post-tension companies.

Telesure Headquarters: Problems with connections between in-situ concrete and structural steel elements.

Outsurance Head Office: Problems with fixing of reinforcement from slabs, columns and post-tensioning at column heads due to thin slab sections.

Brits Granite Factory: Late changes from client affecting structural steelwork as all steelwork is galvanised.

MTN Centurion: Complex reinforcement configuration to suit haunches for precast beam supports.

Garsfontein reservoir: Late change from in-situ roof construction to precast roof created various soft issues such as joints, waterproofing, etc.

Heritage issues required that the new structures be built above and around existing buildings. Deep excavations close to existing structures were difficult and time consuming.

Heritage issues required that facades of certain existing buildings be retained. This required the demolition of these buildings while propping and protecting the facade.

Ground conditions required raft foundations. This meant that services for ground floor shops and restaurants had to be installed at a very late stage and could not be changed. This affected the programme. Piled foundations could have resolved the issue, but at a greater cost which would have meant that the project would not have proceeded. Curved long-span trusses were difficult to splice on the ground and lift. Straight trusses would have been easier and quicker, but the architecture required the curve.

The interface between concrete and steel structures often caused problems with fit of steel.

The architect requested timber ply shuttering for the off-shutter concrete retaining walls, which were relatively thick. This resulted in fine thermal cracks on the external faces. Timber formwork tends to trap heat within the concrete, more so than steel, resulting in higher temperature differentials, which in turn led to cracking. This could've been avoided by removing the formwork sooner to allow heat to escape, or by using steel formwork.

The roof for the Peter Mokaba stadium proved to be a constructability challenge.

Constructability plays a key role in the planning and conceptualisation of a long span structural solution. The design is to a large degree dictated by the following:

- Construction sequence
- Erection methods
- De-propping procedures
- Consideration of construction loading
- Differential deflections during erection that may affect fit, i.e. consideration of theoretical vs. deflected shape
- Temperature effects, e.g., sometimes the last key element of a long-span structure will only fit if the temperature is below a certain value.

Shifting of structural grids (e.g. where residential occupancy is positioned over parking garage) leads to use of transfer beams, which has an impact on program and costs. If possible, better to plan the grids to coincide. This decision is, however, not only up to the structural engineer.

Grout loss (honey-combing) due to congestion of reinforcement. Use of larger reinforcement bars more widely spaced often leads to better accessibility for poker.

Excessive deflection of metal decking in composite construction due to incorrect methods of concrete placement.

Damage to starter reinforcement bars at construction joint positions, particularly where follow-on pour is carried out at a much later date; e.g. at openings for tower crane which are filled in later. Possibly better to use couplers or a specifically detailed joint around infill slab, but there would be cost implications for a 'better design'.

Stitching in new concrete elements to existing elements by means of dowelling. Interface often poorly prepared and insufficiently saturated (use of wet-to-dry epoxy can be counter-productive if follow-on pour takes place too long after application of epoxy).

Appendix D: Summary of interviewee responses for first round of interviews

Table D-8-1: Summary of interviewee responses for first round of interviews

Theme No.	Theme	Sub-Theme	Contractor	Response Summary
1	Span length ranges		A	Only reinforcement changes but doesn't make a significant change to the formwork needed. Company doesn't do coffer slabs or rib and block systems. Very seldom use hollow-core as well.
			B	Formwork layout is the most important. Comfortable with up to 6 m for one-way slabs, 8 m for two-way slabs, 6 m for flat slabs, 10 m for coffer slabs, 12 m for coffer slabs with integral beams, 8 m for one-way and flat post-tensioned, 7 m for 150 mm thick hollow-core, 9 m for 180 mm thick hollow-core, 8m for 150 mm hollow-core pre-stressed, 13 m for 170 mm thick hollow-core pre-stressed and 6 m for rib and block systems.
			C	Comfortable with up to 5 m for one-way and flat slabs, 7 m for two-way slabs, 8 m for post-tensioned slabs, 3 m for hollow-core and rib and block, 4 m for hollow-core pre-stressed.
			D	Possible to build a span as long as required. Rather aim for economic span lengths and force designer to design slabs as thin and long as possible.
			E	Has nothing to do with length, more about thickness needed.
			F	Pretty comfortable with 7.5 m. Does not really matter. More about functionality of building. Has not done coffer slabs for several years.
			G	Does not really matter. Longer spans are quicker to install or construct due to less columns and foundations, etc. needed. Shorter spans have better quality and finishing.
			H	Constructability not really a concern here. Contractors want less columns. Do not want column heads at all due to it being very cumbersome. Length is influenced by layout and function. Comfortable with 6 m for one-way and two-way. Coffers are not popular anymore, very expensive in terms of formwork and labour. Uses subcontractor for post-tensioned. Takes longer and changes in service layout can't happen. Precast depends on functionality. Hollow-core works good for up to 8 m. Rib and block up to 6 m.
2	Precast slabs	Available lengths	A	Transport constraints generally limit length more so than production limitations.
			B	Ask supplier, but typically 6 m for both hollow-core types and rib and block systems.
			C	Available on websites.
			D	Available on website (Portland).
			E	Can be found on Google.
			F	See Topfloor website. Always use a subcontractor. Side panels of a rib and block system can be a problem if the width is not at a multiple of the blocks used. Will cost extra for additional formwork, concrete and reinforcement.
			G	Available on websites. Accessibility needs to be verified for trucks.
			H	See website. Investigate hybrid construction, it's becoming increasingly popular.
		Application	A	Generally for buildings not more than 3 floors.
			B	1 or 2 storey building with brick supporting walls.
			C	Usually for apartment-type buildings. Depends on location and type of project. Would also use when there is insufficient space for formwork.
			D	Not more than 3 stories typically, depends on functionality.
			E	Typically for households. 40 m ² with max spans of 5 to 6 m for rib and block systems. Does not require cranes or pumps. Hollow-core used for 3 to 4 storey buildings. Column and flat slab systems used for 4 or more storey buildings.

			F	Typically for flats, apartments and offices with 5 to 6 m spans. Has only done up to 3 storeys. Would, however, always prefer in-situ due to having more control.
			G	Very repetitive projects. Very project-specific. Only use if there is not another option. Prefers in-situ. Will use if there isn't enough space for formwork underneath.
			H	Used for residential, flats and for smaller loadings. Very fast and does not need propping. Depends on application. If there can be chosen, then rather use precast. Use precast if speed is needed and no special aesthetic requirements exist.
		Constructability concerns with supports (Temporary and Permanent)	A	Nothing specific.
			B	Temporary supports (propping) can be very congested and in the way.
			C	Precast panel sizes do not always fit.
			D	NHBRC gives required lintels depths in walls and more. Joints can cause cracking and ground conditions also have a big effect.
			E	No problems due to design. Levels can be a concern.
			F	Nothing specific.
			G	No problems due to design. Accuracy of lengths and connections can be difficult.
			H	Levelling is a concern. More detail in design of formwork needed. If precast slabs then also use precast beams. No propping needed for hollow-core under 8 m, longer than 8 m requires propping in the middle. Rib and block requires propping.
3	Monolithic concrete pouring		A	Mostly impossible but would prefer it for down-stand beams and not for upstand beams. If not monolithic then 'cold joints' form and epoxy is needed if at outside of building.
			B	Prefers to cast beams until reasonably set and then cast the slab. Does not form a 'cold joint'. Face between old and new concrete must be scabbled before new concrete can be poured, requiring extra machinery and cost. Could also possibly require wet to dry proxy, resulting in extra cost and time used.
			C	Prefers to monolithically cast beams and slabs. 'Cold joints' form, repair works needed, re-inspections needed, loss of concrete, structural implications and extra formwork required if not cast monolithically.
			D	Prefers to monolithically cast beams and slabs, but is more expensive. Mostly done with two pours. If not monolithic, then different settlements, 'cold joints' and cracking can occur.
			E	Prefers to monolithically cast down-stand beams with slabs, but not upstand beams. Takes much longer when not casting monolithic.
			F	Prefers to monolithically cast slabs and beams, except for upstand beams. 'Cold joints' is a concern when not casting monolithically.
			G	Prefers monolithic, except for upstand beams. If not possible, then it is not a concern. Aesthetic problems at joints occur if not monolithic.
			H	Always for down-stand beams, otherwise 'cold joints' form and aesthetics can be an issue.
4	Standard costs		A	Depends significantly on the type of concrete and site location.
			B	Concrete is R1400/ton (includes delivery), but if supplier is very far from site it would be much more expensive. Reinforcement is R11000/ton plus fixing of reinforcement is R1300/ton.
			C	Concrete cost including labour for placing is R2000/m ³ , formwork for flat slabs 400/m ² , formwork for columns and walls R800/m ² and reinforcement R1000/ton.
			D	Can find out from supplier (Lafarge), differs for different projects due to heights, strengths required, etc. Unifying materials would help a lot.
			E	Cannot provide rates. Confidential.
			F	Not allowed to provide rates.
			G	30 MPa concrete plus labour costs R1250/m ³ . Reinforcement remains a certain percentage of the concrete, which means it will increase or decrease with the same ratio if concrete is increased or decreased. Weight plays a role in formwork costs and also the range in which the lengths fall (can be found on website).

		H	Slabs cost about R5500/m ³ for labour and material.
5	Columns, beams and wall widths	A	Prefers columns and beams in walls having the same widths as the walls due to easier finish and ease in installing showers and cupboards. Possible for 220, 230, 270 (cavity wall), 280 (cavity wall), 330 mm thick walls.
		B	Prefers columns and beams in walls having the same widths as the walls. Saves time and money. Possible for 230 mm and 280 mm (cavity wall) thick walls. Always try to make concrete less to save money.
		C	Prefers columns and beams in walls having the same widths as the walls. Results in faster construction. Possible for 300, 600, 900 and 1200 mm (see Peri website).
		D	Prefers columns and beams in walls having the same widths as the walls. Increases buildability through easier formwork. Widths can be found on website (see Peri website).
		E	Prefers columns and beams in walls having the same widths as the walls. Walls have to conform to structural elements. Saves time. Possible for 230, 270 mm thickness.
		F	Prefers columns and beams in walls having the same widths as the walls, but only helps for aesthetics.
		G	Prefers columns and beams in walls having the same widths as the walls. Helps for aesthetics and makes brickwork easier. Possible for 230, 280, 330 (cavity), 350 mm thicknesses.
		H	Prefers columns and beams in walls having the same widths as the walls. Better aesthetics and easier formwork. Possible for 230 (internal walls) and 280 mm (cavity/external walls). Also try to keep columns and beams at the same widths if no walls. Results in easier formwork and better aesthetics.
6	Slab thickness	A	Prefers slabs to be at multiple of the brick height used, but it's more important that the distance between slabs are at a multiple of the brick height used. Honeycombing occurs in thicker slabs.
		B	Prefers slab to be at multiple of the brick height (process should ask size of bricks used plus 10 mm concrete between bricks). Weather steps should also be at increment of the brick height. Bricks must be level on each side of a wall, otherwise a massive loss in the integrity of the wall would occur (especially in load-bearing walls).
		C	Does not make a difference if slab thickness is at a brick height multiple. Prefers slabs to be between 170 and 230 mm. 300 mm and thicker becomes difficult due to powerfloating and curing problems.
		D	Would help if slabs are at a multiple of the brick height used, but not important for a cavity wall. Would have a bigger influence if floor-to-floor height is at a brick height multiple.
		E	Would only prefer slabs to be at a thickness which is a multiple of the brickheight used if a brickface finish is required on the outside. Would have a small influence however. Would prefer weathersteps to be in 25 mm increments due to formwork available, otherwise more expensive. Would prefer floor-to-floor height to be at a multiple of the brickheight used.
		F	Only prefers slab being at a multiple of brick height when a brick finish is required on the outside. Want floor-to-floor height to be at a multiple of the brick heights used, saves time and money.
		G	Does not really matter if slab thickness is at a multiple of the brickheight used. Floor to floor height at a brick height (typically 60 mm for brick plus 15 mm for concrete) multiple would have a bigger impact. Would, however, not adjust structure to fit into brick heights. Slabs must be made as thin as possible which reduces thickness and strength of formwork needed, but cover can become a concern at a certain point.

			H	Not required that slab thickness is at a multiple of the brick height used, but would make construction easier. Would help if brickface finish is required or when slab is supported on inside bricks. Would not make a difference if slab goes all the way through the wall. Would help if floor-to-floor height is at a multiple of the brick height for external and internal walls (85 mm normally).	
7	Down-stand beams		A	Prefers slabs without down-stand beams. Takes longer and compaction can be difficult.	
			B	Prefers to not have to construct down-stand beams. More expensive and time-consuming.	
			C	Prefers to not have down-stand beams. Honeycombing is a concern. Rubble usually ends up at bottom of formwork resulting in rework, which is costly.	
			D	Prefers to not have down-stand beams. Honeycombing due to compaction difficulty often occurs. Difficult to clean out formwork beforehand usually, resulting in having to break out debris after concrete setting and re-applying concrete which gives an undesirable finish. Reinforcement cover can be a problem.	
			E	Prefer to not have down-stand beams. Formwork costs, more time and 'kicking' are the most significant problems.	
			F	Does not matter. Sleeves for services can be difficult in down-stand beams. Placing of lights is very important.	
			G	Prefer to not have down-stand beams due to extra time and also having to prepare joints if not monolithically cast.	
			H	Does not matter if there are down-stand beams. Depends on what is required.	
8	Raking columns	Construction of raking columns	A	Prefers to not have raking columns. Formwork is more complex and concrete placing is more difficult. Would only use if very special columns is needed.	
			B	Prefers to not have raking columns. Honeycombing often occurs.	
			C	Prefers to not have raking columns. Compaction, honeycombing and fitting the 'poker' between reinforcement becomes problematic.	
			D	Prefers not having raking columns. Honeycombing often occurs, formwork design is difficult, quality can be lost and extra machinery is needed	
			E	Does not mind.	
			F	Prefers not having raking columns. Costs more due to special formwork required.	
			G	Prefers not having raking columns. Accuracy is difficult, compaction can be a problem and special formwork is required that costs more.	
			H	Prefers not having raking columns. Costs more due to special formwork required. Compaction is difficult. Structurally needed sometimes.	
		Precast raking columns		A	Prefers a raking column to be precast.
				B	Prefers a raking column to be precast. Would result in faster construction.
				C	Would prefer raking column to be precast, which would result in faster construction. Precast is, however, not as effective, should only use for strange staircases, etc.
				D	Prefers raking columns to be precast, due to having better control, but connections could be difficult between in-situ and precast elements.
				E	Would not prefer to rather have precast raking columns than in-situ raking columns due to precast columns most likely being too heavy to lift and difficult to install.
				F	Would not want to install. Would be possible but would only be a special feature. Connections would be difficult.
				G	Would not prefer a precast raking column due to difficulty of accuracy.
				H	Would prefer raking column to be precast. Would make formwork easier and no problems with blow-holes at bottom of formwork. Connections would be difficult and would be more design intensive.

9	Internal load-bearing walls	Construction of internal load-bearing walls	A	Higher costs occur due to having internal masonry load-bearing walls due to formwork staying longer. Less load-bearing walls would result in faster and more efficient construction.	
			B	Can be a problem. Would prefer less load-bearing walls.	
			C	Does not cause constructability problems but having less internal load-bearing walls would result in faster and more efficient construction.	
			D	Height not at multiple of brickheight can be a issue. Congested formwork can be a problem for small rooms/areas (contact Peri to get sizes). Would prefer less internal load-bearing walls. Possible to reduce amount of internal load-bearing walls through using longer spans.	
			E	Prefers internal load-bearing walls due to not having to struggle with the fitting of bricks afterwards like with column-slab structures. Less internal load-bearing walls would result in faster and more efficient construction. Can be reduced by using post-tensioned slabs.	
			F	No constructability problems related to design. Getting correct heights and lengths on site is important. Having less internal load-bearing walls would not really result in faster construction.	
			G	Takes longer to build a wall than a column. Would prefer having only columns. Having less internal load-bearing walls would result in much faster construction and can be done by changing to columns carrying the loads.	
			H	Multiples of brick heights are important. Needs slip-joint at the top between slab and wall. Less internal load-bearing walls would result in faster construction.	
			Precast load bearing elements	A	Using precast load-bearing elements would result in faster construction.
	B	Would result in faster construction. Design is very important in terms of connection. Crane placement is also very important.			
	C	Has not used precast load-bearing elements.			
	D	Would not make a difference in terms of construction efficiency.			
	E	The use of precast load-bearing elements would result in faster construction.			
	F	Would not make a difference.			
	G	Does not have any real experience with precast load-bearing elements.			
	H	Would result in faster construction, but more attention to detail would be required.			
	10	Cranes		Project size for type of crane	A
			B		Mobile cranes would be used for a building with a minimum of 2 stories, with good accessibility and which has precast elements. Tower cranes would be used for buildings with 6 storeys or more, depends on access, time frame and the type of construction.
C			Would only use mobile crane for projects with a short duration and if a tower crane cannot be used due to there being insufficient space for its erection. Also, only used for projects with a short duration. Would use tower crane for a building with a minimum of 6 storeys.		
D			Crane choice is based on logistics, accessibility, reach, parking, location, etc.		
E			Would use mobile cranes only for specialist jobs like placement of floors on top. This is due to mobile crane renting being very expensive. Would use tower cranes for buildings with 2 or more storeys.		
F			Mobile cranes are very expensive (R2000 or R3000 per day). Tower cranes are about R30000 for a month plus R70000 for assembly and again for disassembly. All depends on type of project. Use self-rigging tower crane for small projects and tight spots.		

			G	Mobile crane is used for small areas, when there are separate small constructions (especially housing developments) and accessibility is not a concern. Requires better planning. Would prefer mobile if it can reach everywhere and can easily move. 20-30 ton mobile crane is still affordable. Tower cranes are used when large reaches are required horizontally and vertically. Can be used for more areas/activities at once.
			H	2 types of mobile cranes, i.e. hard and all-terrain. Would use if everything is precast and there is sufficient accessibility all around the site. Very project-specific. Most important factors in rather using tower crane is the restricted accessibility and if there are many wet trades used in the construction.
		Crane usage	A	Cranes are used to lift formwork from floor to floor with the use of a platform on the side of a building. Cranes can typically lift 3 to 4 ton maximum.
			B	Cranes are used to lift formwork from floor to floor with the use of a loading platform on the side of the building. Column cages cannot be too heavy for the cranes. Weight which cranes can lift depend on the size of the crane (see Liebherr website).
			C	Use cranes to lift formwork from floor to floor with a platform. Column cages are never too heavy to lift (see Liebherr website).
			D	Cranes are used to lift formwork from floor to floor. Column cages cannot be too heavy. Can always lift the largest single panel. Cages have to be broken down into at least 2 separate parts anyway. Need to take crane loading capacities into account however.
			E	Use cranes to lift formwork from floor to floor. Column cages has to be broken down into at least 2 separate parts. Impossible to remove column cages as a whole. When column cages are too heavy to lift with a crane then it is a result of poor planning.
			F	Cranes are used to lift formwork from floor to floor. Largest single formwork panel can be lifted with crane. Column cages needs to be disassembled to at least halves.
			G	Does not use cranes to lift formwork from floor to floor. Column cages need to be disassembled when stripped from columns and can't be too heavy for cranes. Require crane to lift 'gang-form' (formwork for walls).
			H	Cranes are used to lift formwork from floor to floor. Largest single formwork panel can be lifted with crane. Column cages needs to be disassembled to at least halves.
		Problems with crane usage	A	Nothing specific.
			B	Better to pump concrete to certain floor. Use cranes mostly for lifting of formwork.
			C	Buckets for concrete can be up to 3.5 tons and can be too heavy for certain cranes to lift.
			D	Weather can be a issue and the number of activities that need to be performed can also be too many for a single crane.
			E	Nothing specific. Almost always have a crane for a project.
			F	Only mechanical breakdowns.
			G	Placement to reach everywhere where it is required can be a issue. Weather dependent.
			H	Nothing specific.
11	MEP Services	A	Prefers to not install services horizontally through steel and/or concrete columns. Vertical services installation is fine, but horizontal can pose problems. Services for hollow-core would typically be between ceiling and bottom of slab and not in hollow-core tubes. Easier to install lights in walls. Biggest issues occur when services don't fit due to bad planning.	

			B	Prefers to not install services horizontally through steel and/or concrete columns. Sleeves for services should be tied to the bottom reinforcement in a slab, possibility of cracking increases if tied to the top reinforcement. Services in beams often clash with steel for two-way slabs. Size of horizontal services in coffer slabs are limited and often clashes with steel. Cut-outs for services in hollow-core slabs must be done prior to placement. Services in rib and block systems would require holes through blocks, which needs to be sealed.
			C	Prefers to not install services horizontally through steel and/or concrete columns. Electricity conduits must be fixed to bottom steel in slab and drainage pipes to top steel. Most problems are usually due to clashing of services. Rib and block services would be soffit mounted.
			D	Prefers to not install services horizontally through steel and/or concrete columns. Coordination between designer and contractor is important. Position of penetrations need to be considered.
			E	Prefers to not install services horizontally through steel and/or concrete columns. Most issues are due to MEP service designers only deciding after a slab has been constructed that certain things should change.
			F	Prefers to not install services horizontally through steel and/or concrete columns. Clashing of services often occurs. Coordination between services and reinforcement needs to be carefully planned. Most problems occur due to bad planning of services layout. Services designs are often not completed when construction starts.
			G	Prefers to not install services horizontally through steel and/or concrete columns and rather through masonry. Services in 110 mm walls should be kept to a minimum. Services problems are mostly caused by insufficient planning.
			H	Prefers to not install services horizontally through steel and/or concrete columns. Stormwater pipes down column centres works well. Coordination of design between architect and engineers is important. Changes not incorporated in design becomes a concern. Services need to be spread out and not congested. Attaching services to bottom of precast slabs are the most effective (would mostly have a drop ceiling as well) and the cutting of precast panels on site should be kept to a minimum. Not practical to use hollow-core tubes for services.
12	Connections	Slab and column connections	A	Can be a problem. Can be difficult to pour concrete and to install services.
			B	Compaction can be difficult. Not a issue in slabs thicker than 150 mm
			C	Not a issue for slabs thicker than 240 mm. Reinforcement fixing, compaction and cover becomes a problem.
			D	Fixing of reinforcement at column heads can be a issue for thin slabs. Obtaining specified cover can be difficult. Reinforcement clashing can occur. Not a problem in slabs thicker than 200 mm.
			E	In thin slabs, the biggest issue is to obtain sufficient cover. The actual thickness of the slab is not the real issue.
			F	Can be a problem for slabs thinner than 250 mm.
			G	Can be a issue for slabs thinner than 200 mm. Compaction and cover can be a concern. Need spacing of at least 50 mm to get 'poker' in. Also prefer cover of 50 mm due to ribbing of reinforcement having a tolerance of 4 mm on each rod, meaning that if two rods are used it can reduce the cover by 8 mm.
			H	Can be a problem for columns narrower than 250 x 250 mm in terms of steel placement.
		Slab and lift shaft/stair wall connections	A	Nothing specific. Different ways exist to do.
	B		Nothing specific.	
	C		Done the same for all types of in-situ slabs. Lap lengths, anchorage lengths, cover, compaction and scabble can all be problems at connections.	
	D		Nothing specific.	
	E		The same for all types of slabs. Precast can't be tied, lift shafts and stairwalls are built at the same time.	
	F		Nothing specific.	

			G	There is nothing that can be done to improve it.
			H	Nothing specific.
13	Formwork	Wood versus steel formwork	A	Wood formwork is more flexible in terms of sizes and is easy to cut. Can only be used 4-5 times. Steel formwork is better for repetitive work, lasts longer, more economical, gives a better finish, less likely to be influenced by weather and requires less maintenance. Repetition is also, however, very important.
			B	Wood can be cut into any desired size and is much lighter. Steel gives better finish.
			C	Wood formwork is lighter, has better workability (easier to carry on site) and is cheaper. Steel works good for columns and all repetitive work. Repetition increases constructability immensely.
			D	Always use subcontractor.
			E	Don't use steel formwork anymore.
			F	Wood formwork is lighter. Steel mostly used for special circumstances like curved columns. Steel gives better finish and is also faster.
			G	Wood is more expensive due to only being able to use it a few times. Steel would only be used for special cases. Custom steel is expensive to make. Steel formwork lasts 40 years.
			H	For wooden formwork, more specific sizes are easier made. More degrees of freedom. Steel lasts longer and is cheaper. There must be focussed on repetition, for which steel formwork is the best alternative.
		Cutting and erecting own formwork	A	Prefer to use a subcontractor. Subcontractor would have a wastage allowance in his rates.
	B		Would use own staff to cut and erect formwork for projects smaller than 500 m ² . Over 500 m ² then a subcontractor would be considered. Wastages are a problem, expensive to buy formwork material and also can't reuse most of the material.	
	C		Would do for small projects (less than R50000 cost). Takes time, costs more, requires skilled labour and installation has difficulties.	
	D		Always use subcontractor.	
	E		Always cut and erects own formwork.	
	F		Always use subcontractor.	
	G		Would always use a subcontractor for buildings. Would use own specialist teams for structures. Safety and wastages are a problem when cutting own formwork.	
	H		Project-specific, but significant wastage occurs if done on own.	
		Standard formwork sizes	A	Even with the use of standard formwork sizes, adjustments are always required. Columns need to fit into standard wall widths, which are 220, 230, 270, 330 mm.
	B		Would help to have members in standard formwork sizes. Especially in repetitive situations. Standard formwork sizes of columns are 300 x 300/600, 230 x 230, 280 x 280, 300 x 400 mm. Standard formwork sizes of beams are 300/400/600 mm.	
	C		When using a subcontractor, it costs extra if beams, columns and slabs are not in standard formwork sizes. Prefers that elements are in standard formwork sizes. Sizes are 300, 600 and 900 mm (See Peri website).	
	D		Always use subcontractor.	
	E		Don't get standard formwork sizes for 230, 270 mm walls. Problem is that our formwork standard sizes come from Europe, which isn't applicable to our local industry. Standard sizes are in 50 mm increments from 200 mm to 900 mm.	
F	Does not matter if slabs or beams are in lengths or widths which are in multiples of standard formwork sizes. Does matter for columns.			
G	When using subcontractor for formwork, it would cost extra if members are not in standard formwork sizes. Much cheaper if members are in sizes for which standard formwork sizes can be used. Sizes for columns are 230/250 x 450/600 mm or 300 x 450/600 mm.			

			H	Would prefer beams, slabs and columns in sizes for which standard formwork sizes can be used. 250 x 250 mm or 300 x 300 mm would help a lot for columns. Lengths are 2.4, 3 and 3.6 m, but only for aesthetic areas where no additional finishing is desired afterwards.
14	Experience	Common constructability problems	A	Already stated everything that is commonly encountered.
			B	Try to use the same type of concrete everywhere. The re-use of formwork and repetition of work is very important. Vehicle accessibility and crane positioning can be problematic.
			C	Already stated everything that is commonly encountered.
			D	Brickheights can be problem. Spanlengths must be in rounded values. Congestion of reinforcement, especially in corners of a slab, can be a problem for post-tensioned slabs. Always use subcontractors for precast slabs.
			E	The ease of installing and stripping formwork is very important. Having many different materials is not such a big issue. Repetition is very important. Having less penetrations through slabs makes everything easier and faster. Only about 1500 m ² of coffer slab systems left in South Africa. Nobody builds it anymore. Always use a subcontractor for a post-tensioning system.
			F	Repetition is important. Would help if less types of concrete is used in a project. Helps if bottom floor uses 30 MPa and the rest is 25 MPa concrete. Makes material ordering much easier and less complicated (first thing that is verified on designs).
			G	Want thinner slabs. The bigger the area that can be cast per day the better (300 m ³ /day can be done). Too many types of concrete is unnecessary. Only use two types. Use a strong 40 MPa and a 25/30 MPa. No real difference between 25 MPa and 30 MPa. Always need to verify for overhead power lines for cranes, trucks and ladders. Also important to verify that working area is safe (edges, confined space, heights).
			H	Already stated everything that is commonly encountered.
		Quantification of experience	A	Difficult to define.
			B	Experienced when having constructed 10 one-way, two-way, flat, coffer slabs, 20 to 30 post-tensioned slabs and 5 precast slabs.
			C	Experienced when having constructed about 50 slabs of each type.
			D	More about having done all the different types, but post-tensioning requires more.
			E	Differs from person to person.
			F	More about number of years. at least 5 to 7 years' experience.
			G	Would know how to construct if already done 2 slabs of each type.
H	Experienced when having constructed about 20 slabs of each type.			
15	Labour	Use of local labour	A	Don't do jobs outside the Cape area. Appoint labourers from the surrounding area if it is a tender requirement. If difficult to find skilled labourers, then they would appoint a subcontractor.
			B	Would typically appoint local labourers for projects that are for the government. Easy to find labourers for unskilled jobs.
			C	Never appoints labourers from local communities.
			D	Do appoint local labourers for a project, but they will only do basic jobs.
			E	Not difficult to find local labourers.
			F	Yes, depends on project-specifics. Easy to find the labourers needed.
			G	Must use local labour for public projects and some private projects. Not hard to find labourers.
			H	Appoint local labourers for most projects. Not hard to find labourers.
		Labour for skilled construction activities	A	Always use own permanent labourers for skilled jobs/activities.
			B	Difficult to find skilled labourers, would typically use own permanent employees for skilled jobs.

			C	Always use own permanent labourers for skilled jobs/activities.
			D	Always use own permanent labourers for skilled jobs/activities.
			E	Always use own permanent labourers for skilled jobs/activities.
			F	Always use own permanent labourers for skilled jobs/activities.
			G	Always use own permanent labourers for skilled jobs/activities.
			H	Always use own permanent labourers for skilled jobs/activities.
16	Transportation		A	Hollow-core longer than 11 m becomes a transport issue and can be expensive when far from site. Reinforcement and formwork transport is not a concern.
			B	Limits precast element sizes.
			C	Must be considered.
			D	More about logistics in terms of traffic, etc.
			E	Everything gets delivered. More about site accessibility.
			F	Transportation is not a problem. Only for special cases such as large roof trusses.
			G	Only a limitation for precast members. Also important to consider if crane can still lift members.
			H	Only a limitation for precast members. Length and heights need to be verified. Larger than 2.5 m wide then it is already wider than a truck. Do not want to have to obtain abnormal load permits due to it being very costly. Prefer transportable sizes.
17	Curing		A	Does not differ due to type of slab.
			B	No significant difference between types of slabs. Usually takes about 7 days. Post-tensioned can take about 5 days. Rib and block systems need to stay propped for at least 5 days.
			C	Is the same for all types.
			D	All the same. More about thickness of concrete.
			E	The same for all types.
			F	The same for all types. More about thickness of concrete.
			G	The same amount of effort for all types. More about thickness of concrete.
			H	Depends on thickness, surroundings, weather and location within building. Not about type.
18	Influence of enhanced constructability		A	Would save time.
			B	Would be a great advantage.
			C	Would save time and money and improve quality.
			D	Would only have advantages.
			E	Would save time and money.
			F	Would help a lot.
			G	Would be an advantage for client, designers and contractors. Everyone would save money.
			H	Slabs and their supports are a critical path of a project and better constructability could result in less labour and supervision requirements. Time and money would be saved in terms of Preliminary and General costs which can be between 10 and 20% of the total project cost.

Appendix E: Summary of verifications' score

Table E-1: Summary of verifications' score

Criteria / Verification No.	Possible relative cost, time and quality implication	Relative interviewee emphasis on significance	Final score
1.1	4	2	6
1.2	3	2	5
1.3	3	3	6
1.4	3	2	5
2.1	3	2	5
2.2	1	2	3
2.3	4	3	7
2.4	1	1	2
2.5	3	2	5
2.6	1	1	2
2.7	1	1	2
2.8	1	1	2
2.9	4	2	6
5.1	3	4	7
5.2	4	3	7
6.1	2	3	5
6.2	4	4	8
6.3	3	3	6
6.4	1	3	4
7.1	3	4	7
8.1	4	3	7
8.2	2	2	4
9.1	3	4	7
9.2	3	1	4
10.1	4	3	7
11.1	4	4	8
11.2	2	4	6
11.3	4	3	7
11.4	3	4	7
11.5	3	4	7
11.6	1	2	3
11.7	2	3	5
11.8	1	2	3
11.9	4	3	7
12.1	3	4	7
12.2	3	2	5
12.3	4	4	8
12.4	2	2	4
12.5	4	3	7
13.1	4	4	8
13.2	4	3	7
13.3	3	2	5
14.1	4	4	8
14.2	4	2	6
14.3	2	3	5
14.4	3	2	5
14.5	2	2	4
14.6	4	3	7
14.7	4	2	6
14.8	3	2	5
16.1	4	3	7

Appendix F: Determining presence of wall elements

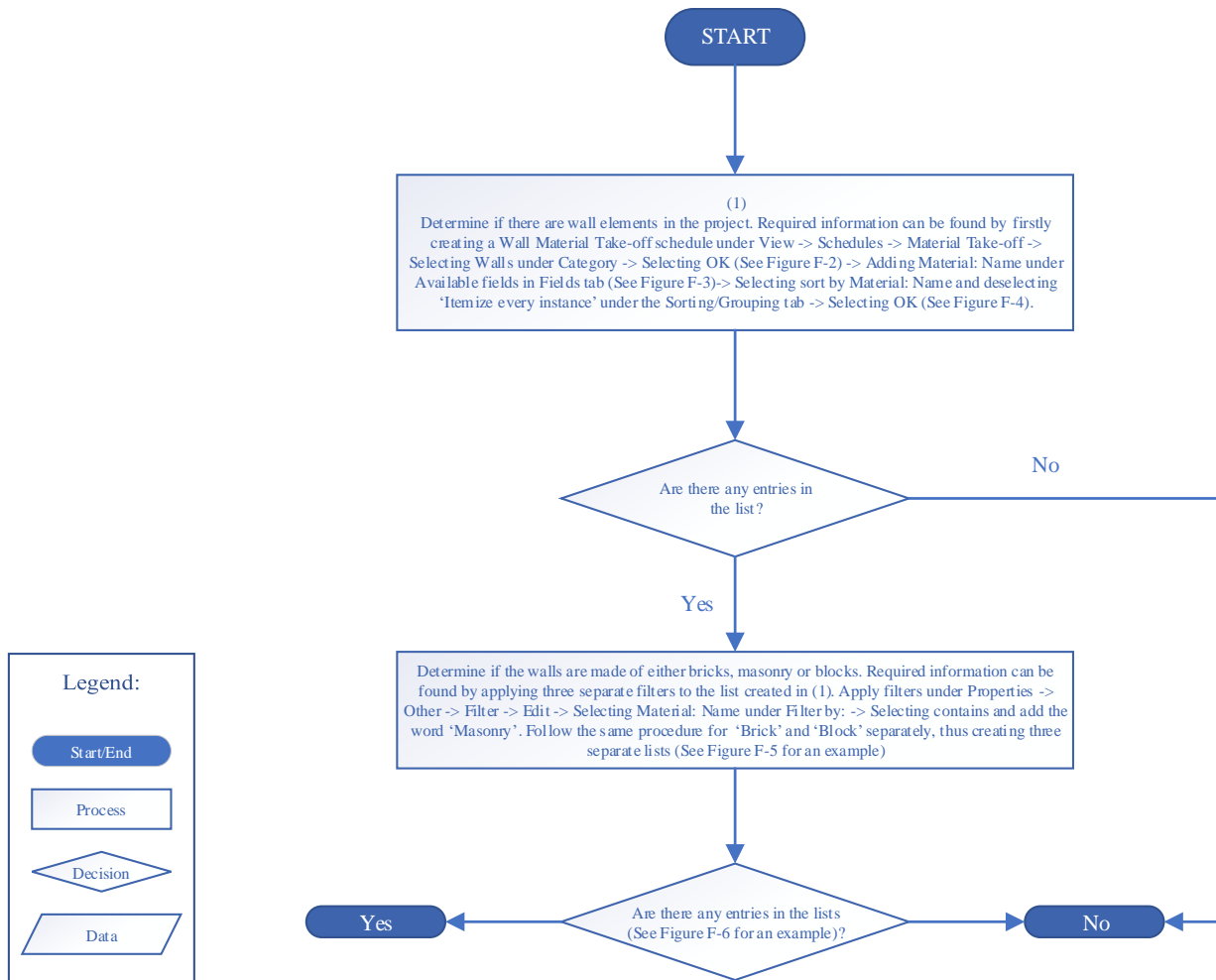


Figure F-1: Determining presence of wall elements

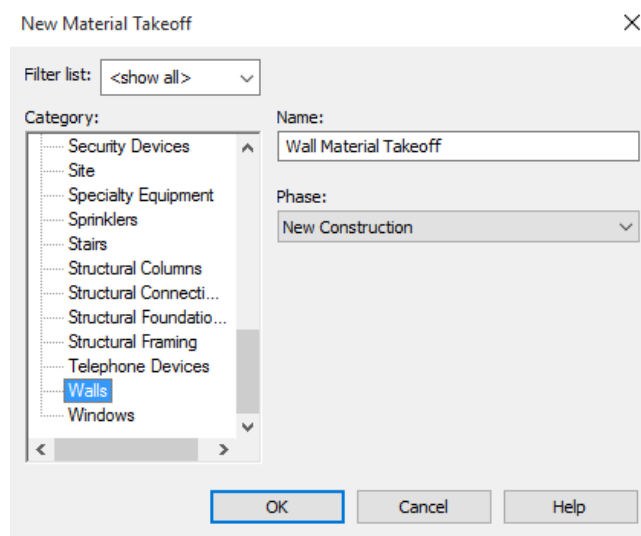


Figure F-2: Creating wall material takeoff schedule

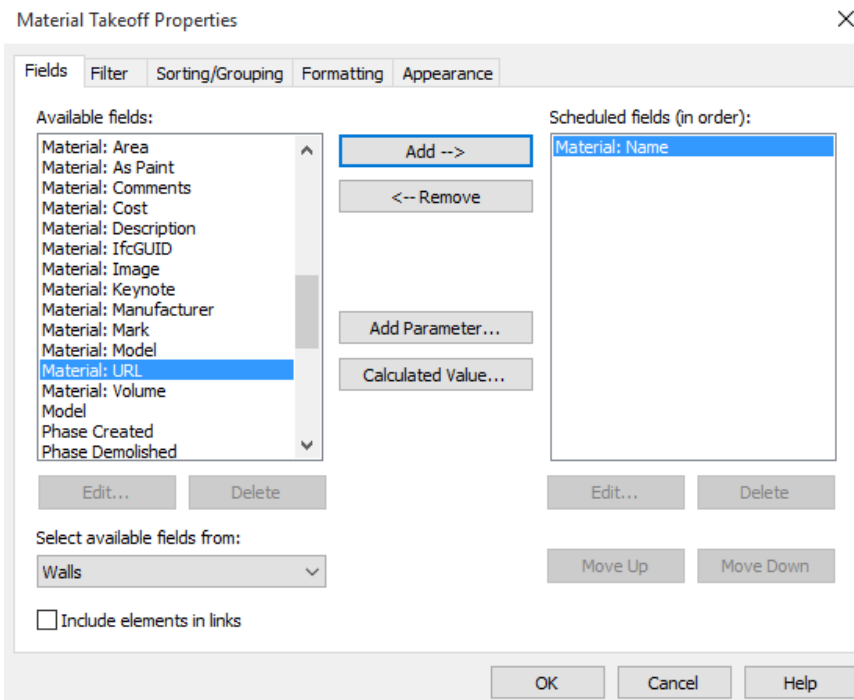


Figure F-3: Adding fields to material takeoff schedule

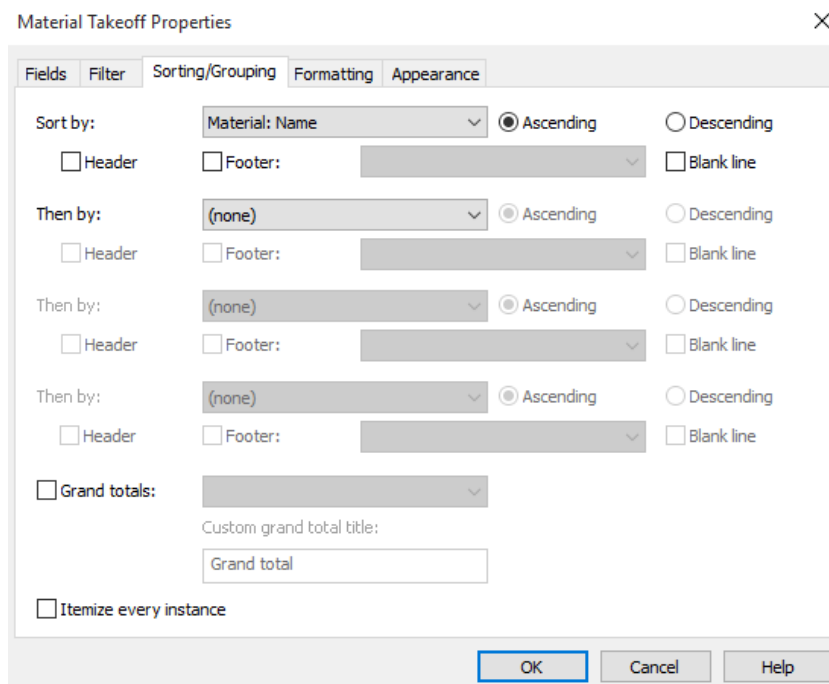


Figure F-4: Sorting takeoff schedule

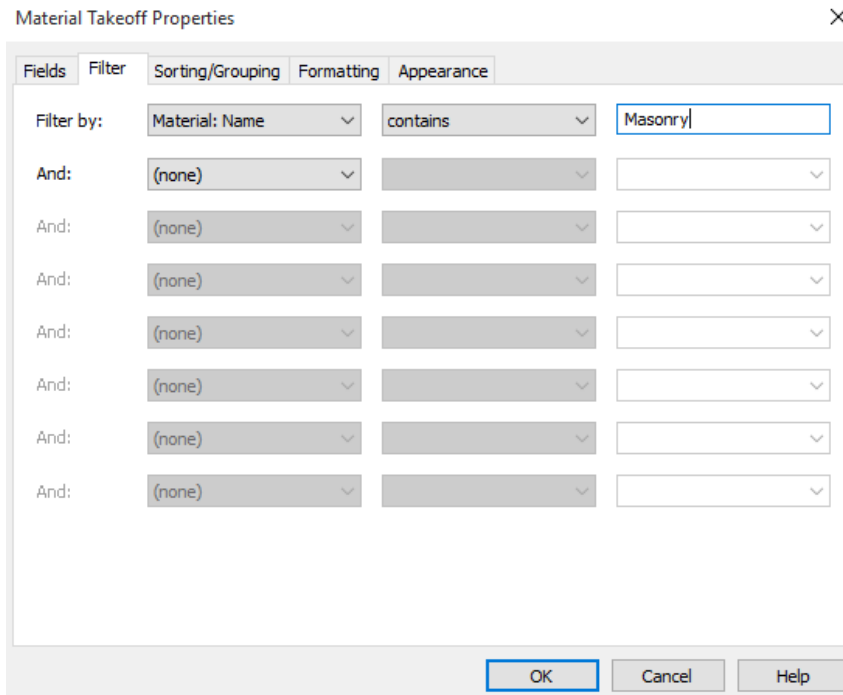


Figure F-5: Filtering takeoff schedule

<Wall Material Takeoff>
A
Material: Name
Concrete Masonry Units
Concrete, Cast-in-Place gray

Figure F-6: Example of material takeoff schedule

Appendix G: Determining if in-situ-cast concrete will be used

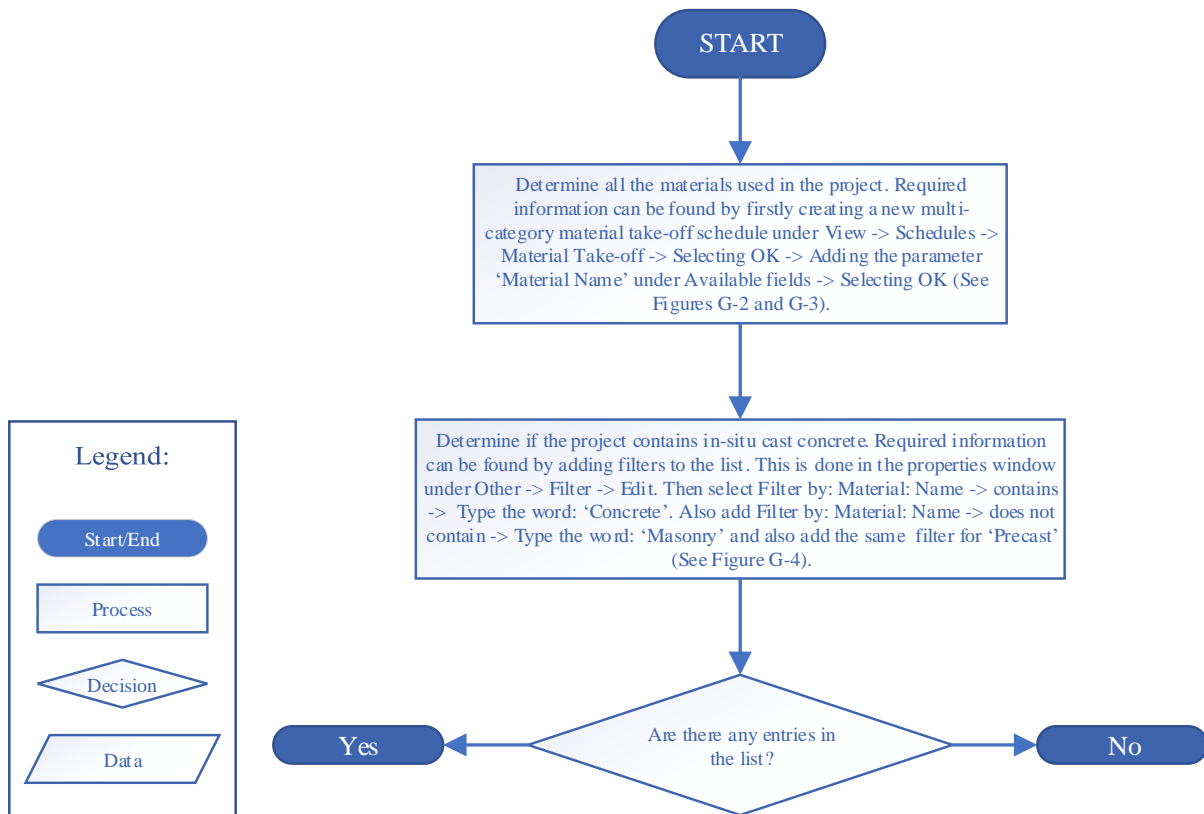


Figure G-1: Determining if in-situ-cast concrete will be used

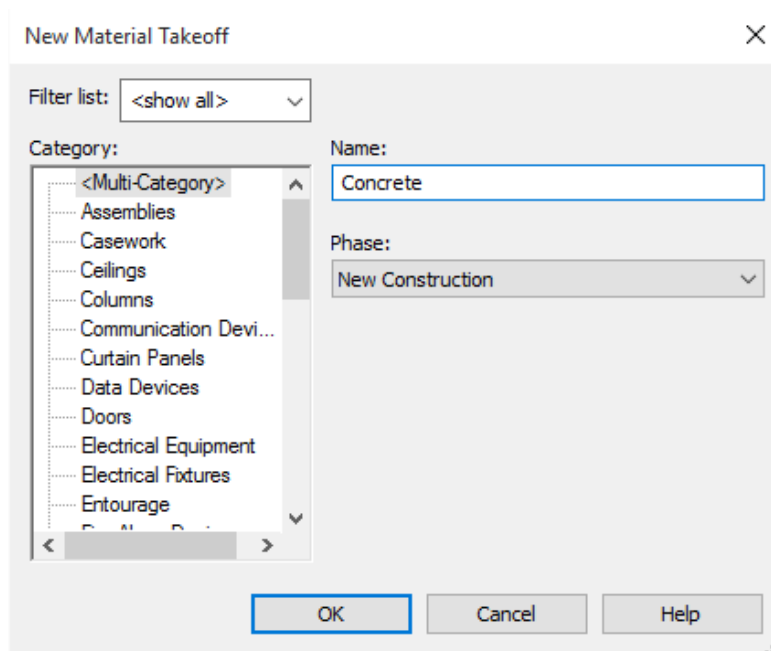


Figure G-2: Creating a new material takeoff schedule

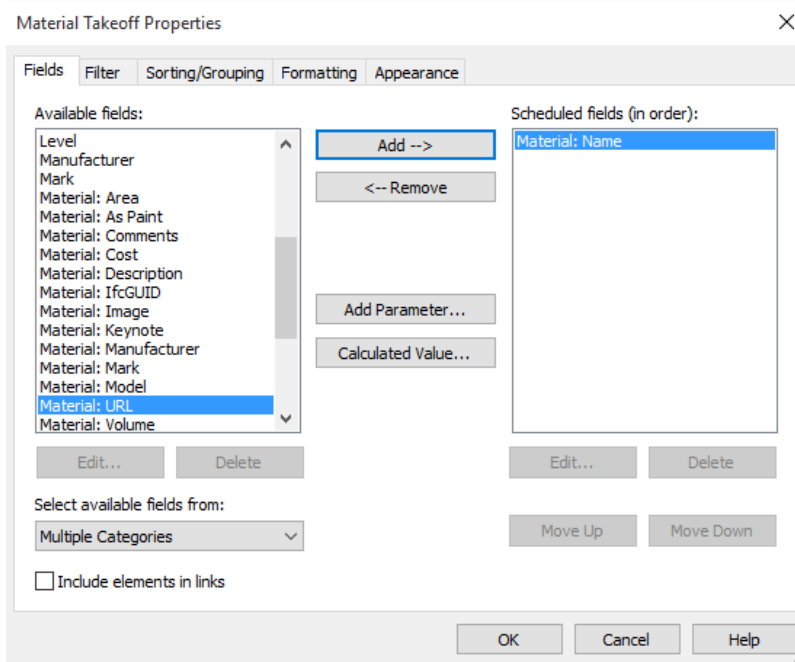


Figure G-3: Adding fields to material takeoff schedule

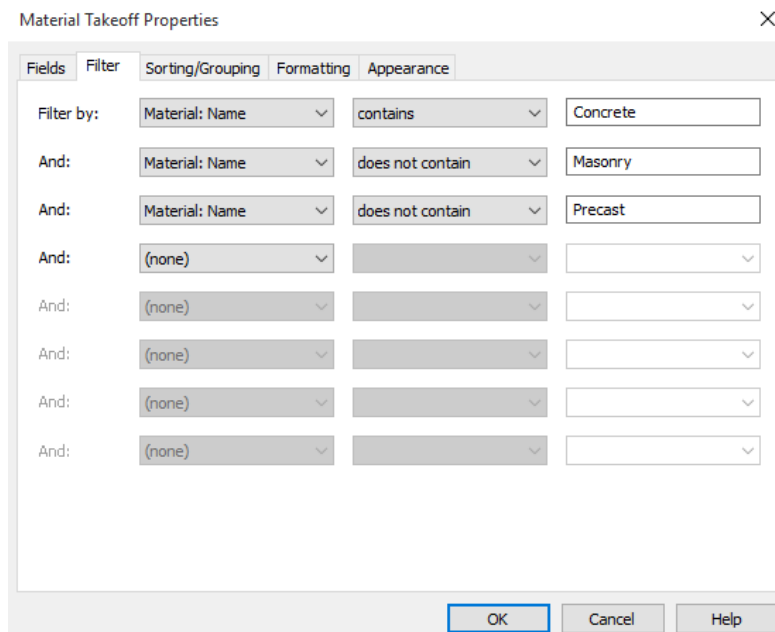


Figure G-4: Filtering the material takeoff schedule

Appendix H: Determining if in-situ concrete column elements will be used

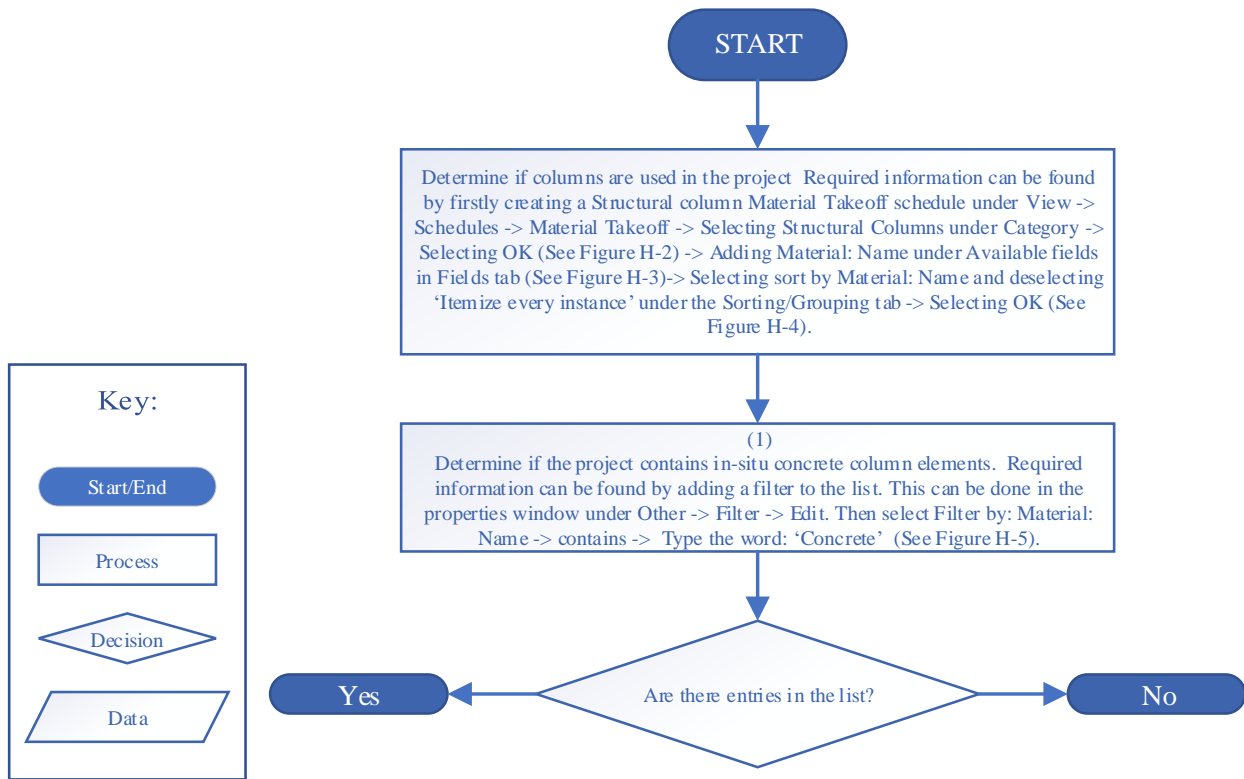


Figure H-1: Determining if in-situ concrete elements are used

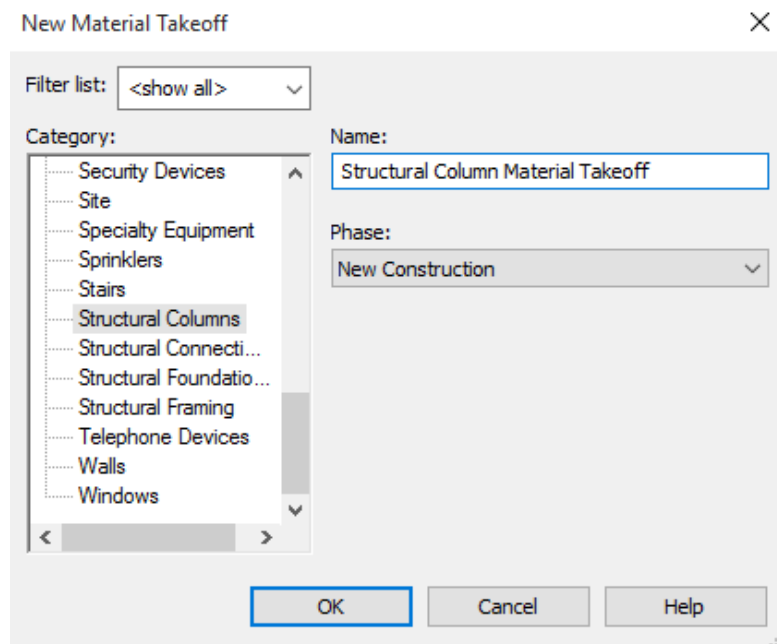


Figure H-2: Creating a new structural column material takeoff schedule

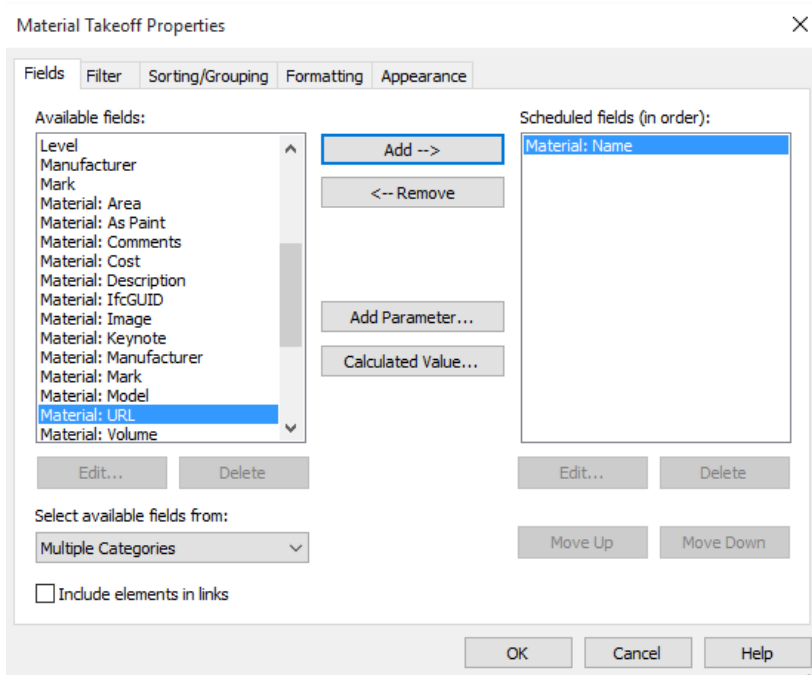


Figure H-3: Adding fields to structural column schedule

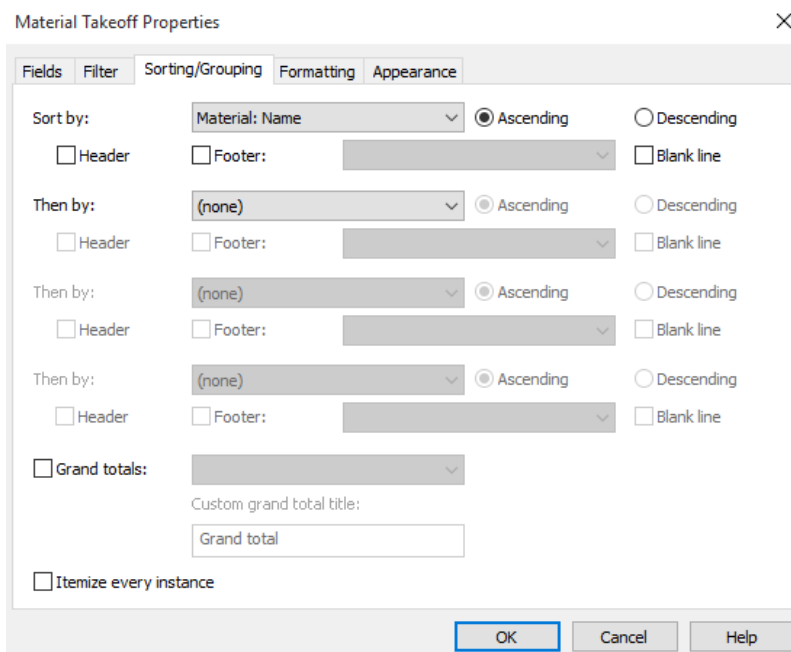


Figure H-4: Sorting structural column schedule

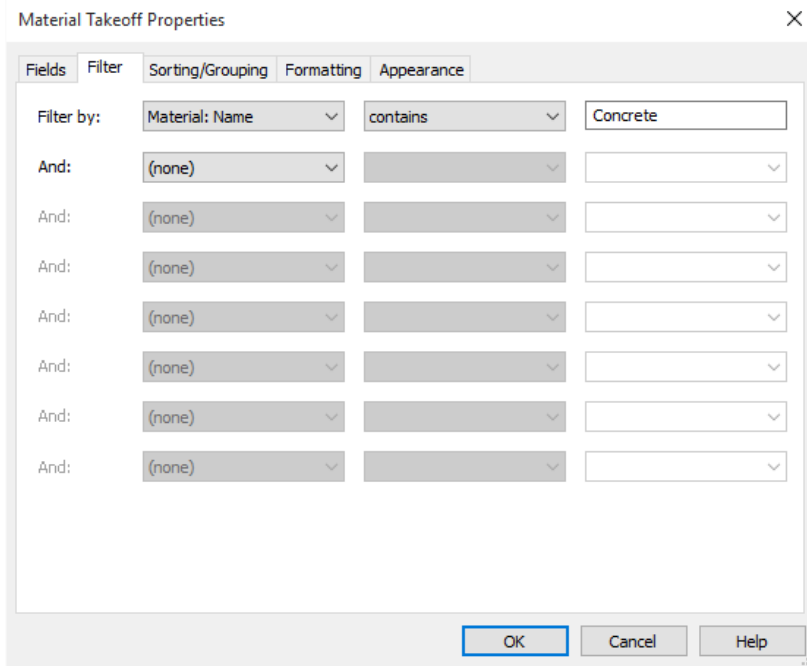


Figure H-5: Filtering structural column schedule

Appendix I: Determining the different types of cross-sections that will be used

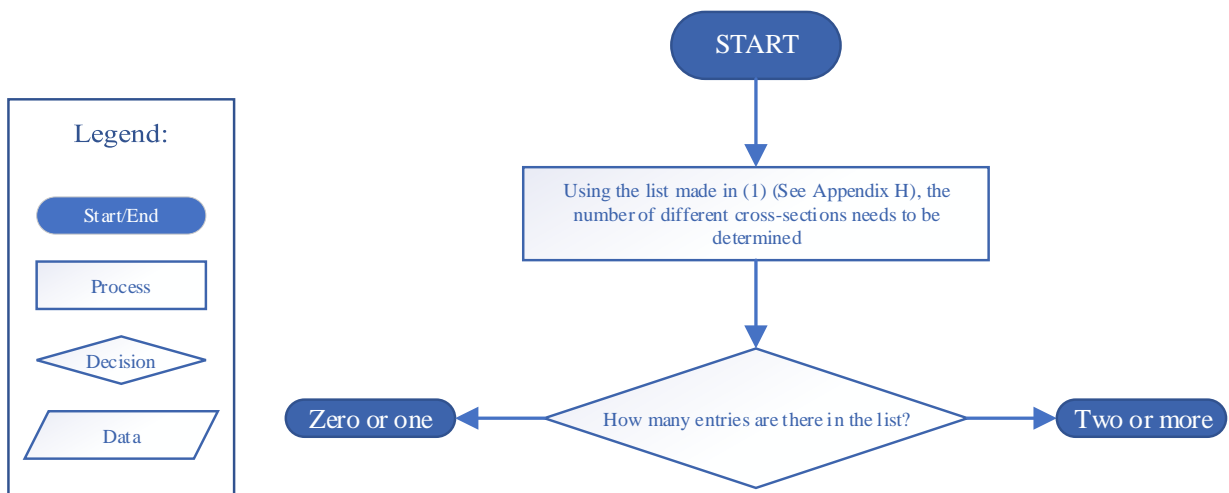


Figure I-1: Determining different types of concrete used

Appendix J: Determining the different types of concrete that will be used

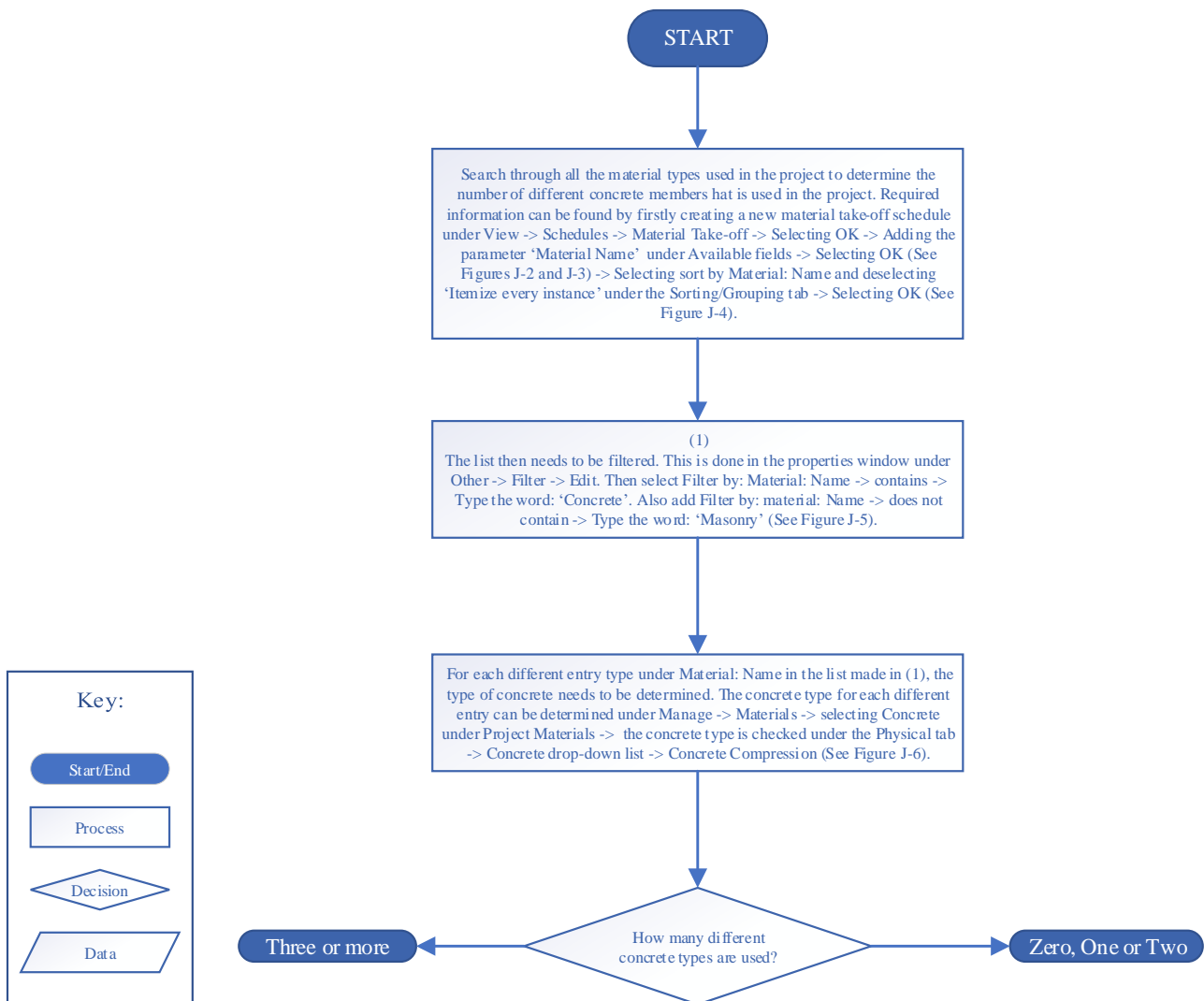


Figure J-1: Determining different types of concrete used

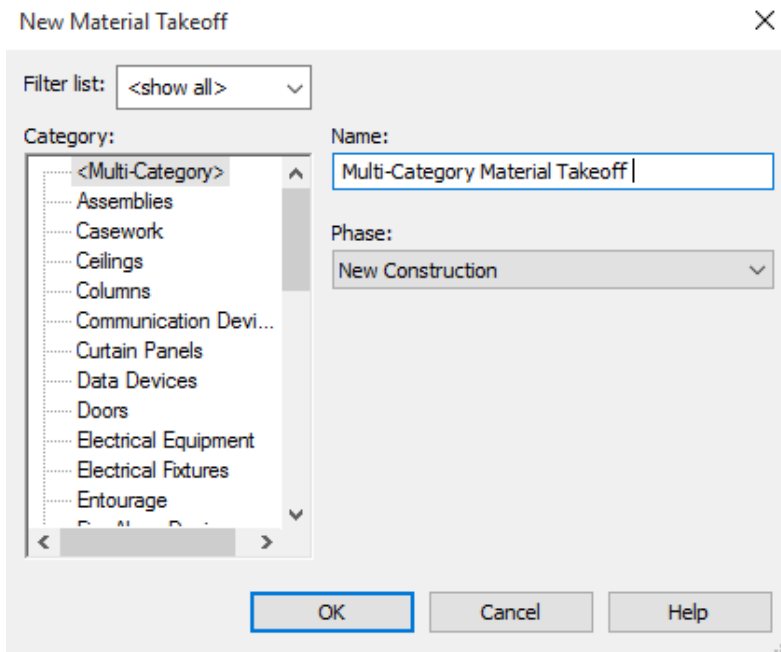


Figure J-2: Creating new multi-category material takeoff schedule

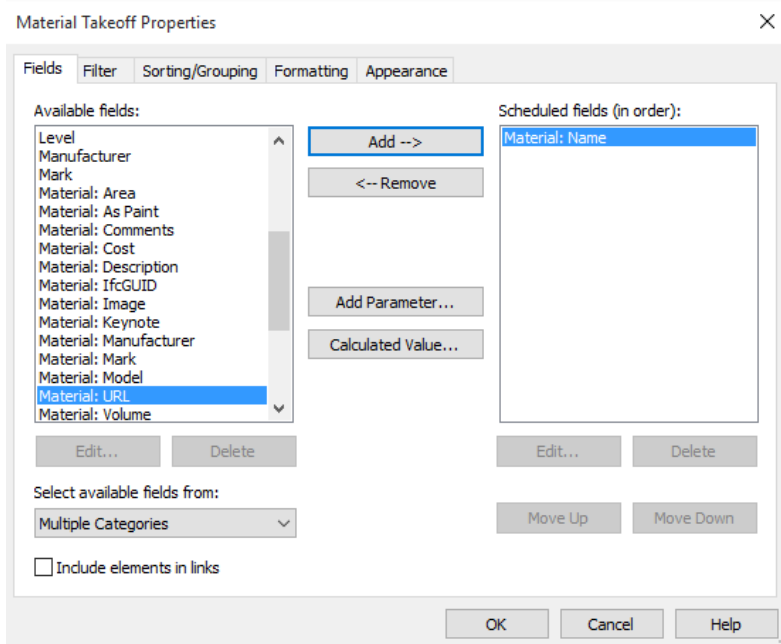


Figure J-3: Adding available fields to material takeoff schedule

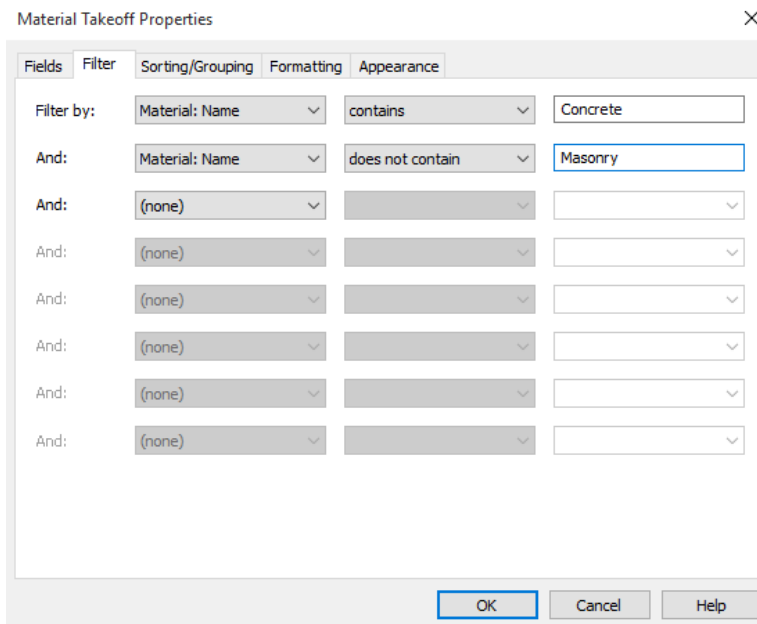


Figure J-4: Filtering material takeoff schedule

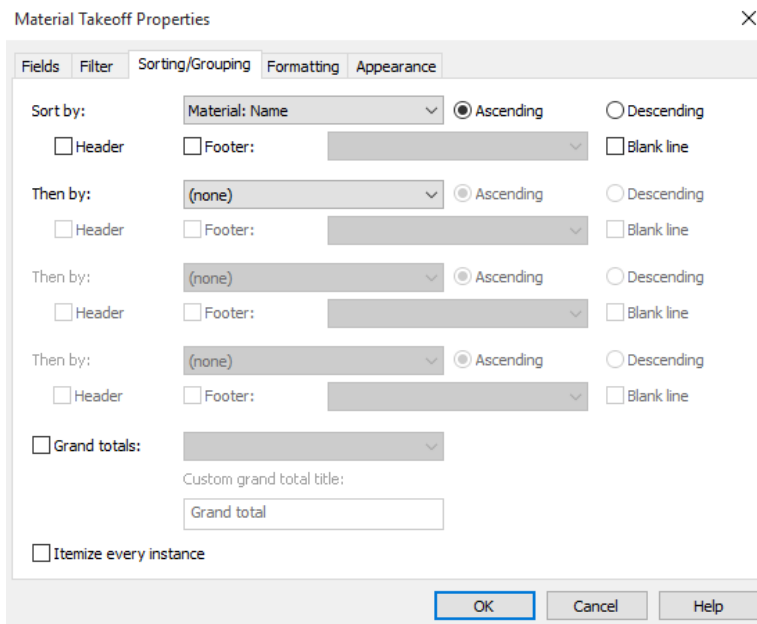


Figure J-5: Sorting material takeoff schedule

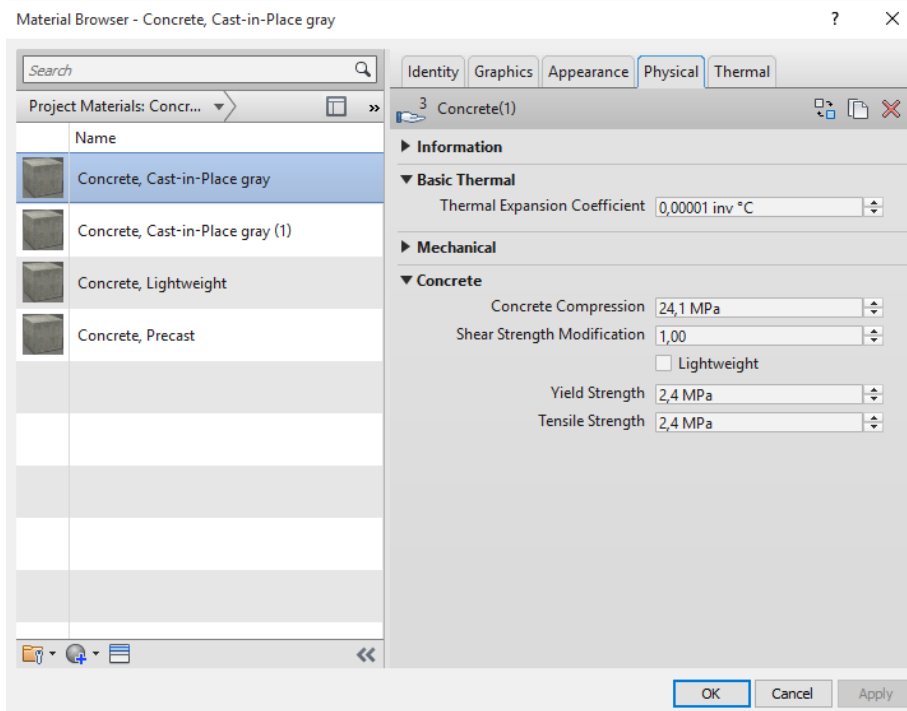


Figure J-6: Determining concrete types

Appendix K: Consent form for second round of interviews



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CONSENT TO PARTICIPATE IN RESEARCH

You are invited to take part in a study conducted by Dirk Jacobus Kotzé, from the Department of Civil Engineering at Stellenbosch University. You were approached as a possible participant because you fit into our research category of designer, consultant or experienced with civil engineering design software.

1. PURPOSE OF THE STUDY

The aim of the research is to determine the logic behind a process that analyses the constructability of suspended floor slabs and also to give a representation of how the proposed process could be implemented on Autodesk Revit. The process will be aimed at analysing the common suspended floor slab types used in the South African construction industry. The process will analyse aspects of floor slabs from the perspective of the contractor to help improve the constructability of floor slabs. The process will give possible constructability problems, advantages and important constructability characteristics as a reminder to the user (the designer) to help them in the process of making a decision on which type of floor slab will be most efficient for the specific situation.

2. WHAT WILL BE ASKED OF ME?

If you agree to take part in this study, you will be asked to answer questions administered during one-on-one interviews. The questions to be asked are all based on how a designer would prefer a constructability improvement process would be implemented on Autodesk Revit. The interviews will aim to identify the best possible, or most practical, way in which such a process could be implemented on Autodesk Revit. The experience of each participant with Autodesk Revit, or similar software, will also be asked.

3. POSSIBLE RISKS AND DISCOMFORTS

The time required for one-on-one interviews could possibly disturb the interviewees' daily routine, therefore the interviews will be kept as short as possible.

4. POSSIBLE BENEFITS TO PARTICIPANTS AND/OR TO THE SOCIETY

The possible benefits for the participants will be that the process would improve the constructability of floor slabs by analysing the constructability at the design stage which would result in fewer constructability issues occurring during the construction phase. This would make projects more cost and time efficient.

5. PAYMENT FOR PARTICIPATION

Participants will be interviewed on a voluntary basis and no compensation will be given for participation.

6. PROTECTION OF YOUR INFORMATION, CONFIDENTIALITY AND IDENTITY

You have the option of being completely anonymous at the interview. If you choose to stay anonymous then any information you share with me during this study that could possibly identify you as a participant will be protected by using pseudonyms and not the actual names of the participants. This

will be done by making sure that the one-on-one interviews are kept confidential.

The information will be shared only for academic purposes.

If the results obtained are to be published the real names of the participants will not be published but pseudonyms will be used instead to retain confidentiality.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to participate in this study or not. If you agree to take part in this study, you may withdraw at any time without any consequence. You may not remain part of the study if you are unable to answer key questions that will lead to the successful completion of the study. The researcher may withdraw you from this study if you violate the terms and conditions under which the research is to be conducted. If you choose to withdraw from the study, then all the information that you have given up to that point will be disposed of.

8. RESEARCHERS' CONTACT INFORMATION

If you have any questions or concerns about this study, please feel free to contact Dirk Jacobus Kotzé (16960548@sun.ac.za) and/or the supervisor Prof Jan Wium (janw@sun.ac.za) from the Department of Civil Engineering at Stellenbosch University.

9. RIGHTS OF RESEARCH PARTICIPANTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

DECLARATION OF CONSENT BY THE PARTICIPANT
--

As the participant I confirm that:

- I have read the above information and agree that it is written in a language that I am comfortable with.
- I have had a chance to ask questions and all my questions have been answered.
- All concerns related to privacy, and the confidentiality and use of the information I provide, have been explained.

By signing below, I _____ agree to take part in this research study, as conducted by Dirk Jacobus Kotzé.

Signature of Participant

Date

DECLARATION BY THE PRINCIPAL INVESTIGATOR
--

As the **principal investigator**, I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition, I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator (who has signed a non-disclosure agreement), and this 'Consent Form' is available to the participant in a language in which the participant is fluent.

Signature of Principal Investigator

Date

Appendix L: Interview schedule for second round of interviews



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Identifying regular or potential constructability problems related to suspended floor slabs and the related site efficiency problems in terms of crane placement and truck accessibility in the South African construction industry.

Introduction

With the increase in the complexity of modern day construction projects, the issue of constructability has become increasingly important. It is recognized that the integration of construction information in the early stages of a project provides a good opportunity for significant time-and cost-savings (Hanlon & Sanvido, 1995). It is important that design professionals need to be alert to the possible issues and claims that can result from a design's constructability profile. When a project has inherent constructability problems, the results of litigation can involve change order disputes and issues, delay claims and owner dissatisfaction. In more extreme cases, direct claims could be made against the company responsible for the design. The claims could be for poor plans, estimates, specifications or schedules that either made the project difficult to build, more time consuming or more costly than had been planned.

To integrate information regarding constructability efficiently and effectively into the design phase, it should be organised and be accessible in a format that is desirable to its users (mostly designers). An even further, and more effective, improvement would be possible if the software that designers use for their designs were able to identify possible future constructability problems whilst the designer was using the software.

Building Information Modelling is becoming increasingly popular internationally and the benefits of its use have been proven to be immense. Using Building Information Modelling to increase the constructability of projects could possibly have significant advantages in saving time and costs.

Questionnaire is to be administered using one-on-one Interviews

Interview guide for designers/consultants/experienced civil engineering design software users

Interviewee details:

- 1) Name (not required)
- 2) Pseudonym for name if choosing to stay anonymous
- 3) Interviewee's position in company
- 4) Interviewee's tertiary education and degree(s)
- 5) Number of years the interviewee has been working in the consulting industry
- 6) Number of years the interviewee has been involved with the use of Civil engineering design software
- 7) Number of years the interviewee has been involved with the use of Autodesk Revit as a design tool

General:

- 8) Does your company use Building Information Modelling?
.....
.....
- 9) Would a designer (experienced or inexperienced) benefit from a process that identifies possible constructability concerns through the use of checks such as:
 - Floor-to-floor brick height increment check which measures floor-to-floor height and compares it to increments of brick heights depending on the specific brick height used
 - Concrete cover check which reminds the designer to increase cover to incorporate manufacturing tolerances and human error on the construction site
 - Cross-section repetition check which advises a designer to use less cross-section types to enhance repetition
 - Mechanical, electrical and plumbing services coordination check which aims to determine if MEP services layout has been finalized after coordination between the engineer and MEP services designer has taken place
 - Concrete types check which advises the designer to use less different types of concrete if more than two types are used

*Note: -Checks only act as examples to illustrate the capability of BIM to improve constructability
-The word 'check' refers to a verification of constructability
.....
.....
.....

Initial Process:

Please select which of the following options you would prefer while using a constructability analysis/enhancement tool on Autodesk Revit:

10) Which of the following would you prefer?

- i. To be able to tick which constructability checks you would like to be performed on your model (See Figure 1 below)
- ii. The process must perform all the possible incorporated constructability checks that it has (See Figure 2 below)

***Note: Consider the list will have several more options (50 other checks were identified in this study alone)**

Please select which of the following checks you wish to be performed:

Name	Description	Additional information required:
<input type="checkbox"/> Floor-to-floor brick height increment check	Measures floor-to-floor height and compares it to increments of brick heights depending on the specific brick height used	Brick height that will be used (mm): <input type="text"/> Height of mortar between bricks (mm): <input type="text"/>
<input type="checkbox"/> MEP services coordination check	Aims to determine if MEP services layout has been finalized after coordination between the engineer and MEP services designer has taken place	Please confirm if the following has been done: <input type="checkbox"/> Coordination between engineer and MEP services designer regarding final layout <input type="checkbox"/> Clash detection on final layout <input type="checkbox"/> Final MEP services layout is completed
<input type="checkbox"/> Cross section repetition check	Advises a designer to use less cross section types to enhance repetition	
<input type="checkbox"/> Concrete cover check	Reminds the designer to increase cover to incorporate manufacturing tolerances and human error on the construction site	
<input type="checkbox"/> Concrete types check	Advises the designer to use less different types of concrete if more than two types are used	

Figure L-1: Option 1

Please provide the relevant information needed

Name	Description	Additional information required:
Floor-to-floor brick height increment check	Measures floor-to-floor height and compares it to increments of brick heights depending on the specific brick height used	Brick height that will be used (mm): <input type="text"/> Height of mortar between bricks (mm): <input type="text"/>
MEP services coordination check	Aims to determine if MEP services layout has been finalized after coordination between the engineer and MEP services designer has taken place	Please confirm if the following has been done: <input type="checkbox"/> Coordination between engineer and MEP services designer regarding final layout <input type="checkbox"/> Clash detection on final layout <input type="checkbox"/> Final MEP services layout is completed
Cross section repetition check	Advises a designer to use less cross section types to enhance repetition	
Concrete cover check	Reminds the designer to increase cover to incorporate manufacturing tolerances and human error on the construction site	
Concrete types check	Advises the designer to use less different types of concrete if more than two types are used	

Figure L-2: Option 2

Comments:

.....

.....

.....

Investigation of possible constructability concerns:

11) Which of the following would you prefer?

- i. To be able to choose which constructability concerns to view (See Figure 3)
- ii. To view all the constructability concerns from the start (See Figure 4)

*Note: In the case where no concerns were found, Figure 5 will be shown

The following checks identified areas where constructability improvement is possible:

Name	
Floor-to-floor brick height increment check	<input type="button" value="Investigate"/>
MEP services coordination check	<input type="button" value="Investigate"/>
Cross section repetition check	<input type="button" value="Investigate"/>
Concrete cover check	<input type="button" value="Investigate"/>
Concrete types check	<input type="button" value="Investigate"/>

Figure L-3: Option 1

The following checks identified areas where constructability improvement is possible:

Name

Floor-to-floor brick height increment check

MEP services coordination check

Cross section repetition check

Concrete cover check

Concrete types check

Figure L-4: Option 2

No areas were found in which constructability can be improved

Figure L-5: No concerns found message

Comments:

.....

12) If option 2 in Question 11 was selected, which of the following would you prefer?

- i. To view all the areas of possible constructability concerns, identified by the checks, at once.
- ii. To view them one-by-one

Comments:

.....

Viewing constructability concerns:

13) While viewing the message given regarding an identified possible constructability concern, which of the following would you prefer?

- i. To be able to choose to ignore or rectify later for each identified concern and then afterwards have a list which shows what checks were ignored and which were chosen to rectify (See Figures 6 and 7 for an example)
- ii. To just be able to state okay (See Figure 8 for an example)

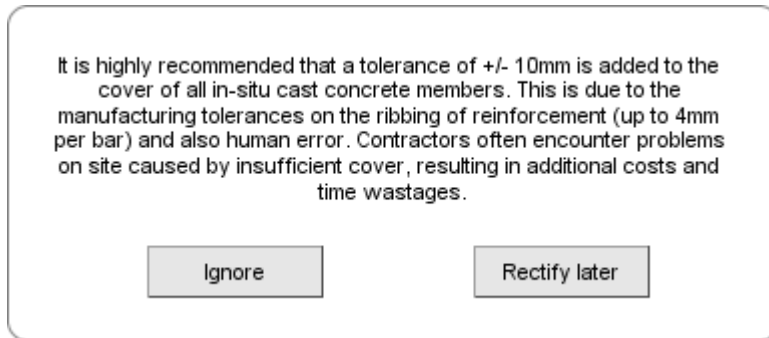


Figure L-6: Option 1

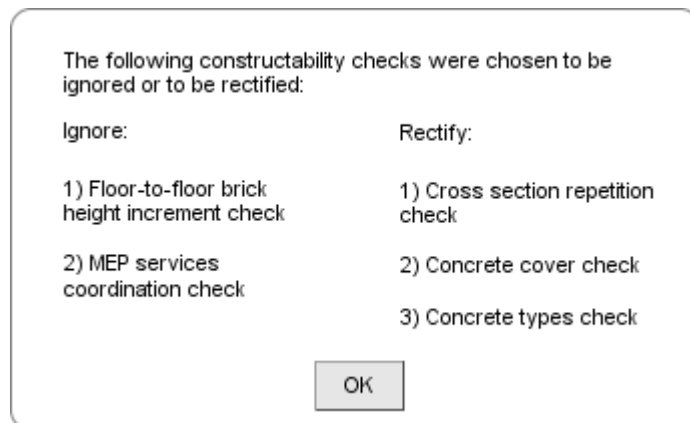


Figure L-7: Option 1 list

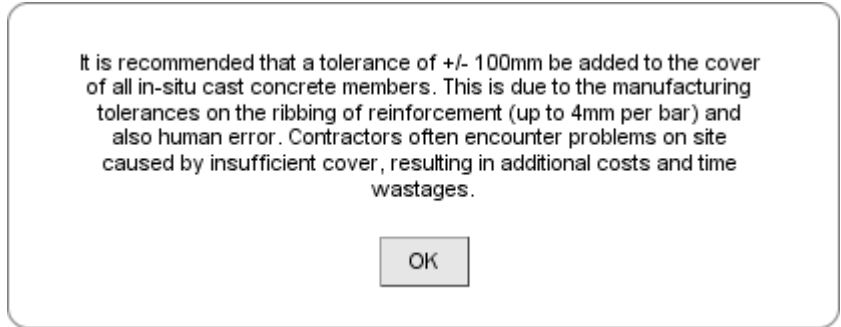


Figure L-8: Option 2

Comments:

.....
.....
.....

Frequency of constructability concern messages:

14) Which of the following would you prefer?

- i. To view a single message and have all the areas of possible constructability problems highlighted which have the same possible problem
- ii. View a message at each area of possible constructability problems

Comments:

.....
.....

Detail level provided in concern messages:

15) Please state which of the following options you would prefer to be given when investigating a constructability concern:

- i. What the potential problem is
- ii. Origin of concern (what contractors have encountered regarding a certain problem)
- iii. Recommendation on how to rectify the concern
- iv. Possible advantages if the concern is rectified

Comments:

.....
.....
.....

Implementation of the constructability analysis process:

16) At what stage during design would you prefer to be able to do these constructability checks?

.....
.....
.....

Implementation of project-specific parameters

17) Would you want a consideration of project-specific parameters to be incorporated at some stage during the design? These parameters can include project location, distance from suppliers (precast, concrete, etc.), preference of contractors in the area, weather, etc. Could this be valuable?

.....
.....
.....

18) If yes, at what stage during the development of the design would you prefer the parameters be incorporated (before design starts, after design is completed along with constructability checks)?

.....
.....
.....

Design procedure:

19) How does your general design procedure work when a new project is undertaken?

.....
.....
.....

Concluding remarks:

20) Are there any further comments and/or tips that you would like to provide?

.....
.....
.....

Thank you for your cooperation

Appendix M: Summary of validation interview responses

Table M-1: Summary of validation interview responses

Section	Question	Contractor	Interviewee Response Summary
General	8	A	Yes, they use Autodesk Revit, Tekla Structural Designer and Sumo (Prokon).
		B	Draftsmen used Autodesk Revit and consultants used Tekla when the consultant was working full-time.
		C	Yes, they use Autodesk Revit, Navisworks, BIM 360 and BIM 360 glue.
		D	Yes, they use Autodesk Revit.
		E	Yes, they use Revit and Tekla BIMsight.
		F	Yes. Tekla BIMsight and MasterSeries.
	9	A	It would be very practical and can help a lot
		B	Would help a lot but must be easy and fast to use. Floor height increment and concrete types verification must be available as early as possible.
		C	Can have advantages. Floor-to-floor height increment verification not that important and is mostly the architect's job to check. Detailing code and SANS 282 specify tolerance on cover for concrete cover verification.
		D	Contractor would mostly benefit from it but would help consultants as well.
		E	Yes, it is good practice to integrate constructability at design and planning phase.
		F	Yes, especially for inexperienced designers.
Initial Process	10	A	Option 1. For certain cases certain checks would be irrelevant.
		B	Option 1. Be careful of liability (e.g. for the MEP services verification). Could also implement a process to delegate certain things for other designers.
		C	Option 2
		D	Option 1. Divide into categories and sub-categories.
		E	Option 1. Add check all tick box and add categories
		F	Option 1. Add check all tick box.
Investigation of possible constructability concerns	11	A	Option 1
		B	Option 1
		C	Option 1
		D	Option 1
		E	Option 1
		F	Option 1. Also state which verifications are satisfied.
	12	A	Not applicable
		B	Not applicable
		C	Not applicable
		D	Not applicable
		E	Not applicable
		F	Not applicable
Viewing constructability concerns	13	A	Option 1
		B	Option 1. Add option for the user to state why he/she wants to ignore or rectify in order to have a record of decisions

		C	Option 1. Make process similar to what is done in Navisworks. In Navisworks, a user can choose if a problem is a proper clash, approved problem or resolve.
		D	Option 1. Change 'Rectify later' to 'Accept'.
		E	Option 1. Change 'Rectify later' to 'User Correction'. After ignore option is chosen the user must give a reason why. User must be reminded of concerns that must be fixed until they are fixed. State the number of concerns that are still pending somewhere.
		F	Option 1. Would prefer process to be running whilst designing.
Frequency of constructability concern messages	14	A	Option 1
		B	Option 1. Could have browser next to the view port which shows all the concerns and when a concern is selected it takes you to the potential problem
		C	Option 1. Wants two things. Wants a list of all the concerns with each element ID and the concern and to see where the potential problem is graphically.
		D	Option 1
		E	Option 1
		F	Option 1
Detail level provided in concern messages	15	A	1, 2, 3 and 4
		B	1, 2, 3 and 4. Implement a cost-impact in the verifications
		C	1 and 3. Must make process more project-specific. Must be able to state which parameters are known (e.g. lengths and widths) in an interface.
		D	1, 3 and 4.
		E	Only 1. It should not influence engineering judgement of user with too much information
		F	1 and 2.
Implementation of the constructability analysis process	16	A	When its needed, thus after something has been designed
		B	Depends on which verifications. All as early as possible. Must still be able to change design without large cost implications
		C	Ideally before tender is issued.
		D	As early as possible, which would be at tender stage.
		E	Should be able to do at any time.
		F	Would prefer to be able to perform at any time.
Implementation of project-specific parameters	17	A	Yes, location for steel structures can be a significant factor as an example.
		B	Depends on how much is known about a project. Must be easy. Add quality of construction in area. Give simple ratings or criteria for parameters.
		C	Yes, would be good to consider, but shouldn't be a problem.
		D	Not really but could help in certain special cases.
		E	Yes, would help a lot. Team leader must fill in but must be able to bypass. Add formwork stripping time, crane heights, if cranes can be used, site boundaries and geotechnical considerations such as the supporting of slopes.
		F	Yes, good to consider everything and to be reminded of parameters.
	18	A	Before design starts, i.e. during tender/conceptual stage.
		B	As early as possible. Architect and quantity surveyor must also know the parameters.
		C	At conceptual stage.
		D	At conceptual stage.
		E	When opening a new project.

		F	Right at the beginning.
Design procedure	19	A	Architect sends plans, engineer marks up drawings, engineer identifies problematic areas and makes recommendations and architect implements changes.
		B	Depends on project. Different role players can get involved at different times.
		C	In some jobs they work with the architect and some jobs they only get after budget is made and architect is mostly done. Nowadays, everyone mostly works together on a BIM model and certain things need to be done at certain times.
		D	Receive drawings from architect, determine general sizes, send back to architect, some coordination between architect and designer until client is happy and then the drawings are finalized.
		E	Client appoints architect, conceptual design is done, coordination between engineers, architect and clients and then designs are finalized. Process should occur during design development phase.
		F	Receive plans from architect, design accordingly, coordination between designers and client or architect, finalize designs and develop drawings.
Concluding remarks	20	A	Add checks which gives cost per kilogram for different steel sections. Incorporate cube test results as reference in the BIM model. BIM model must show changes between old and new drawings.
		B	Certain verifications can be too late in design process. Implement a tier approach for when certain verifications need to be implemented. BIM models might not be set up yet when certain verifications have to be done.
		C	
		D	
		E	Must be simple and easy to use. Incorporate possibility of user being able to set tolerances on verifications involving measurements. Add headroom check on stairs.
		F	