The Implementation of Constructability Concepts for Design-bid-build Construction Projects

by
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Declaration

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Abstract

The construction industry continually seeks innovative approaches to improve project outcomes and maximize operational efficiency. This study addresses the need for improved constructability considerations during the design phase of design-bid-build projects by introducing an intuitive constructability tool and by advocating intentional collaboration. Traditional procurement methods, such as design-bid-build, retain prominence in the construction industry, particularly for public projects. However, such methods often lack early collaboration between designers and contractors, resulting in missed opportunities for constructability improvements.

Concentrating on design-bid-build projects, this study proposes a mobile application as a constructability aid for design engineers to augment their construction considerations during the design phase. It also identified a need to bridge the gap between design engineers and construction specialists through constructability-focused collaboration during mobilization. Despite the significance of constructability considerations in improving construction project outcomes, limited research is available on its implementation in design-bid-build projects.

The prevailing literature predominantly focuses on design-build processes, leaving a gap in addressing the unique challenges of early collaboration and knowledge exchange in design-bid-build projects. In this study, construction expert knowledge, obtained through interviews, is utilized in the mobile application and it shows how construction knowledge can be shared with design engineers to support them in creating constructible designs. Additionally, a constructability-centred collaboration plan is presented that project managers can utilize in design-bid-build projects to improve the identification of constructability problems.

From the interviewee feedback, 201 advice phrases are derived, which are categorized into 12 groups, shedding light on important aspects of successful project delivery. Distinct clusters of advice were linked to different roles within the construction industry, with practicality, collaboration, and safety as dominant themes. New constructability concepts emerged from these advice phrases, emphasizing mentorship, communication, continuous learning and practical design decisions, unveiling previously unaddressed dimensions.

A novel approach, inspired by Integrated Project Delivery (IPD) principles, is presented and validated through interviews with industry participants. Notably, the mobilization phase encompasses activities extending beyond mere site preparation, including project setup, safety planning, project scheduling, contract coordination and stakeholder engagement, which are collaborative activities. Despite the mobilization phase's potential for collaboration, interview feedback reveals a general lack of effective implementation.

Challenges identified through the validation interviews relate to biases, resistance to change and difficulties in incorporating diverse perspectives. Six considerations to elevate collaboration, including incorporating positive incentives, tool implementation and fostering a culture of collaboration are presented. The validation interviews confirm the feasibility of this approach, emphasizing the significance of addressing challenges and clarifying participants' responsibilities to drive constructability-centred collaboration.

The proposed constructability tool, supported by constructability-focused collaboration during mobilization, holds promise for amplifying project outcomes and instilling a culture of design mindful of construction constraints.

Opsomming

Die konstruksiebedryf soek voortdurend innoverende benaderings om projekuitkomste te verbeter en operasionele doeltreffendheid te optimeer. Hierdie studie spreek die behoefte aan verbeterde boubaarheidsoorwegings in die ontwerpfase van ontwerp-aanbod-konstruksie-projekte aan deur ‘n intuïtiewe boubaarheidsinstrument, en doelgerigte samewerking voor te stel. Tradisionele verkrygingsmetodes, soos ontwerp-aanbod-konstruksie, bly prominent in die konstruksiebedryf, veral vir openbare projekte. Sulke metodes ontbeer dikwels vroeë samewerking tussen ontwerpers en kontrakteurs, wat lei tot gemiste geleenthede vir konstrueerbaarheidsverbeterings.

Hierdie studie fokus op ontwerp-aanbod-konstruksie-projekte en poog om die gaping tussen ontwerpingenieurs en konstruksiespesialiste te oorbrug deur boubaarheid-gefokusde samewerking tydens mobilisering. Ten spyte van die belangrikheid van boubaarheidsoorwegings in die verbetering van konstruksieprojekuitkomste, is daar beperkte vorige navorsing oor die implementering daarvan in ontwerp-aanbod-konstruksie-projekte.

Die literatuur fokus hoofsaaklik op ontwerp-bou-prosesse, wat nie van die unieke uitdagings van vroeë samewerking en kennisuitruiling in ontwerp-aanbod-konstruksie-projekte aanspreek nie. In hierdie studie word konstruksie kennis, verkry deur onderhoude, en toegepas in 'n mobiele toepassing. Dit toon aan hoe konstruksiekennis gedeel kan word met ontwerpingenieurs. Daarbenewens word 'n boubaarheid-gefokusde samewerkingsplan voorgestel wat projekbestuurders kan gebruik in ontwerp-aanbod-konstruksie-projekte om die identifisering van boubaarheidsprobleme te verbeter.

Uit die terugvoer van onderhoude is 201 advies items afgelei, wat in 12 groepe gekategoriseer is en lig werp op belangrike aspekte van suksesvolle projek uitvoering. Nuwe boubaarheidskonsepte is geïdentifiseer uit hierdie advies items en beklemtoon mentorskap, kommunikasie, deurlopende leer en praktiese ontwerpsbesluite wat voorheen onaangespreek gelaat is.

'n Nuwe benadering, geïnspireer deur die beginsels van Geïntegreerde Projeklewering, word voorgestel en bekragtig deur onderhoude. Die mobiliseringsfase behels aktiwiteite wat verder strek as blote terreinvoorbereiding, insluitend projekskedulering, kontrakkoördinering en betrokkenheid van belanghebbendes, wat samewerkende aktiwiteite is. Ten spyte van die mobiliseringsfase se potensiaal vir samewerking, toon die onderhoude 'n algemene gebrek aan effektiewe implementering.

Uitdagings wat deur die bevestigingsonderhoude geïdentifiseer is, hou verband met vooroordele, weerstand teen verandering en probleme met die insluiting van diverse perspektiewe. Ses oorwegings om samewerking te verhoog, sluitend in aansporings, implementering van tegnologie en die bevordering van 'n kultuur van samewerking. Die bevestigingsonderhoude ondersteun die lewensvatbaarheid van hierdie benadering.

Die voorgestelde boubaarheidsinstrument, ondersteun deur boubaarheids-gefokusde samewerking tydens mobilisering, hou belowende resultate in om projekuitkomste te verbeter en 'n kultuur te vestig van ‘n konstruksiegerigde ontwerpbenadering.

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Last, but certainly not least, my family – especially my ever-supportive parents and my adoring partner – deserve recognition beyond measure. Your steadfast belief in me has been my driving force. To my father; I am profoundly thankful for your mentorship. To my partner; the late-night conversations about everything under the sun offered my brain and heart essential rest. You are my anchor.

In closing, please accept my heartfelt thanks, not just as words on a page, but as a genuine reflection of the profound gratitude and affection that fills my heart.

Table of Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

BIM	Building Information Models
CII	Construction Industry Institute
CIRIA	Construction Industry Research and Information Association
CCs	Constructability Concepts
CPs	Constructability Principles
ECI	Early Contractor Involvement
GB	General Building
CE	Civil Engineering
CIDB	Construction Industry Development Board
MBA	Master of Business Administration
MD	Managing Director
BSc	Bachelor of Science
BTech	Bachelor of Technology
Beng	Bachelor of Engineering
Meng	Master of Engineering
NQF	National Qualification Framework
IPD	Integrated Project Delivery
ECSA	Engineering Council of South Africa
SHEQ	Safety, Health, Environment and Quality

Chapter 1: Introduction

1.1 Background and overview

The profession of the "Master Builder", revered for its comprehensive responsibilities encompassing architecture, design, construction management and structural integrity, held great esteem before the 19th century. Considered historical icons in fields such as architecture and civil engineering, Master Builders played a pivotal role in construction projects (Flavell, 2011). However, the emergence of two influential figures, the general contractor and Sir John Soane, known as the "father of modern architecture", marked a turning point that eroded the status of the Master Builder (Dinsmore, 2021). In the book, "The Architect", the author shares Sir John Soane's writing about an architect: *"With what propriety can his situation and that of the builder, or the contractor, be united?"* (Kostof, et al., 1977).

By the 1900s, the once esteemed profession of the Master Builder had largely vanished, and construction responsibilities were divided into distinct "designer" and "contractor" roles, effectively separating the construction process into two phases. As training schools and academic institutions evolved, designers became less versed in construction processes, while contractors received limited design training (Flavell, 2011). Researchers in the 20th century discovered that consultants, including engineers and architects, lacked the necessary knowledge and experience to effectively address constructability issues during construction (O'Connor, 2009). These constructability problems significantly impact project cost, time and quality.

In the present era, with the proliferation of diverse materials, specialized construction equipment, evolving codes and standards, site-specific requirements and complex engineering, no individual possesses the knowledge required to oversee all aspects of a complex construction project (Flavell, 2011). A project manager assumes the responsibility of managing the project as a whole, focusing on schedule and cost. Architects develop the initial design to meet client requirements, while design engineers ensure structural integrity. Contractors, on the other hand, determine construction methods, materials and processes, manage site employees, consider cost and quality and ensure a realistic implementation of the architect's vision. This fragmentation of roles creates numerous challenges, particularly in terms of collaboration and knowledge sharing among project participants (O'Connor, 2009). Vitruvius, a prominent historical architect, held a contrasting opinion to Sir John Soane, cautioning that architects who rely solely on theory without understanding the craftsmanship involved in building with their own hands follow a mere illusion rather than reality (Kostof, et al., 1977).

The construction industry has become so complex that a vast group of professionals is now required to fulfil the roles that were historically carried out by a single individual. Therefore, effective collaboration among various stakeholders is imperative to achieve reasonable project completion time and cost, ensure structural integrity and create aesthetically pleasing and high-quality structures.

This level of collaboration poses particular challenges in design-bid-build projects, also known as design-by-employer projects (CIDB, 2019). Many governments advocate for or mandate design-bid-build procurement methods due to their competitive bidding requirements, such as the Competition Act of 1998 in South Africa. This act helps prevent corruption, fraud and tender favouritism (Flavell, 2011). The design-bid-build procurement process effectively negates the concept of the Master Builder, while the design-build procurement process embraces certain aspects of the Master Builder approach (Flavell, 2011).

Dinsmore (2021) argues for a return to the Master Builder method, which has been tried and refined over 5000 years. However, Flavell (2011) concludes that the complexity of modern society impedes any individual from attaining the necessary knowledge and understanding required to assume the role of the Master Builder today. Moreover, traditional procurement methods such as design-bid-build are widely used and solutions to enhance construction ease and collaboration should be sought within this framework.

The present research aims to explore the potential implementation of constructability in design-bid-build projects by proposing a constructability tool to assist design engineers in considering constructability during the design phase when early contractor involvement cannot be obtained. Constructability, constructability concepts, constructability tools and techniques, early contractor involvement and building information model (BIM) maturity serve as the foundation for the current research, providing insight into the challenges and opportunities in achieving constructability in design-bid-build projects. The main concepts that provide the foundation for the current research are defined in Table 1-1 and are discussed in more detail in Chapter 2: Literature review.

Table 1-1: Important concepts to be defined

Concept	Definition
Constructability	Constructability involves evaluating a design's feasibility, efficiency and effectiveness for successful implementation in construction. It encompasses the assessment of construction methods, processes and sequences, considering factors like ease of construction, trade coordination and resource optimization (Anderson, et al., 2000) (CII, 1986)
Constructability concepts	Constructability concepts involve principles and strategies aimed at improving the ease of construction for a project. These concepts include evaluating design feasibility, optimizing construction processes and addressing potential challenges to improve efficiency (Fisher, et al., 2000) (Kifokeris & Xendis, 2017).
Constructability tools and techniques	Constructability tools and techniques include a range of methods and resources used to assess, enhance and manage constructability in construction projects. These tools include software applications, checklists and collaborative processes that support efficient construction planning and execution (Amade, 2016) (Fisher, et al., 2000).
Early Contractor Involvement (ECI)	Early contractor involvement is a project delivery approach that engages the contractor during the early stages of a construction project. It allows the contractor to contribute expertise and provide input on constructability, cost estimation and schedule, leading to improved project outcomes (Wondimu, et al., 2016) (Yuan, et al., 2022).
Building Information Model (BIM) maturity	Building information model maturity denotes the progressive development and utilization of BIM within a project, organization or country. It encompasses various levels of BIM implementation, ranging from basic 3D modelling to advanced integration of data, collaboration and automation. (Eastman, et al., 2011) (Li, et al., 2021).

To further explore the historical context, it is worth noting that design-bid-build practices may differ significantly between developed and developing countries. In developed countries, where advanced technologies and well-established processes are more prevalent, design-bid-build projects might benefit from integrating constructability concepts through advanced constructability tools and seamless collaboration between project stakeholders (Nascimento, et al., 2017). However, in third-world countries, where limited resources and infrastructure challenges persist and where BIM has a low maturity, design-bid-build projects may encounter additional obstacles in effectively implementing constructability concepts (Hanlon, et al., 2012). Addressing these disparities requires nuanced approaches that consider the specific socio-economic context of each country.

In South Africa, a study conducted by Othman (2011) revealed that 84% of design organizations are aware of the concept of constructability. However, research by Kuo & Wium (2014) indicated that the knowledge of constructability is predominantly possessed by contractors rather than consultants and it is often implicit rather than explicitly documented. This implicit knowledge presents challenges in effectively sharing it with designers. Difficulties in knowledge sharing arise when collaboration is not prioritized and when consultants have limited involvement in project close-out meetings (Kuo & Wium, 2014).

Within the realm of design-build projects, predominantly utilized in the private sector, implementing constructability concepts is feasible and early contractor involvement is easily achievable. Contractors often take the lead and employ design engineers and architects, thereby ensuring contractor involvement and evaluating designs to enhance constructability. The current 23 constructability concepts by Kifokeris & Xendis (2017), presented in Chapter 2, prove well-suited for turnkey projects or design-build endeavours. However, in the case of design-bid-build projects, where early contractor involvement is absent, implementing the 23 constructability concepts presents a significant challenge within the existing format and phases. These findings highlight the need to adapt constructability approaches and strategies to suit different project delivery methods.

As with most innovations, adopting and implementing new methods and procedures encounters resistance when traditional approaches have yielded satisfactory results and gained industry-wide acceptance. Enhancing constructability in design-bid-build projects through advanced software, clash detection software or complex tools demands a considerable degree of adoption propensity. Given the construction industry's inherent aversion to risk, these solutions may encounter delays in widespread adoption and implementation.

The awareness of constructability concepts among design organizations in South Africa underscores the growing recognition of their importance in construction projects. Hence, it becomes imperative to focus on feasible adjustments to existing procurement methods and propose constructability tools and techniques that are easily comprehensible and more likely to be embraced by a risk-averse industry. However, to drive progress in the industry, pragmatic solutions that align with existing practices and are readily embraced by stakeholders need to be explored. The implementation of constructability concepts and the introduction of constructability-centred collaboration in the design-bid-build process present opportunities to identify problems earlier and address the challenges posed by modern construction practices.

1.2 Problem statement

The design-bid-build procurement method, inherent in its nature, prevents early contractor involvement, thereby impeding the efficient implementation of constructability concepts and principles. Design engineers often lack the necessary knowledge and experience in construction to adequately consider constructability during the design phase (O'Connor, 2009). This omission of constructability consideration during design gives rise to several challenges during construction, impacting project costs and schedule (Fisher, et al., 2000).

Addressing the challenges posed by the design-bid-build method requires a comprehensive understanding of the interplay between constructability and the procurement process. By delving into these questions, it becomes possible to develop tailored approaches that promote collaboration, bridge knowledge gaps and mitigate constructability issues during the design phase. The items that require investigation, which are identified from literature discussed in Section 1.1, are shown in Figure 1-1.

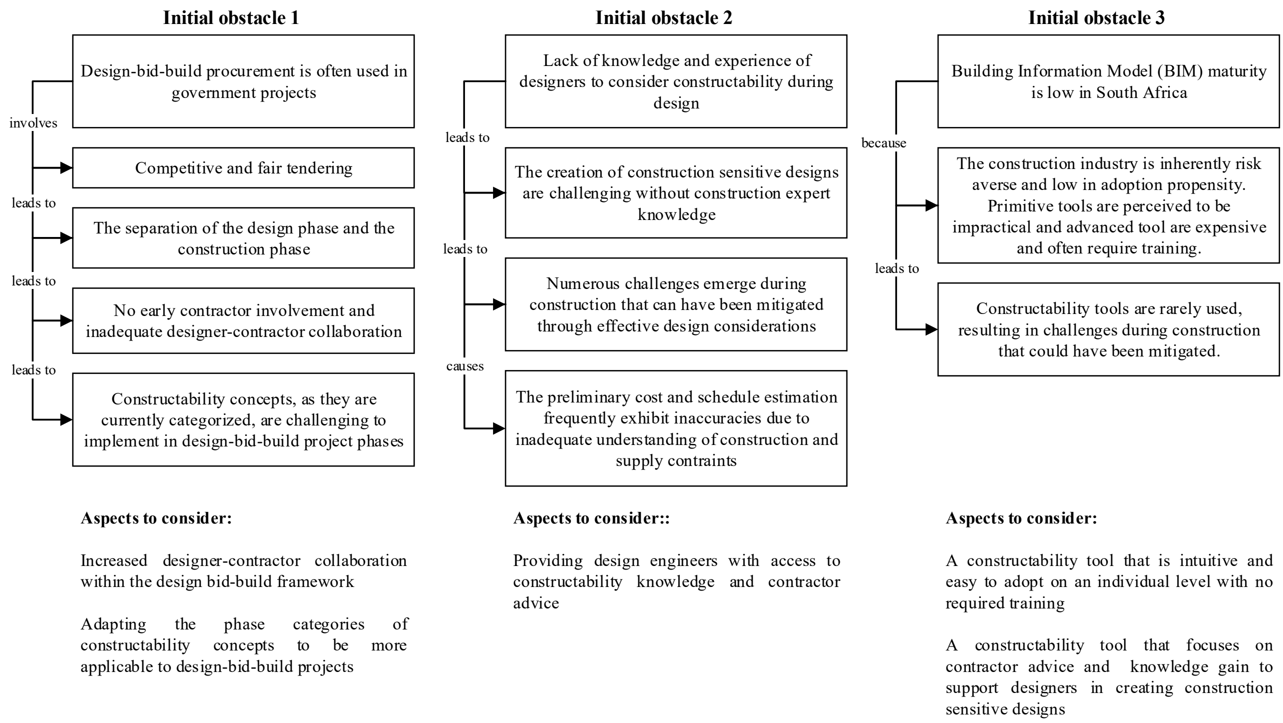


Figure 1-1: Identified obstacles, links between concepts and aspects to be considered

Regarding **initial obstacle 1**, completely avoiding or eliminating design-bid-build procurement is not a feasible suggestion. The competitive tendering process and the separation of design and construction phases are inherent aspects of this approach. Therefore, the challenge lies in addressing the lack of collaboration between designers and contractors within the existing design-bid-build framework. It is also important to explore how constructability concepts can be effectively implemented in design-bid-build projects by potentially redefining the concepts and allocating them to more suitable phases.

Concerning **initial obstacle 2**, expecting a design engineer to consider a broader scope of factors may pose challenges. However, it is feasible to provide designers with constructability knowledge and suggestions to enhance their ability to consider construction methods that improve cost, schedule and safety. By equipping designers with this knowledge, the ease of construction can be enhanced.

As for **initial obstacle 3**, this study does not address the low maturity of BIM or solve the adoption propensity of innovative technologies. Instead, the focus is on investigating the implementation of constructability concepts in the design phase and developing a constructability tool that is easily adoptable, easily implementable and presents contractor advice to a designer.

To address these challenges, a solution is proposed in alignment with the research aim presented in Section 1.3. The development and validation of a new constructability tool is proposed. This tool aims to raise awareness and increase understanding of constructability concepts and offer advice and suggestions from construction specialists to assist design engineers in being more mindful of construction constraints. The tool must be user-friendly and easily adopted within a consulting organization, by a project team or by individual designers themselves.

In the pursuit of the research aim, an aspect for future research is identified: the mobilization phase as the ideal phase in a design-bid-build project for designer-contractor collaboration that focuses on constructability. The challenges associated with implementing a designated phase for constructability-focused collaboration must also be addressed. The constructability concepts should be linked to the appropriate phases of a design-bid-build project to ensure that the designer is provided with relevant knowledge during each phase.

1.3 Aims and objectives

This research aims to develop an intuitive and accessible constructability tool that empowers designers to consider constructability during the design phase of design-bid-build projects, in the absence of direct contractor collaboration. This tool aims to increase the early detection of constructability problems and construction constraints by integrating constructability principles into the design process in the form of expert construction advice. Table 1-2 presents the research aim, along with the respective objectives.

Table 1-2: Research aims and the respective objectives

Aim	Develop an intuitive and accessible constructability tool to enhance designers' consideration of constructability during the design phase in design-bid-build projects without direct contractor collaboration.
Objective 1	Solicit input from contractors and construction specialists to identify constructability considerations and the need for designers
Objective 2	Thematically and contextually analyze the collected data to gain deeper insights into the dataset for the development of the constructability tool for designers, in the form of a mobile application, and for general advice on construction in design.
Objective 3	Validate the effectiveness of the proposed constructability tool through contractor and/or construction specialist feedback and identify areas for improvement.

By pursuing these objectives, this research aims to contribute to an approach to improve the constructability of design and to improve collaboration between designers and contractors, ultimately improving project outcomes in design-bid-build projects.

1.4 Methodological approach

Figure 1-2 outlines the sequential steps undertaken in this study, from data collection, data preparation and data analysis, to the validation of the outcomes related to the research aim. These steps serve as a structured framework to ensure a systematic research process.

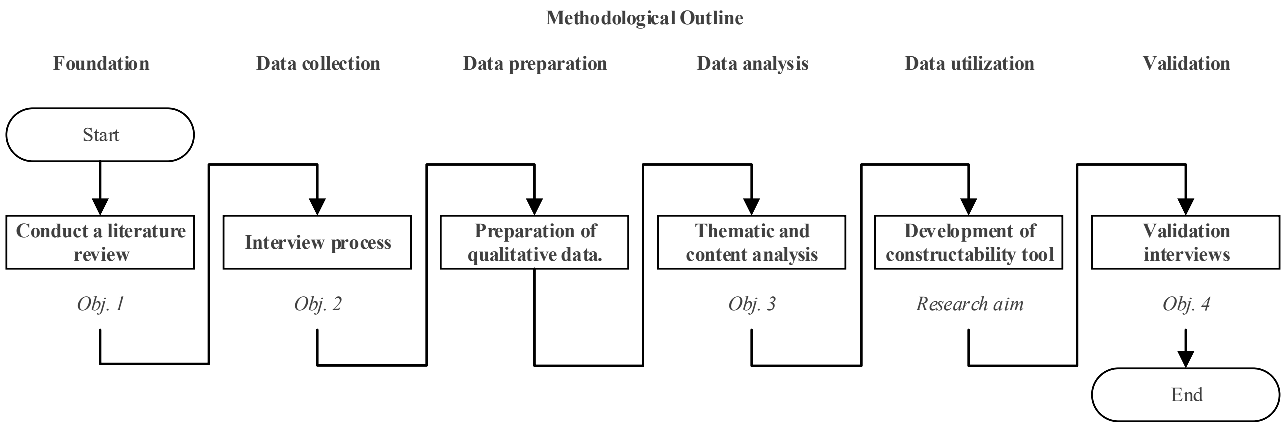


Figure 1-2: Methodological Outline

The **foundation** of knowledge was obtained through a literature review that aims to clarify definitions, address the research problem and highlight the interconnectedness of these concepts. A structured interview was chosen as the **data collection** method, suitable for the collection of subjective opinions with contextual information. This ensured that the collected data had depth and breadth and could be further clarified if needed. **Thematic and content analyses** were performed using Statistica Software to analyse the collected data. The **data utilization** phase focused on the research aim, which involved creating a constructability tool for designers. This process of analysing the data and creating the tool led to the identification of an aspect for future research, namely, the constructability-centred collaboration between the designer and the contractor during the mobilization phase. The mobilization phase occurs after the tender award and before construction commencement. It is the first phase that the contractor is fully involved in. To **validate** the outcomes of the research aim, a second round of interviews was conducted with five previous participants. This validation process aimed to assess the acceptability and approval of both the constructability tool and the idea of constructability-centred collaboration during mobilization. The methodology is discussed in detail in Chapter 3.

1.5 Scope and limitations

This section clarifies the research focus for the study and acknowledges the limitations that impact the generalisability and validity of the findings and research outcomes.

The primary focus of this study is the development of a proof of concept of a constructability tool for designers. This tool will offer "contractor advice" to designers during the design phase, aiming to improve the constructability and streamline construction processes. The tool was also validated by interview participants based on the value of such a tool in improving the constructability of designs during the design phase. The constructability tool, as a proof of concept, is not a fully developed tool and, therefore, cannot be validated based on functionality by the interviewees.

It is important to note that this approach may not be equally applicable to other procurement types, such as turnkey or design-build projects. Nonetheless, designers, in general, can benefit from the contractor advice provided by the tool, enabling them to enhance their understanding of constructability and their role in improving construction efficiency.

The main subjects investigated in this study include constructability, early contractor involvement and design-bid-build procurement. BIM as a constructability tool is explored, along with the role of designers in enhancing constructability. While other procurement methods are not extensively examined, the focus remains on investigating the aforementioned concepts and their implications within the design-bid-build context. The interviews focused on investigating the following seven constructability aspects (found in Table 3-3):

1. The availability of resources
2. Primary construction methods
3. Site accessibility and spatial requirements
4. Creating simple and rational designs
5. The standardization of elements or units
6. Preassembly, prefabrication and/or modularization
7. Site safety

Participants in the interviews were specifically requested to provide their responses concerning low to medium-rise structures within the context of design-bid-build projects. This was deemed necessary to focus the responses on similar scales and types of projects. The focus, in turn, led to eventually exhausting the potential range of responses, with very little additional or new information offered by the later interviews. Table 1-3 illustrates the limitations during the study along with a concise description of each limitation.

Table 1-3: Limitations of the research

Limitation	Brief discussion
Literature review investigation	Limited research exists on the implementation of constructability in design-bid-build projects. Existing literature focuses on design-build or turnkey processes, making it challenging to find relevant information. The arrangement of the 23 constructability concepts does not align optimally with the design-bid-build process and no literature was identified that addresses this particular issue. While this obstacle remains unresolved in the present study, it presents an opportunity to contribute to the field.
Interview questions	The interview questions focus on seven specific constructability concepts, excluding other aspects that could have influenced participants' advice. The deliberate selection of these concepts ensures that the contractor's feedback can be compared and analysed thematically and contextually. However, this conscious delineation may limit the exploration of broader constructability perspectives and potential themes.
Sample size	The study involved 20 participants, which was sufficient to extract 201 "contractor advice" items or phrases from the data. The study reached information saturation during the interviews, with little new information emerging towards the end. This indicates that the key issues were largely exhausted and that a larger sample size would probably not have yielded significant additional insights. Nonetheless, the small sample size limits generalisability and population representation.
Analysis methods	Thematic and content analysis, while suitable for qualitative data, have drawbacks. Interpretations can be subjective and influenced by researchers' perspectives. Coding and categorization may be influenced by subjective judgment. Condensing large volumes of data into themes or categories can oversimplify the information.
Constructability tool software	The chosen software, Thunkable, adequately supports the goal of creating a proof-of-concept implementation of key features of the proposed application. However, it has limitations in importing large data sets. To address this, the data was divided into separate data sets for each project phase. For full implementation of the constructability tool application, software capable of handling large databases is recommended.

1.6 Overview of research paper content

Table 1-4 provides an outline of the main objectives, approaches and contributions of each chapter.

Table 1-4: Research paper content for each chapter

Chapter	Outline
Chapter 2: Literature review	Chapter 2 corresponds to research objective 1, which involves a literature review focusing on the key concepts of constructability, early contractor involvement and design-bid-build procurement. The purpose of this chapter is to provide the theoretical underpinnings of the study to establish the interrelationships among these concepts. It aims to provide a cohesive understanding of the subject matter, thereby strengthening the overall research framework.
Chapter 3: Methodology	Chapter 3 serves as a comprehensive exposition of the research methodology. It clarifies the rationale behind the methodological decisions and outlines the tools and techniques employed throughout the research process. The objective of this chapter is to offer a lucid account of the data collection and analysis procedures, ensuring transparency and rigour in the research methodology.
Chapter 4: Results and discussion	Chapter 4 aligns with research objective 3, which involves the thematic and contextual analysis of the collected data to identify themes and patterns relevant to the research objectives. The primary objective of this chapter is to examine the data through thematic and contextual lenses, with particular emphasis on two key aspects: (1) identifying the four constructability aspects that participants ranked as most problematic and (2) identifying the 24 most frequently mentioned "contractor advice" items.
Chapter 5: Constructability-centred collaboration during the mobilization phase	Chapter 5 presents a significant aspect identified for future research that emerged during the pursuit of the research aim – the re-evaluation of the mobilization phase to prioritise designer-contractor collaboration with a focus on early identification of constructability challenges. The primary focus of this chapter is to explore the possibility of collaboration during the mobilization phase, to clarify the rationale behind its suitability for collaboration and to discuss the potential implications.
Chapter 6: Constructability tool proposal	Chapter 6 aligns with the research aim of developing an intuitive constructability tool that assists designers in enhancing constructability considerations during the design phase of design-bid-build projects, independent of contractor collaboration. This chapter presents the conceptual development of the constructability tool, along with the implementation of four features in the "Thunkable" visual coding software, demonstrating a proof-of-concept of the application.
Chapter 7: Conclusions and recommendations	Chapter 7 concludes by summarizing the most important findings of the research, interpreting the research results in light of the objectives, proposing recommendations and determining important avenues for future research.

Chapter 2: Literature review

2.1 Introduction

This literature review serves as a preliminary investigation to examine the interconnections among constructability, early contractor involvement and design-bid-build procurement. Its primary objective is to determine the potential challenges associated with the integration of constructability and early contractor involvement within the design-bid-build paradigm. Additionally, to identify the opportunities for a new constructability tool to facilitate constructability considerations. Consequently, the review not only provides valuable insights into the subject matter but also facilitates an understanding of the multifaceted relationships at play.

As illustrated in Figure 2-1, the subsequent sections of this review are systematically organized to ensure a logical and coherent flow of information. Each topic is examined, unveiling its inherent significance and implications in the context of constructability, early contractor involvement and design-bid-build procurement.

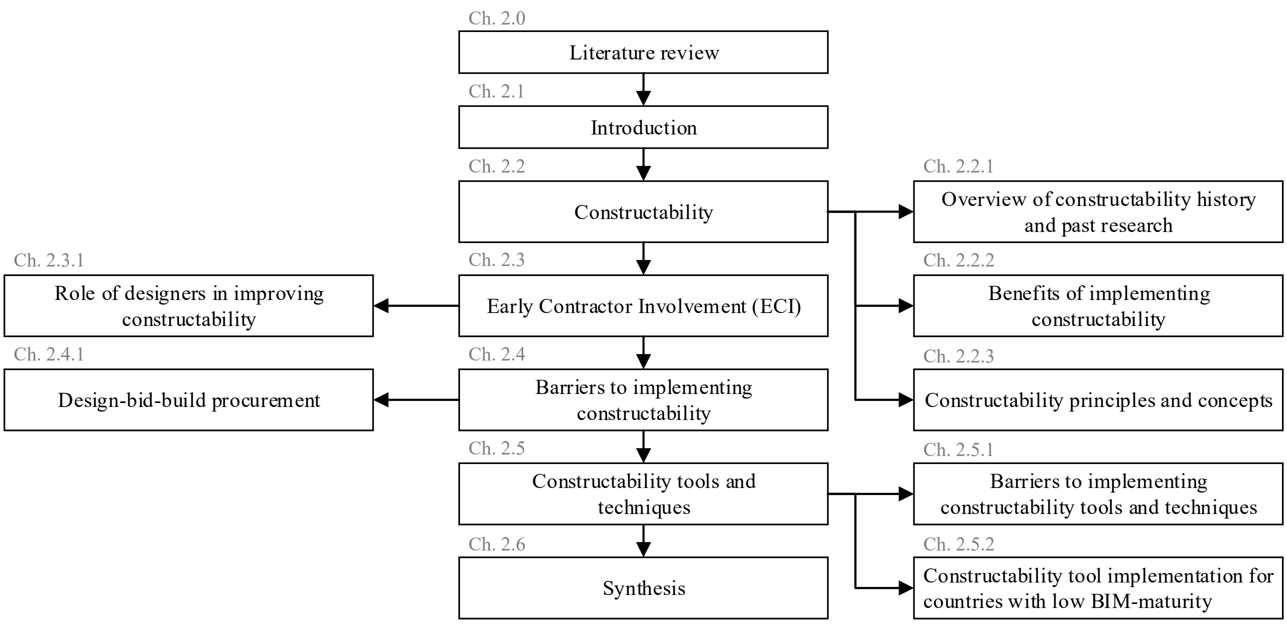


Figure 2-1: Literature review arrangement

Early contractor involvement constitutes an important component of constructability, contributing to enhanced project outcomes and efficiency (Abdul-Rahman, et al., 2020). However, the conventional design-bid-build procurement method, characterized by sequential project phases, poses barriers to both constructability and early contractor involvement (Marzouk, et al., 2019) Thus, it becomes imperative to address these interconnected topics collectively, recognizing their interdependencies and the challenges associated with their independent treatment.

Furthermore, an additional challenge emerges when considering the adoption of advanced software or technology within countries characterized by low BIM maturity levels. The review will address this issue, shedding light on the challenges and potential strategies for leveraging technology effectively in such contexts.

2.2 Introduction to constructability

This study is grounded in three interconnected concepts: constructability, early contractor involvement and design-bid-build procurement. Early contractor involvement serves as a fundamental prerequisite for implementing constructability, while design-bid-build procurement poses significant obstacles to both early contractor involvement and constructability.

Constructability, as defined by the Construction Industry Institute (CII), entails the optimal utilization of construction knowledge and experience in planning, design, procurement and field operations to attain overall project objectives (CII, 1986). Furthermore, constructability can also be referred to as "buildability," a term defined by the Construction Industry Research and Information Association (CIRIA) as the extent to which the building design facilitates ease of construction, considering the overall requirements for the completed structure (CIRIA, 1983). Both terms emphasize the integration of construction knowledge into the design phase to enhance construction feasibility. Employing constructability as a project management technique throughout the project lifecycle yields benefits such as cost reduction, schedule optimization and improved quality (Wimalaratne, et al., 2021) (Sheng Ding, et al., 2020).

Researchers such as Jergeas and Van der Put (2001) have used the terms "constructability" and "buildability" interchangeably, arguing that both concepts involve integrating construction knowledge into all project phases to identify construction-related issues early on and minimize rework costs. Implementing constructability can lead to cost reductions of up to 35%, improved accuracy in delivery time estimation, and substantial enhancements in project quality (Samimpey & Saghatforoush, 2020) (Jergeas & Van der Put, 2001).

In addition, early contractor involvement plays a pivotal role in the successful implementation of constructability. By incorporating the expertise of construction specialists during the design phase, constructability challenges that may arise during construction can be proactively addressed and mitigated (Wong, et al., 2006). While design-bid-build projects may benefit from designers with extensive construction experience, the maximum benefits concerning constructability are realized when the individual responsible for the project's construction is the one to provide input during design (Jergeas & Van der Put, 2001). However, in design-bid-build projects, personnel with construction expertise are typically appointed only after the bidding phase when the design is already 60% to 90% complete, thereby impeding the implementation of both constructability and early contractor involvement (Othman, 2011).

Design-bid-build procurement, commonly employed in government-funded projects within developing countries (Dada, 2012), remains the prevailing approach. While some researchers, such as Dada (2012), defend this traditional method, others like Allen and Smallwood (2014) criticize it and advocate for design-build as an alternative. However, given the importance of combating corruption, the traditional procurement method ensures a fair tendering process, particularly in countries prioritizing this objective. Consequently, transitioning from design-bid-build to alternative procurement methods for government-funded projects could be a time-consuming endeavour, implying the continued use of design-bid-build procurement in South Africa for the foreseeable future.

Given the prevalent use of design-bid-build procurement in South Africa and the challenges associated with transitioning to alternative methods, it is important to explore the feasibility of implementing constructability and early contractor involvement within the framework of a design-bid-build project.

One potential strategy to overcome the barriers imposed by design-bid-build procurement is to foster increased collaboration and communication among designers, contractors and construction experts. By promoting an integrated approach wherein construction knowledge is integrated as early as possible, the likelihood of constructability issues arising during construction can be minimized. This collaborative endeavour aligns with the principles of early contractor involvement, facilitating smoother project execution and enhanced constructability outcomes.

Research by Yuan et al. (2022) supports the notion that early contractor involvement and constructability can be implemented within the constraints of design-bid-build procurement. The study emphasizes the significance of cultivating a collaborative environment where contractors, designers and construction professionals closely cooperate to identify potential constructability challenges and explore innovative construction techniques.

Moreover, technological advancements such as BIM can play a pivotal role in enhancing constructability within the design-bid-build framework. BIM facilitates the virtual modelling of construction projects, enabling better coordination and communication among project stakeholders.

Li et al. (2021) highlight the promising results of BIM implementation in improving constructability outcomes, reducing errors and conflicts and enhancing construction efficiency.

While adjustments, and a departure from traditional practices, may be necessary, the implementation of constructability and early contractor involvement within design-bid-build procurement holds the potential to significantly reduce costs and improve overall construction quality.

2.2.1 Overview of constructability history and past research

Since the inception of constructability, various definitions of constructability and buildability have emerged. Researchers such as Wimalaratne et al. (2021) and Sheng Ding et al. (2020) have conducted studies to compare and analyse these definitions, shedding light on both the similarities and differences. Buildability definitions focus on streamlining construction processes and integrating expert construction knowledge into the design phase.

Kifokeris and Xendis (2017) propose that buildability should be regarded as a component of constructability, specifically implemented during the early stages of a project. According to their research, the concept of constructability has been distorted due to attempts to categorize it as just one of many managerial techniques employed in construction projects. Instead, constructability should be perceived as a comprehensive approach encompassing managerial techniques, decision-making methodologies and performance evaluation. Table 2-1 presents a compilation of various definitions of constructability and buildability that have emerged in past research.

Table 2-1: Definitions of constructability and buildability

	Definition	**Source**
1	"Construction-oriented input into the planning, design and field operations"	(Pepper, 1994)
2	"Integrating construction knowledge, resources, technology and experience into the engineering and design of a project"	(Anderson, et al., 2000)
3	"Process of doing everything possible to make construction easy, to improve quality, safety and productivity, to shorten construction schedules and to reduce rejection and rework"	(Kerridge, 1993)
4	"Optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall project objectives"	(CII, 1986)
5	"A measure of the ease with which a facility can be constructed"	(Hugo, et al., 1990)
6	"Optimum use of construction knowledge and experience by the owner, engineer, contractor and construction manager in the conceptual planning, detailed engineering, procurement and field operations phases"	(Nima, 2001)
7	"The feasibility of a considered project to be performed by a specific technology based on the construction knowledge learned from past projects"	(Skibniewski, 1999)
8	"The ease with which the raw materials of the construction process can be brought together by a builder to complete the project in a timely and economic manner"	(Glavinish, 1995)

In the realm of constructability and buildability, there exists a degree of ambiguity regarding the specific definitions and their interchangeability. Figure 2-2, derived from Wimalaratne's (2021) analysis, offers a visual representation of the similarities and differences among these definitions. The corresponding numbers in the figure relate to the first column in Table 2-1.

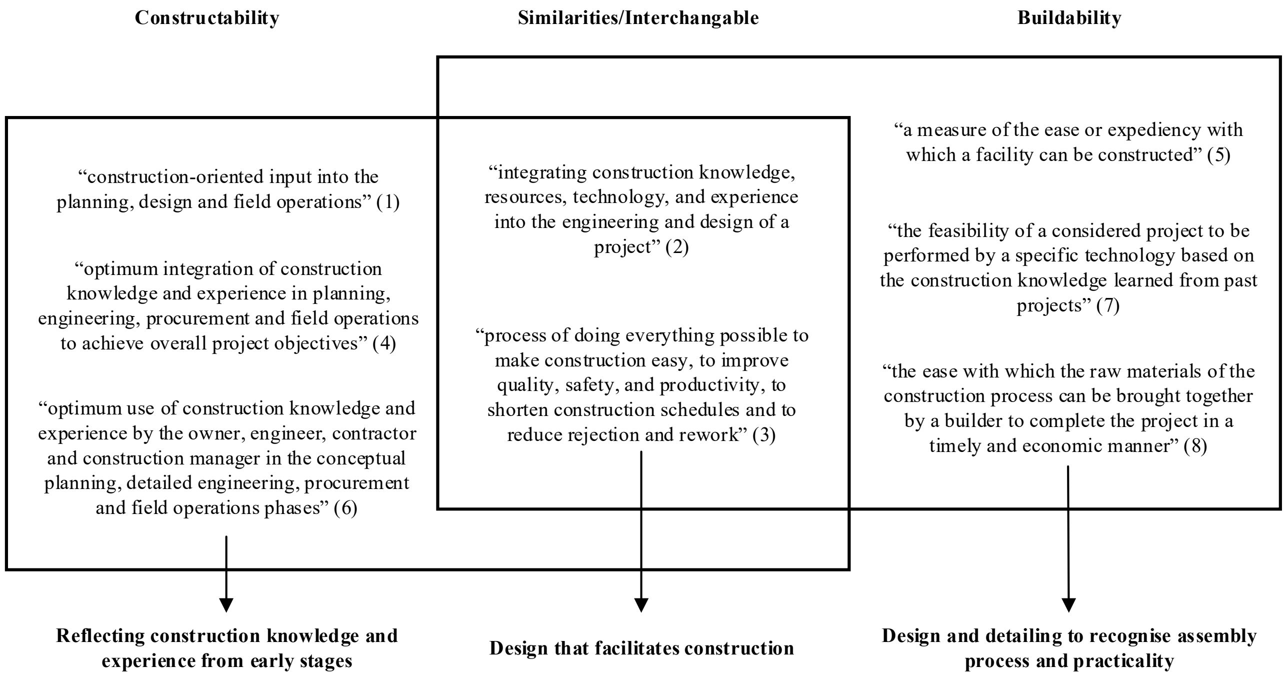


Figure 2-2: Similarities and differences between constructability and buildability

To address the research objectives at hand, a specific definition stands out as most relevant. According to Kerridge (1993), constructability can be defined as the "process of doing everything possible to make construction easy, to improve quality, safety and productivity, to shorten construction schedules and to reduce rejection and rework". This definition will serve as the cornerstone of the thesis, with constructability and buildability being used interchangeably based on this understanding.

2.2.2 Benefits of implementing constructability

The implementation of constructability yields numerous advantages for construction projects. It serves as a proactive strategy to identify potential obstacles that may prevent effective construction progress, cause delays or result in cost overruns (Othman, 2011). By adopting the 23 constructability concepts outlined in Table 2-2, Table 2-3 and Table 2-4, construction processes can be streamlined, saving valuable time and reducing costs (Othman, 2011). These concepts are implemented while considering standard code requirements and client specifications, ultimately contributing to improved project success (Othman, 2011).

An essential aspect of constructability implementation involves integrating the expertise of construction specialists during the design phase. However, design team members without specialized construction experience often face challenges in envisioning the complete project as well as the potential construction constraints (Othman, 2011). While designers with construction experience can provide valuable insights, the involvement of actual contractors responsible for the construction work is preferable. Contractors bring diverse specialities and extensive experience with various construction methods and techniques, making them the most suitable candidates to contribute during the design phase (Jergeas & Van der Put, 2001).

The increasing specialization within the Architecture, Engineering and Construction (AEC) industry, combined with the complexity of modern construction projects, presents significant challenges. Factors such as the proliferation of building materials, rapid technological advancements, stringent regulations and codes differing for design and construction, as well as disparities in academic and practical training, have further complicated the construction landscape (Dinsmore, 2021). Architects, engineers, and contractors tend to prioritize specific aspects of the project, which, although beneficial for specialized expertise, often leads to fragmented collaboration and a limited understanding of the holistic project requirements (Uhlik & Lores, 1998).

To address these challenges and achieve optimal project outcomes, it is important to recognize the interdependence between design and construction. Incorporating specialist construction knowledge early in the design phase enables the development of the most effective and cost-efficient design solutions (Uhlik & Lores, 1998). By fostering a collaborative environment where owners, project managers, architects, engineers, contractors, subcontractors and suppliers exchange their expertise, a more holistic and integrated approach to construction projects can be achieved. While specialization remains essential for complex projects, bridging the gap between design and construction through collaboration is important to achieve improved project outcomes (Sheng Ding, et al., 2020).

2.2.3 Constructability principles and concepts

The application of constructability principles and concepts holds significant benefits throughout the various phases of a project. Adams (1989) identifies 10 constructability principles (CPs) that serve as fundamental guidelines and provide a basis for effective implementation. Furthermore, Nima (2001) and Kifokeris & Xendis (2017) extend these principles by presenting 23 constructability concepts (CCs) that can be customized to address specific project requirements and challenges.

Understanding and applying the constructability principles and concepts outlined by Adams (1989), Nima (2001) and Kifokeris & Xendis (2017) enables project stakeholders to systematically address potential construction-related issues. These principles include various aspects such as ease of construction, productivity improvement, quality enhancement, schedule accuracy and cost reduction. The 10 constructability principles (CPs) identified by Adams (1989) are as follows:

CP1	Project integration
CP2	Implementation of construction expert knowledge
CP3	Appropriation of project team skills
CP4	Understanding of overall and specific project objectives
CP5	Consideration of available resources
CP6	External factors and site accessibility
CP7	Realistic and construction-sensitive project program and construction methodology
CP8	Transparent specifications
CP9	Innovation
CP10	Acquirement of post-project information and knowledge feedback for the creation of best practices and lessons-learned databases

* CP – Constructability Principles

The 10 constructability principles provide a foundational framework for incorporating constructability considerations into project planning and execution. The constructability concepts, on the other hand, address more specific challenges and include a broader range of areas such as site layout, design specification, technology, innovation and construction safety. By adhering to these specific guidelines, project teams can proactively identify and mitigate risks, avoid rework and promote efficient construction practices (Adams, 1989) (Nima, 2001).

Nima (2001) and Kifokeris & Xendis (2017) categorized the 23 constructability concepts into three project phases: initiation, execution and delivery. Table 2-2, Table 2-3 and Table 2-4 illustrate the concepts associated with each phase and the corresponding constructability concepts.

Table 2-2: Constructability concepts to be applied during the initiation phase (Nima, 2001) (Kifokeris & Xendis, 2017)

Initiation phase	
▪ ▪ ▪	**Feasibility study** **Design and construction contractual procurement** **Conceptual Planning**
C1	The constructability program is an integral part of the project execution plan and constitutes the output of the conclusive contribution of the project developers at all stages.
C2	The project team should include all key stakeholders to ensure uninterrupted implementation of constructability requirements throughout the project's lifecycle.
C3	The effective integration between design and construction should be achieved through the exploitation of up-to-date construction knowledge and experience brought by practitioners into the early conceptual planning and design drafts.
C4	The contractual framework that governs the project should align with the applied construction methods.
C5	The scheduling goals should be construction-driven and assigned as early as possible.
C6	The early scrutinization and selection of the primary construction methods should frame the design to achieve smooth field operations.
C7	The proper study of the site's layout should ensure uninterrupted and efficient workflows and resource performance throughout the project's lifecycle.

The initiation phase includes the constructability concepts related to the integration of key stakeholders, the utilization of construction knowledge and experience in early planning and design stages and the significance of prioritising construction as the basis for early decisions. These considerations demonstrate the proactive approach necessary to enhance constructability in the initiation phase of a construction project. However, in design-bid-build projects, the "effective integration between design and construction" (Kifokeris & Xendis, 2017) cannot be achieved early in the project lifecycle.

Table 2-3: Constructability Concepts to be Implemented during the Execution Phase (Nima, 2001) (Kifokeris & Xendis, 2017)

Execution phase	
▪	**Subcontractual procurement**
▪	**Continuation of designs**
▪	**Start of field operations**
C8	The planning and construction operations sequence should precede the rest of the plans because it dictates the design and procurement of equipment and materials.
C9	The cooperation of all specialists should be facilitated through advanced information technologies, thus overcoming the fragmentation of specialized roles during the project lifecycle.
C10	The widest possible simplifications and rationalizations should be implemented in the designs and the reviews contracted by qualified construction personnel so that the designs can be configured to enable efficient construction.
C11	Standardization of project elements should be selected whenever possible, but not to the extent of qualitatively worsening the project outcome.
C12	The technical specifications should be simplified and configured for efficient construction, but not to the extent of qualitatively worsening the project performance.
C13	The modularization and preassembly of structural elements should be considered, studied carefully, and used when they can facilitate their fabrication, transportation, and installation.
C14	Exploitable resources must be properly positioned at the site at the design stage.
C15	Construction should be scheduled for processing under suitable weather conditions. When not possible, alternatives such as more extensive prefabrication should be available.

The execution phase includes the constructability concepts related to the significance of allowing planning and construction operations to guide the design and procurement of equipment and materials. The cooperation among specialists is facilitated through advanced information technologies to overcome the fragmentation of roles. Rationalisation in designs, reviewed by qualified construction personnel, enables efficient construction without compromising quality. Standardization of project elements is favoured when feasible, while technical specifications are simplified for efficient construction. Strategic positioning of resources, consideration of suitable conditions and the availability of alternative methods further contribute to construction success in the execution phase (Kifokeris & Xendis, 2017). However, for design-bid-build projects, many of these decisions are made before the contract award, which precludes such projects from the benefits of integrated construction knowledge on decisions that greatly impact construction.

Table 2-4: Constructability Concepts to be Implemented during the Delivery Phase (Nima, 2001) (Kifokeris & Xendis, 2017)

Delivery phase	
▪ ▪ ▪	**Finalization of designs** **Finalization of field operations** **Project delivery**
C16	Construction activities should be effectively planned for the prevention of conflicts of resource usage and productivity reduction.
C17	Issues not covered by the design concerning the implementation of the construction process should be treated with an innovative and out-of-the-box approach.
C18	Innovation to decrease labour intensity and increase mobility, safety, and site accessibility of the personnel should be pursued.
C19	Innovation in the introduction, use, selection, and modification of the available equipment should be considered.
C20	Optional preassembly should be encouraged to increase site productivity, safety, and mobility.
C21	Innovation in the use, reuse, and post-construction function of temporary facilities should be considered.
C22	The contractors' appraisal procedure should be established to constitute a further and crucial criterion of selection for future collaboration.
C23	The constructability program's appraisal should be established and documented per case to enhance knowledge-based construction management.

The delivery phase includes constructability concepts 16 to 23, which focus on innovations and considerations aimed at enhancing different facets of the construction process. These concepts highlight the importance of effective planning to prevent conflicts and reduce productivity constraints. They emphasize the need for an innovative approach to address construction challenges. Consultants need to understand and support these concepts, traditionally addressed by contractors, in design-bid-build projects during the construction phase.

Constructability concept 18 addresses labour intensity. While this approach aligns with regions where labour costs significantly outweigh the cost of machinery, it is important to acknowledge the context-specific variations. In South Africa, for example, maximizing labour employment aligns with economic and social priorities. Job creation is slow in South Africa, leading to a higher demand for job opportunities than the supply. South Africa's strategy is to "increase the labour absorptive capacity of the economy" (Department of Finance Republic of South Africa, 2022). The application of concept 18, therefore, requires a nuanced understanding of broader socio-economic objectives. This example highlights the need for tailored strategies of constructability concepts in different contexts.

In the execution and delivery phases, the progression and finalization of the design process generate contemplation regarding the compatibility of these phases with the design-bid-build procurement method. In a design-bid-build project, the procurement phase typically commences when the design reaches completion of 60% - 90%, leaving the continuation and finalization of designs to be carried out during the mobilization phase and the construction phase (Othman, 2011). The emphasis on early contractor involvement in the initiation phase also suggests that design-bid-build procurement is not suitable for implementing these 23 constructability concepts in their current arrangement.

2.3 Early Contractor Involvement (ECI)

Early contractor involvement assumes an important role in achieving project success by integrating expert construction knowledge into the design phase. Engaging with the personnel who will be responsible for the construction enables the acquisition of valuable insights and contributions, thereby mitigating potential construction problems and facilitating more accurate cost and time estimations (Wondimu, et al., 2016). Construction personnel possess valuable experience in material acquisition time-frames, practical building methods, common construction problems and implicit constructability knowledge. However, in design-bid-build projects, it is difficult to obtain early contractor involvement due to procurement rules and consultants alone often overlook practical considerations due to their limited construction experience.

The implementation of ECI in the design phase yields several benefits:

(Wondimu, et al., 2016)

- Enhances the accuracy and quality of design drawings
- Improves the practicality, efficiency and constructability of final designs
- Constructability problems can be identified at an early stage, minimizing rework and costly delays during construction
- Facilitates a more precise assessment of the available supply of materials
- Real-time information on pricing fluctuations and alternative material options enables better decision-making
- Improved mitigation for material shortages or substitutions that impact project timelines, cost and quality
- Promotes the flow of information and collaboration among project stakeholders
- Active engagement between designers and contractors, facilitating the exchange of knowledge and insights
- Improved coordination and streamlined project execution

The implementation of ECI in a design-bid-build procurement process will present challenges in government projects that require adherence to competitive, fair and transparent tendering processes (Lahdenpera, 2013). Striking a balance between the principle of transparency and fairness and the benefits of early contractor involvement necessitates careful consideration and the establishment of appropriate contractual arrangements to ensure compliance while maximizing collaboration.

2.3.1 Role of the designer in improving constructability

While early contractor involvement is valuable, it is the design team's responsibility to take the lead in improving constructability throughout the project lifecycle, particularly during design. It is important to acknowledge that the design phase significantly influences the construction process and the challenges that follow (Lam, et al., 2005).

Traditionally, designers have focussed on the aesthetics, structural integrity, spatial layouts and functionalities of a building, often overlooking the intricate details of how practical it is to build the final product. (Lam, et al., 2005). While design aesthetics are important, this emphasis can neglect critical considerations related to constructability. Consequently, contractors are left to deal with constructability issues, resulting in delays, out-of-sequence work and subsequent impacts on project schedules and budgets. When these aspects are not properly addressed, it is mostly the contractor who bears the burden of rectifying problems while still expected to adhere to the project schedule (Lam, et al., 2005).

To address these challenges, designers must actively seek to integrate construction knowledge into their design decisions. This requires a collaborative approach, wherein designers work closely with construction specialists and other relevant stakeholders to identify and solve constructability issues at an early stage (Wondimu, et al., 2016). In the context of design-bid-build projects, establishing direct communication channels between designers and construction experts can be challenging. Consequently, exploring strategies to support design engineers in integrating practical construction knowledge into their design repertoire must be advantageous. By adopting a constructability mindset and being conscious of construction constraints, designers can optimize their designs to enhance efficiency during construction, minimize conflicts in construction activities and minimize rework.

Furthermore, designers should leverage technological advancements such as BIM tools to improve constructability. BIM enables designers to visualize and simulate construction processes, identify clashes, and evaluate constructability constraints and problems before the construction phase commences (Eastman, et al., 2011).

2.4 Barriers to implementing constructability

Barriers to the integration of design and construction processes are many. The work by Jadidoleslami et al. (2018) has identified various barriers, which are classified into three categories: managerial, engineering and environmental. This section examines these barriers in detail and supplements them with additional insights from relevant scholarly sources.

Among the **managerial barriers**, ineffective communication and inadequate information exchange between designers and builders emerge as significant barriers (Jadidoleslami, et al., 2018). Furthermore, deficiencies in coordination and cooperation within the team, coupled with a lack of alignment among key stakeholders, further impede the implementation of constructability. Overcoming these barriers requires a transition toward integrated project delivery approaches that promote teamwork and shared objectives (Jadidoleslami, et al., 2018). Table 2-5 presents a list of managerial barriers identified by Jadidoleslami et al. (2018).

Table 2-5: Managerial barriers (Jadidoleslami, et al., 2018)

Managerial barriers	
▪ Inadequate information exchange between the designer and builder (poor communication)	▪ Existence of traditional contracts
▪ Insufficient coordination and cooperation	▪ The absence of an independent and experienced team to implement constructability
▪ Insufficient flexibility in contracts to make logical adjustments	▪ Poor integrity among key members of the project team
▪ Inability to identify problems and opportunities	▪ Insufficient knowledge of employers about the benefits and advantages of applying constructability
▪ Separate managerial process in design and construction	▪ Existence of contractual problems in determining the constructability domain

Engineering barriers pose notable challenges in the implementation of constructability, in terms of both executive and technical/technological aspects. Jadidoleslami et al. (2018) identify two prominent barriers within this category: a lack of executive experience within design teams and limited knowledge of construction technologies. These barriers emphasize the need for designers to possess an understanding of construction processes and techniques to ensure the efficiency of their designs. It is imperative to evaluate the feasibility and applicability of designs by integrating design science with construction experience. Table 2-6 presents a list of engineering barriers to the implementation of constructability.

Table 2-6: Engineering barriers (Jadidoleslami, et al., 2018)

Engineering barriers	
▪ Lack of flexibility in design services	▪ Lack of executive experience in the design team
▪ Lack of flexibility in standards and regulations of design and implement	▪ Lack of integration design science and executive experience
▪ Lack of knowledge about construction technologies	▪ Designer imagination of increasing responsibilities in implementing constructability principles
▪ Lack of evaluation of the applicability of designs	

The implementation of constructability also faces barriers stemming from **environmental barriers**, including cultural and legal aspects. Key barriers, identified by Jadidoleslami et al. (2018), include blind support of the status quo and the absence of commitment to implementing constructability. These factors prevent progress by perpetuating resistance to change and inhibiting the adoption of constructability practices. Misconceptions surrounding constructability, such as concerns about delays and risk aversion, as well as a lack of mutual respect between designers and contractors, further contribute to these barriers. Overcoming these obstacles requires a cultural shift that recognizes the benefits of constructability practices. Table 2-7 presents a list of environmental barriers.

Table 2-7: Environmental barriers (Jadidoleslami, et al., 2018)

Environmental barriers	
▪ Acceptance of the status quo	▪ Risk aversion and distrust of builders
▪ Absence of an official commitment to implementing constructability	▪ Competitive restrictions of selection and rules in the procurement process
▪ The misconception that constructability leads to delays in projects	▪ Not enough mutual respect between the designer and the builder

The barriers to implementing constructability are well-supported by additional sources, further corroborating the findings of Jadidoleslami et al. (2018). Eldin (1999) highlights the lack of practical construction knowledge within design teams and emphasizes the conflicts that can arise between contractors and designers during the construction phase. Moreover, Eldin (1999) also identifies risk aversion and regulatory requirements as significant barriers to constructability implementation. These findings underscore the importance of skilled management and support to effectively integrate constructability into projects.

While there have been improvements in bridging the cultural divide between design engineers and contractors, particularly in some regions of the world, significant gaps persist, especially in developing countries where the design-bid-build procurement process remains prevalent for government-funded and donor-funded projects. Design-bid-build procurement itself contributes to the barriers presented in Table 2-7. Addressing these barriers requires improved communication, coordination and cooperation among project team members, as well as a shift towards integrated project delivery approaches.

Design-bid-build procurement is widely employed in South Africa to uphold fair and competitive tendering processes (Lahdenpera, 2013). While the private sector is increasingly adopting design-build projects, design-bid-build remains prevalent and will continue to be extensively used in the foreseeable future. Therefore, it is necessary to explore the implementation of constructability concepts within design-bid-build projects, particularly for developing countries aiming to enhance project efficiency and cost-effectiveness.

Design-bid-build is a well-established procurement process that is familiar to industry professionals. This study, therefore, does not delve into a description of its phases. Rather, the focus is on two facets, highlighting design-bid-build procurement as a barrier to implementing constructability and exploring the prospects of integrating constructability into such projects through a customized and innovative approach.

As discussed in the section on constructability principles and concepts, construction-driven design specifications, decisions and material choices are important. However, introducing the contractor during the design phase presents a challenge due to the design-bid-build framework limitations. An alternative approach is to initiate contractor-designer collaboration as soon as possible after tender selection, during the mobilization phase. During this phase, participants are awaiting permit approvals and the contractor is preparing for construction (Singh & Arora, 2018). With designs often only partially completed (60% to 90%) at the tender phase, the contractor can provide valuable contributions to refine the design and review its constructability (Othman, 2011).

However, if the collaboration during mobilization results in desired changes in the design, some challenges may arise concerning the sharing of savings, the willingness of the designer to redesign and conflict management. Nonetheless, by addressing these challenges, it is possible to leverage the expertise of both contractors and designers to achieve more construction-sensitive and financially predictable projects.

2.5 Constructability tools and techniques

Traditionally, the incorporation of constructability tools and techniques has been perceived as an unstructured process (Amade, 2016). However, with the advancement of technology and the emergence of BIM, the landscape of constructability tools has transformed, shifting towards computer-based solutions that emphasize enhanced effectiveness and collaboration within project teams (Amade, 2016).

Past research on constructability tools predominantly focused on manual, paper-based techniques such as brainstorming, peer reviews and constructability checklists (Fisher et al., 2000). Although these techniques prove to be valuable tools, they have limitations in fully harnessing the potential of technology for constructability improvement.

In recent years, the integration of BIM has revolutionized the field of constructability. BIM is a digital representation of the physical and functional characteristics of a construction project, facilitating effective information sharing and coordination among various stakeholders (Autodesk, n.d.). By leveraging BIM and other computer-based technologies such as automated design and augmented reality, construction professionals now have access to a wide array of advanced constructability tools and techniques.

These modern constructability tools and techniques aim to mitigate project planning, design and construction processes, leading to more accurate project schedules and costs and allowing designers to identify key problems early in the project. Table 2-8 provides an overview of notable traditional tools and techniques and Table 2-9 provides an overview of notable technology-based tools and techniques. Each table highlights the ideal phase of implementation of the tools and the objectives they seek to achieve.

Table 2-8: Notable traditional constructability tools and techniques

	Constructability tools or techniques	**Ideal phase**	**Objective**	**Source**
1	Checklist	▪ Planning phase ▪ Design phase	Constructability review checklists are predefined sets of items or questions used to verify project plans, specifications, and schedules. They ensure thorough consideration of constructability, including conflict identification, schedule feasibility evaluation, documentation, and fostering collaboration and communication.	(Douglas, 2008)
2	Brainstorming	▪ Conceptualization phase ▪ Design phase	Brainstorming stimulates creativity by encouraging participants to freely express their ideas and solutions in a non-judgmental environment. It aims to generate numerous diverse perspectives and innovative ideas through collaborative group discussions.	(Amade, 2016)
3	Peer reviews	▪ Design development phase ▪ Construction document phase	Peer reviews evaluate project documents, designs, and plans by knowledgeable individuals to assess constructability. They aim to determine feasibility, efficiency, and adherence to construction practices, ensuring the project's overall quality and suitability.	(Amade, 2016)
4	Discussions with the project team	▪ Throughout the entire project lifecycle	Project team discussions involve proactive communication among key stakeholders to enhance constructability. Architects, engineers, contractors, and others exchange ideas and expertise to improve the project's construction process and outcomes.	(Amade, 2016)

Table 2-9: Notable technology-based constructability tools and techniques

	Constructability tools or techniques	Ideal phase	Objective	Source
1	Constructability information classification scheme	▪ Design and planning phase	The Constructability Information Classification Scheme organizes construction-related information for improved constructability. It enhances collaboration, facilitates knowledge transfer and lessons learned, improves design integration, and promotes continuous improvement through structured information organization.	(Hanlon & Sanvido, 1995)
2	Feedback systems	▪ Throughout the entire project lifecycle	Constructability feedback systems collect and analyse insights from stakeholders to enhance project outcomes. They capture information, evaluate it, integrate actions, promote continuous learning, and engage stakeholders for improved constructability practices and knowledge sharing.	(Amade, 2016) (Kartam & Flood, 1997)
3	Constructability knowledge-intensive database system	▪ Throughout the entire project lifecycle	The Constructability Knowledge Intensive Database System is a centralized platform for constructability-related knowledge. It captures, organizes, classifies, retrieves, and disseminates knowledge. It supports decision-making and promotes continuous improvement through valuable insights from previous projects, standards, regulations, research, and expert input.	(Kartam, et al., 1999)
4	Dynamic design management system	▪ Design phase	A dynamic design management system is software that supports design coordination and management throughout the project lifecycle. It integrates buildability, promotes collaboration, and improves communication and information exchange among stakeholders for enhanced constructability.	(Wong, et al., 2004)
5	Buildability assessment model	▪ Early design stages ▪ Pre-construction planning phase	The Buildability Assessment Model evaluates and improves construction project buildability. It assesses design feasibility, identifies challenges, evaluates methods and processes, offers improvement recommendations, and supports collaboration and decision-making.	(Lam & Wong, 2008)
6	Configuration system	▪ Design phase ▪ Planning phase	A Configuration System optimizes buildability and construction efficiency by arranging project components using digital models and predefined rules. It enhances buildability, streamlines processes, facilitates collaboration, and improves documentation and communication.	(Jensen, et al., 2013)
7	Virtual design and construction	▪ Initial design phase ▪ Pre-construction planning phase ▪ Coordination processes	Virtual Design and Construction uses digital technologies like BIM to create a virtual project representation. It enhances collaboration, improves constructability, facilitates visualization and simulation, supports cost estimation and scheduling, and enables value engineering.	(Harris & McCaffer, 2013)
8	Automated rule-based constructability checking	▪ Early in the design phase	Automated rule-based constructability checking uses computer systems to assess design plans against predefined rules. It detects clashes, assesses coordination, ensures compliance with standards, and optimizes constructability, minimizing issues during construction.	(Jiang & Leicht, 2015)
9	Automated design aid	▪ Early stages of design	Automated design aid uses computer tools to enhance the creation, analysis, and optimization of designs. It offers insights, and recommendations, and facilitates informed decision-making. Objectives include design optimization, evaluating alternatives, considering various factors, and promoting knowledge sharing and collaboration.	(Amade, 2016)

	Constructability tools or techniques	Ideal phase	Objective	Source
10	Construction knowledge expert	▪ Construction phase	Construction Knowledge Expert is a digital platform that consolidates construction-related information for professionals. It provides access to comprehensive knowledge, supports problem-solving, facilitates sharing and collaboration, improves efficiency, and promotes best practices and lessons learned.	(Amade, 2016)
11	Quantitative assessment using 4D simulation	▪ Planning and design phase ▪ Pre-construction phase	Quantitative Assessment with 4D Simulation integrates BIM models and 4D simulation to analyse constructability. It visualizes construction sequences, identifies constraints, quantitatively analyses performance, evaluates risks and safety, and promotes collaboration and communication.	(Zhang, et al., 2016)
12	BIM-Lean approach	▪ Can be applied throughout the entire project, but is utilized best during: ▪ Pre-construction planning phase ▪ Construction phase	The BIM-Lean approach integrates BIM technology with Lean Construction principles for better constructability and project performance. It improves visualization, coordination, communication, and collaboration. It integrates construction principles, avoids clashes, and enables data-driven decision-making.	(Nascimento, et al., 2017)
13	Assessment model	▪ Design phase	An Assessment Model systematically evaluates the constructability of a building design. It identifies issues, optimizes the design for buildability, enhances collaboration and communication, supports decision-making, and promotes continuous improvement.	(Fadoul, et al., 2017)
14	Augmented reality	▪ Construction phase	Augmented Reality overlays virtual elements onto the real-world environment. In construction, Augmented Reality improves constructability, provides on-site workers with real-time information, assists with accurate component placement, enables remote collaboration, and aids in progress monitoring and quality control.	(Zhang, et al., 2021)
15	Visual programming with BIM	▪ Early design phase ▪ Planning phase	Visual programming with BIM uses languages like Grasshopper or Dynamo to improve constructability. It enables custom algorithms, automates design tasks, optimizes construction sequences, and analyses project aspects. Objectives include parametric modelling, rule-based analysis, data exchange, design automation, and iterative feedback.	(Carvalho, et al., 2021)

The field of constructability tools and techniques is characterized by its continuous evolution, fuelled by ongoing research and technological advancement. In Table 2-9, the technology-based tool literature publications range from the year 1995 to 2021, with many older and newer advanced technologies existing in the literature. Researchers and industry professionals are actively exploring innovative approaches to further enhance constructability practices (Jones, et al., 2020). Integrating these modern tools and techniques into construction projects offers the potential to improve collaboration among stakeholders, minimize risks and deliver constructible designs (Lahdenpera, 2013) (Amade, 2016).

However, it is important to acknowledge that the adoption and implementation of constructability tools and techniques come with challenges that cannot be overlooked. These challenges include technological barriers, resistance to change, lack of awareness and knowledge and the need for effective training and education (Amade, 2016). Overcoming these challenges requires a concerted effort from both researchers and industry practitioners to address the barriers and promote the widespread adoption of constructability tools and techniques.

The advancement of constructability tools and techniques in the construction industry requires ongoing research and collaboration between academic institutions and industry practitioners. Such endeavours aim to develop comprehensive frameworks and guidelines for the successful implementation of the most suitable tools, tailored to the specific circumstances of the industry and the country (Shahhosseini, et al., 2018).

2.5.1 Barriers to implementing constructability tools and techniques

The implementation and utilization of constructability tools and techniques in construction face several barriers that impede their effectiveness and hinder their adoption. One of the primary barriers is the fragmented approach of existing tools, which often focus on isolated design aspects rather than considering the entire building design as a complex process (Harris & McCaffer, 2013). This limitation neglects the interdependencies and interactions between different design elements, resulting in suboptimal constructability outcomes. To address this, tools need to be underpinned by a systemic view of the building design process, taking into account the interrelatedness of various design elements (Zhang, et al., 2014).

Another significant barrier is the timing of feedback provided by constructability tools. Many tools offer feedback after the design phase is completed, which is often too late to make substantial improvements (Lam, et al., 2010). Constructability issues identified during the design phase can have a significant impact on project cost, schedule and overall performance. Therefore, tools that provide proactive feedback and support during the design process are more effective in maximizing the benefits of constructability (Zhang, et al., 2014).

The lack of integration between constructability tools and BIM tools used by designers is another challenge. This disconnection hinders seamless information exchange and collaboration among different stakeholders involved in the design and construction process (Zhang, et al., 2014). Integrating constructability tools with BIM tools can enhance coordination and communication, enabling effective constructability analysis and decision-making.

Visualization capabilities of constructability tools also play a vital role in their usability and effectiveness. Many existing tools lack visualization features, making it difficult to communicate and comprehend constructability issues effectively (Zhang, et al., 2014). Visual representations can facilitate stakeholders' understanding of the implications of design decisions.

Furthermore, the absence of communication and collaboration features within existing tools poses a significant barrier. Tools that do not incorporate these features limit the exchange of knowledge and expertise and hinder the identification and resolution of constructability issues (Zhang, et al., 2014).

To overcome these barriers, researchers have proposed more powerful tools that address the limitations of current approaches. These tools possess visualization capabilities, store constructability knowledge, enable constructability analysis during the design phase and provide proactive feedback from a construction perspective (Zhang, et al., 2014). Additionally, it is important to consider the readiness of the industry for change and innovation. Lam et al (2010) stated that further investigation into constructability tools is necessary and it should focus on specific project phases and the alignment of innovations with the industry's capabilities and readiness.

Continuous research and development efforts are necessary to overcome these barriers and facilitate the widespread adoption of constructability tools and techniques.

2.5.2 Constructability tool implementation for countries with low BIM maturity

In countries with low BIM maturity and a more risk-averse culture, it is necessary to consider practical and cost-effective alternatives to the advanced software and computer-based tools commonly associated with constructability (Hanlon, et al., 2012). While the literature offers numerous suggestions regarding tools and techniques, many of these options may not be feasible in all project contexts (Lam, et al., 2010) (Nascimento, et al., 2017) (Zhang, et al., 2016).

Given the limitations posed by low BIM maturity and limited access to advanced software, it is advantageous to, instead, identify more primitive tools and techniques that can still deliver significant benefits in terms of constructability. These alternatives can provide a starting point for countries aiming to enhance construction processes and outcomes without requiring extensive investments in technology.

In countries with limited BIM maturity and a risk-averse culture, certain primitive tools and techniques, such as brainstorming, review meetings, checklists, peer reviews and lessons learned workshops, hold potential value. Despite their apparent simplicity when compared to advanced tools, these fundamental approaches become significant in contexts where designer-contractor collaboration is scarce and consultants have minimal involvement in project close-out meetings (Kuo & Wium, 2014) (O'Connor, 2009). By emphasizing the adoption of these more primitive tools and techniques, developing countries with low BIM maturity can still initiate meaningful improvements in constructability. These approaches encourage collaboration, knowledge exchange and proactive problem-solving without relying heavily on expensive technology. As BIM maturity and technology adoption increase over time, these countries can gradually integrate more advanced tools into their constructability practices.

It is important to acknowledge that the suitability and effectiveness of these primitive tools and techniques should be assessed within the specific context of each country. Factors such as local construction practices, available resources and cultural norms must be taken into account when determining the appropriateness of these tools. Moreover, continual research and adaptation of these basic approaches to align with the evolving needs of the industry are important for sustained progress and success in constructability improvement efforts.

2.6 Synthesis of literature review

The construction industry has multifaceted challenges and it is important to seek ways to enhance efficiency, collaboration and project outcomes. Central to this endeavour is the concept of constructability, which aims to integrate construction knowledge into the design process to optimize feasibility, cost-effectiveness and project performance. Early contractor involvement can enable construction expertise to influence designs and identify constructability challenges early in the project.

Constructability principles and concepts highlight the importance of seamless collaboration between designers and contractors. However, the traditional design-bid-build procurement method is a barrier to this collaboration due to its fragmented structure. In such projects, designers focus on aesthetics and structural functionality, often overlooking practical construction details, leading to conflicts and rework during construction. Addressing this disconnect requires a shift to actively integrate construction insights into design decisions, without the contractor's input, to mitigate construction constraints.

Constructability tools and techniques serve as valuable facilitators to consider constructability. While advanced tools, including BIM, offer profound possibilities, countries with low BIM maturity seldom make use of such advanced tools. Leveraging more primitive tools like checklists and peer reviews can still foster collaboration and knowledge exchange. This highlights the importance of tailoring strategies to specific country circumstances.

Barriers that affect the seamless implementation of constructability tools include untimely constructability feedback, fragmented approaches and inadequate communication features. Overcoming these challenges requires the development of more integrated, visual and proactive tools that address the complexities of construction projects. This aligns with the broader need for a culture shift towards recognizing the value of constructability and fostering collaborative environments.

Constructability cannot merely be viewed as a set of principles to consider. To successfully and consistently ensure constructible designs and designers that are mindful of construction constraints, a cultural shift is required from an "every man for himself" approach to intentional constructability-centred collaboration and a collective focus on what is best for the project. A fusion of traditional and integrated delivery methods is required, recognizing both the need for immediate practical solutions and the potential of an adapted culture in the future.

Chapter 3: Methodology

3.1 Chapter overview

The methodology outlines the systematic approach taken to understand the research problem, collect and investigate data, prepare and analyse the data and achieve the research aim and objectives. This chapter describes the research design, data collection methods, data analysis techniques and software selection for the study. The methods and procedures employed show the reliability and validity of the findings, the created constructability tool and suggestions about prioritising collaboration during the mobilisation phase.

3.2 Methodological outline and data utilization goals

The purpose of the data collection was to obtain contractor opinions and experiences to understand the current levels of disconnect between designers and contractors concerning the degree to which designers consider certain constructability aspects. "Contractor advice" is derived from the feedback and included in a constructability tool for designers to consult during the design phase of a design-bid-build project. The data is primarily used to achieve the research aim of creating a constructability tool. However, the process of developing the constructability tool led to two related questions:

1. During what phases in a design-bid-build project should this tool be used?
2. Although the tool is designed to be used during the design phase with no designer-contractor collaboration, construction will most effectively be eased with constructability-centred collaboration between the designer and contractor before construction commencement. Is there a suitable time or phase during a design-bid-build project to prioritise this collaboration?

The research aim is, therefore, also the data utilization goal. During the literature review and data analysis, an aspect identified for future research is that collaboration between designers and contractors must be prioritised during the mobilization phase. Prioritising designer-contractor collaboration during the mobilization phase is discussed in Chapter 5. Figure 3-1 presents a flow diagram that shows the steps taken in the study to achieve the research aim. The figure shows how the research objectives fit into the respective steps in the methodology.

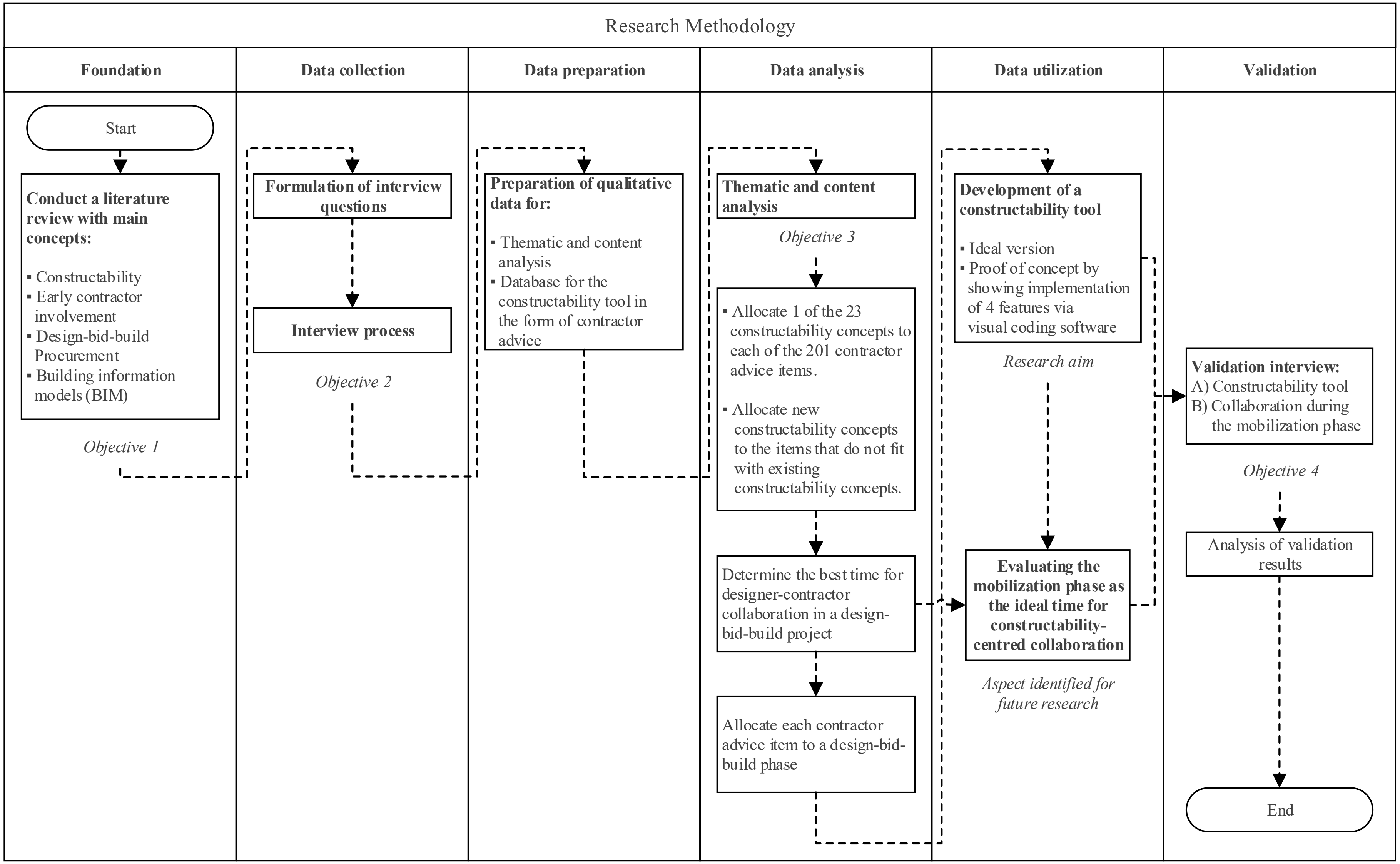


Figure 3-1: Research methodology

The **foundation** of knowledge was obtained through a literature review that focused on constructability, early contractor involvement, design-bid-build procurement and building information models (BIM). The review aimed to clarify definitions, address the research problem, present previous knowledge and highlight the interconnectedness of the concepts.

Data collection involved designing interview questions and implementing a pre-interview process to refine the questions based on lessons learned. Qualitative data was determined to be the most suitable for the research goals, enabling the capturing of in-depth data with detailed descriptions, providing a comprehensive understanding of feedback and allowing flexibility to adjust the data collection approach if necessary. Interviews were chosen as the most suitable data collection method, allowing for the gathering of subjective opinions from construction specialists. The selection of data collection methods is presented in Section 3.3.1. Seven aspects to be investigated in the interview questions were selected based on specific criteria. These criteria, as well as the interview formulation, are presented in Section 3.3.3.

To make the extensive qualitative data manageable for analysis, **data preparation** was necessary. The procedures and steps taken for data preparation are detailed in Section 3.4.1.

A thematic and content **analysis** was performed using Statistica Software to analyse the collected data. Interview question responses were assigned codes to facilitate visual presentation, such as tables and graphs, and to explore correlations between questions and constructability aspects. Statistica Software's suitability for qualitative data analysis is reinforced by its capability to visually represent data through codes imported from an Excel spreadsheet. The selection of data analysis methods and software tools is presented in Section 3.4.2 and Section 3.5, respectively.

During data analysis, the contractor advice phrases derived from the feedback were linked to the 23 constructability concepts identified by Kifokeris & Xendis (2017). If the contractor feedback did not fit into one of the 23 constructability concepts, a new concept was created to address the gap.

In total, eight additional constructability concept groups (allocated A to H) were created. The new concepts, as well as the gaps in prioritization that they indicate, are presented in Chapter 4.

The **data utilization** focuses on the process of creating a constructability tool for designers in the form of a mobile application. The ideal features of the application are presented in Chapter 6. Additionally, four of the features are implemented as a mobile application and presented as proof-of-concept. The aspect identified for future research, namely, constructability-centred collaboration during mobilization, is discussed in Chapter 5.

To **validate** the outcomes of the research, a second round of interviews was conducted with five previous participants. This validation process aimed to assess the acceptability and approval of the constructability tool application and the constructability-centred collaboration suggestion. The validation interview design and interview sheet are discussed in Section 3.6. The validation results are presented and discussed in Chapter 5 and in Chapter 6.

3.3 Methods and procedures for data collection

This chapter provides a comparison of various data collection methods, with a motivation for the choice of a focused interview approach for this study. Furthermore, it explores participant sample information, clarifies the interview design process and outcomes and presents an interview procedure. Approval was obtained from the Stellenbosch University Research Ethics Committee, with reference ING-2022-26506, for the interview process, interview questions and communication methods with interviewees.

3.3.1 Selection of data collection methods

For this study, qualitative data is determined to be the best-suited data type for the goal of obtaining subjective opinions with a contextual understanding. Qualitative data serves the research aim in the following ways:

- Enables the capture of rich and in-depth data with detailed descriptions
- Provides a comprehensive understanding of the feedback
- Allows for the capture of subjective experiences to explore the “why” and “how” behind the feedback
- Flexibility to adjust the approach in the case of unforeseen insights or unexpected themes

Qualitative data collection aims to acquire in-depth insights from participants to understand and explore intricate phenomena. The construction industry, with its complexities and intricate relationships among participants, offers a promising context for collecting valuable qualitative data. In capturing subjective experiences and recollections of situations and problems, it is essential to create an environment where participants feel free to share their knowledge openly. Table 3-1 provides an overview of four qualitative data collection methods, examining their strengths and limitations. The suitability of each method is assessed based on the following criteria:

A Does the data collection method foster participants’ freedom to express their perspectives without constraint?

B Does the data collection method enable participants to elaborate on their responses, providing reasoning and context?

C Does the data collection method minimize the potential for participant dishonesty or rushing through the process?

These criteria serve as a guideline for determining the appropriateness of the data collection methods to the research aim. Table 3-1 shows whether each data collection method satisfies the criteria.

Table 3-1: Comparison of qualitative data collection methods (Rogelberg, 2004)

Data collection method	Strengths	Limitations	Satisfaction of criteria
Surveys/questionnaires systematically collect data through standardized questions from diverse participants to gather information efficiently.	**Efficient data collection**: Surveys/questionnaires gather data efficiently from a large sample. **Standardization:** Standardized questions ensure consistency for comparison and analysis. **Anonymity and confidentiality:** Surveys allow participants to provide honest responses anonymously.	**Limited depth:** Surveys may lack participant elaboration, resulting in less nuanced data. **Response bias:** Participants' socially desirable or biased responses may impact data validity. **Lack of context:** Surveys may not capture participants' full experiences and perspectives.	**A** – Yes, but tedious to do in writing **B** – Yes, but tedious to do in writing **C** - No
Interviews enable in-depth exploration of topics through direct interactions, allowing for open-ended questions and individual or group settings.	**Rich data:** Interviews gather in-depth and contextual information from participants. **Flexibility:** Interviewers adapt questions based on responses, allowing probing and clarification. **Participant perspectives:** Interviews reveal experiences, beliefs, and emotions.	**Time-consuming:** Interviews require significant time for conducting, transcribing, and analysing data. **Subjectivity and bias:** Interviewer presence can influence participant responses, introducing potential bias. **Limited sample size:** Interviews involve fewer participants, affecting generalizability.	**A** - Yes **B** - Yes **C** – Yes
Focus groups involve structured discussions among a small group of participants facilitated by a researcher to explore shared perspectives.	**Group dynamics:** Focus groups explore group norms, consensus, and differing viewpoints. **Synergistic interactions:** Participants build on each other's ideas, generating a wider range of insights. **Efficient data collection:** Multiple perspectives are gathered simultaneously to reduce time and resource requirements.	**Group influence:** Dominant voices or conformity may limit diverse perspectives. **Limited individual depth:** Focus groups prioritize group dynamics over individual insights. **Logistical challenges:** Organizing and coordinating focus groups can be complex.	**A** – Yes, but more difficult in a group setting **B** – Yes, but more difficult in a group setting **C** - Yes
Observations involve the systematic recording of behaviours and interactions in natural settings, with participant-focused or non-participant-focused approaches.	**Authentic data:** Observations capture genuine behaviours and interactions. **Contextual understanding:** Insights into social, cultural, and environmental factors are gained. **Non-verbal cues:** Observations document non-verbal communication, enhancing understanding beyond verbal responses.	**Hawthorne effect:** Participant behaviour may change when aware of being observed, impacting data authenticity. **Access limitations:** Challenges in accessing and observing certain settings or populations may arise. **Subjective interpretation:** Analysing observational data requires careful interpretation and contextual understanding.	**A** - No **B** - No **C** - No

Based on Table 3-1, interviews emerge as the most suitable data collection method for achieving the research goals. Interviews offer a unique opportunity to gather contextual information, seek clarifications and delve into personal experiences and subjective opinions. This approach enables the extraction of advice from construction specialists based on their recollections of past construction project experiences relating to constructability.

However, interviews do possess certain limitations. The subjective nature of the data and potential bias arising from adversarial relationships between designers and contractors could be a concern. Nevertheless, the interviews aim to obtain the most realistic version of advice that contractors would offer design engineers during the design phase, even if it includes candid criticisms. Such advice serves as an objective consideration for the design engineer during the design phase, assisting in the evaluation of the constructability of the design.

Another limitation of interviews is their time-consuming nature, potentially leading to a smaller sample size. It is noteworthy that the interview questions offer three distinct approaches for extracting and formulating contractor advice, which enables the collection of substantial data from a single participant. For example, the following three approaches relate to questions 2, 4 and 5 in the interview process:

- Identify the two most challenging aspects of construction
- Provide an example of repercussions due to neglecting a constructability aspect
- Offer advice to designers on better incorporating specific constructability aspects

Each response can be transformed into actionable guidance for designers, thereby enabling a small sample of interviews to yield a substantial collection of contractor advice. While a smaller sample size might affect the generalizability of the data, the primary aim of this research is to acquire contractor advice for a constructability tool targeting designers. The collected data is therefore sufficient to provide information for developing the tool and to establish a foundation for gathering additional data of a similar nature.

3.3.2 Sample information

The interview participants in this study possess extensive construction expertise, with a minimum of 5 years of experience in roles such as contractors, construction/site managers, project managers, directors or CEOs. It was essential, however, to ensure that the participants did not hold the position of a design engineer at the time of the interview. The interviews were primarily conducted in person, with the majority of participants being interviewed at the research location in Western Cape, South Africa. In cases where virtual interviews were conducted with participants in countries other than South Africa, participants were required to have a minimum of 5 years of contractor or construction/site manager experience in South Africa.

Between November 2022 and February 2023, a total of 20 interviews took place. The initial selection of the first 10 participants involved searching the Register of Contractors maintained by the Construction Industry Development Board. The search criteria included filtering by class of work, specifically general building (GB) and civil engineering (CE), as well as by CIDB designation, limited to CIDB designations 8 and 9. Subsequently, the organizations identified through the search results were evaluated to ensure their relevance to the research objectives and scope. Specifically, the selection was refined to organizations with prior involvement in the construction of low to medium-rise structures, including accommodation facilities, hotels, shopping centres and/or hospitals.

Ten organizations were successfully contacted based on the search results and the scope limitation of low to medium-rise structures, with one participant per organization being interviewed. Following this initial phase, the snowball sampling method was employed. Each of the initial 10 participants was requested to recommend another participant who met the requirements. This iterative process allowed for the expansion of the participant pool, as each interviewee had the opportunity to identify individuals within their professional network possessing the requisite knowledge and experience to contribute to the research data.

Overall, these methodical steps ensured a diverse and representative set of interview participants, combining both targeted selection based on industry registers and the use of snowball sampling to expand the participant pool and tap into valuable networks within the construction field.

3.3.3 Formulation of interview questions and interview procedures

The literature review has identified 10 constructability principles and 23 constructability concepts, which have been instrumental in refining the scope of the interview questions. To determine the aspects most relevant to include in the interviews and to elicit valuable advice from construction specialists, a comprehensive analysis of these 33 principles and concepts was conducted based on four criteria. These criteria served as a guide for selecting aspects for inclusion in the interview questions. The criteria are as follows:

A The aspect should fall within the purview of the design engineer's influence or be amenable to change during the design phase.

B The aspects should be applied within the design-bid-build context.

C The aspects should not already have an efficient building information modelling (BIM) solution or standard in place.

Table 3-2 presents the 10 constructability principles (CPs) and the 23 constructability concepts (CCs) by Kifokeris & Xendis (2017), along with an indication of whether each principle or concept satisfies the three selection criteria. When a principle or concept fulfils all three criteria, it is highlighted, signifying its potential relevance and suitability for inclusion in the interview questions.

Table 3-2: Analysis of the 10 constructability principles and 23 constructability concepts with the selection criteria (Kifokeris & Xendis, 2017)

	Principles and concepts	**Satisfies the criteria**		
		A	**B**	**C**
CP1	Project Integration			✓
CP2	Implementation of construction expert knowledge			✓
CP3	Appropriation of project team skills		✓	✓
CP4	Understanding of overall and specific project objectives	✓	✓	
CP5	Consideration of available resources	✓	✓	✓
CP6	External factors and site accessibility	✓	✓	✓
CP7	Realistic and construction-sensitive project program and construction methodology	✓	✓	✓
CP8	Transparent specifications	✓	✓	✓
CP9	Innovation	✓	✓	
CP10	Acquirement of post-project information and knowledge feedback for the creation of best practices and lessons-learnt data		✓	
CC1	Constructability program			
CC2	Include all key stakeholders throughout the project lifecycle			✓
CC3	Effective integration between design and construction by exploitation of up-to-date construction knowledge and experience			
CC4	Contractual framework to align with the applied construction methods			
CC5	Scheduling goals should be construction-driven	✓		
CC6	Early scrutinization and selection of primary construction methods should frame the design	✓	✓	✓
CC7	The proper study of the site's layout to ensure uninterrupted workflows	✓	✓	✓
CC8	Planning and construction operations sequence should precede other plans since it dictates the design and procurement	✓	✓	✓
CC9	Cooperation of all specialists should be facilitated by advanced technologies to overcome fragmentation		✓	
CC10	The widest possible simplifications and rationalizations should be implemented in the design	✓	✓	✓
CC11	Standardization of project elements should be selected if possible	✓	✓	✓
CC12	Technical specifications should be simplified and configured for efficient construction	✓	✓	✓
CC13	Modularization and preassembly should be considered	✓	✓	✓
CC14	Exploitable resources must be properly positioned at the site during the design stage	✓	✓	✓
CC15	Construction should be scheduled under suitable weather conditions		✓	✓
CC16	Construction activities should be effectively planned for the prevention of conflicts		✓	✓
CC17	Issues not covered by design should be treated with an innovative approach		✓	✓
CC18	Innovation to decrease labour intensity, increase mobility, safety and site accessibility of the personnel should be pursued	✓	✓	✓
CC19	Innovation in the introduction, use, selection, and modification of the available equipment should be considered		✓	
CC20	Optional preassembly should be encouraged	✓	✓	✓
CC21	Innovation in the use, reuse, and postconstruction function of temporary facilities should be considered	✓	✓	
CC22	The contractor's appraisal procedure should be established			
CC23	The constructability program's appraisal should be established			

Table 3-2 presents a total of 14 highlighted principles and concepts that meet the selection criteria. It is important to note that several of these aspects are not mutually exclusive and encompass multiple concepts within a single description. To enhance clarity and coherence, these 14 aspects were organized into cohesive themes and reformulated. As a result, Table 3-3 lists 7 constructability aspects that emerge from this process. These definitions served as the foundation for formulating the interview questions.

Table 3-3: Rephrased and finalized aspects to be used as the basis for the interview questions

	Aspect	Definition
1	The availability of resources	The consideration of the most cost and time-effective construction materials and construction equipment.
2	Primary construction methods	The methods, processes and techniques used, as well as the equipment required, to construct the different elements of a structure.
3	Site accessibility and spatial requirements	The consideration of the external and internal means of accessing areas on the site by personnel and vehicles, as well as the space required on site for vehicles, equipment, personnel and storage. The consideration of the best design for the site layout.
4	Creating simple and rational designs	Engineering designs that are unambiguous. Engineering design decisions that have gone through a process of good reasoning.
5	The standardization of elements or units	Engineering design includes the repetition of elements or units and the regularity of elements or units.
6	Preassembly, prefabrication and/or modularization	Preassembly: Elements or units that are assembled elsewhere and transported to the site. (Preassembled trusses) Prefabrication: Elements or units that are prefabricated elsewhere and transported to the site. (Prefabricated wall elements) Modularization: Standardized and self-contained components or modules of a structure that are fully assembled elsewhere and transported to the site. (Modular bathroom units)
7	Site safety	Hazard identification and safety risk assessments during the design phase.

In line with the selected constructability aspects, a set of six interview questions has been formulated. The complete interview sheet can be found in Appendix A.1.

Question 1 pertains to the participant's background, while question 3 involves the participant ranking each of the seven constructability aspects on a scale of 1 to 5, reflecting their perception of the degree to which designers consider these aspects during the design phase. Questions 2, 3, 4 and 5 are presented in Table 3-4. These questions are presented in this section to clarify the interview process, providing an understanding of how the interviews were conducted.

Table 3-4: Questions 2, 3, 4 and 5 of the interviews

Question 2	In your experience, which 2 aspects increase the difficulty of the construction process the most concerning the design decisions that design engineers make (or do not make)?
Question 3	In your experience, how actively do design engineers consider **the constructability aspect** during the design phase, on a scale from 1 to 5? 1: "Not considering it at all" 5: "Always making a great effort to consider it" *1. * availability of resources ** *2. * primary construction methods ** *3. * site accessibility and spatial requirements ** *4. * creating simple and rational designs ** *5. * the standardization of elements or units ** *6. * preassembly, prefabrication and/or modularization ** *7. * site safety **
Question 4	Could you provide an example of a case where the design engineer did NOT consider **the constructability aspect* *, which resulted in problems during construction?
Question 5	If you could advise a design engineer on what he/she should focus on during the design phase regarding **the constructability aspect* * to create a more construction-sensitive design, what advice would you give?

Questions 3, 4 and 5 are repeated for each constructability aspect. In the case where a participant ranks an aspect with a 4 or 5 in Question 3, indicating a positive perception of the consideration given by design engineers, Questions 4 and 5 become redundant. The interview sheet provided in Appendix A offers an overview of the interview structure.

To ensure the clarity and effectiveness of the interview questions and process, a series of pre-interviews were conducted with two contractor participants and two design engineer participants. While the data collected during these pre-interviews cannot be shared due to ethical considerations, they provided valuable insights. Table 3-5 presents a summary of the insights gained from the pre-interview phase and highlights the adjustments made based on the lessons learned, ensuring the refinement and optimization of the interview design.

Table 3-5: Insights gained from the pre-interview process, as well as the necessary adjustments made

Insight	Adjustments
Concepts such as "constructability" and "modularization" should not be assumed to be widely known or understood. Adequate definitions should be provided for all important concepts.	A definition sheet was emailed to the participant after an appointment had been confirmed and the definition sheet was also made available during the interview to consult if necessary.
The definitions provided, the questions and an introduction to the research should be presented in clear and plain language to avoid confusing the participant with unnecessary words or expressions.	The interview questions, the definitions and the prepared research introduction were formulated clearly and concisely.
Only the necessary background about the research should be provided to the participant as an introduction. Providing extensive information about past research increases the likelihood that the participant will subconsciously agree with the provided insights and formulate answers based on that knowledge.	A brief and to-the-point introduction to the research was prepared and more information was only shared if the participants explicitly requested it.
Although the interview should be kept within the time limit that was communicated to the participant, the participant should be allowed to elaborate on their answers or explain the reasoning behind them if they so choose.	A brief pause followed the answers of the participants to provide them with the opportunity to continue if they so choose. Real-time analyses of the situation was continuously carried out by the researcher to make the interview a positive experience for the participant.

No specific changes were made to the interview questions following the pre-interview process. The insights gained primarily focused on the interview process, while the collected results were deemed satisfactory, rendering adjustments to the questions unnecessary.

3.4 Procedures for data preparation and methods for data analysis

3.4.1 Data preparation procedure

The data preparation, briefly outlined in Section 3.2, is elaborated upon in this section. To enable thematic and contextual analysis, the data required reformatting into a more manageable structure. The flow diagram presented in Figure 3-2 illustrates the transformations applied to the data.

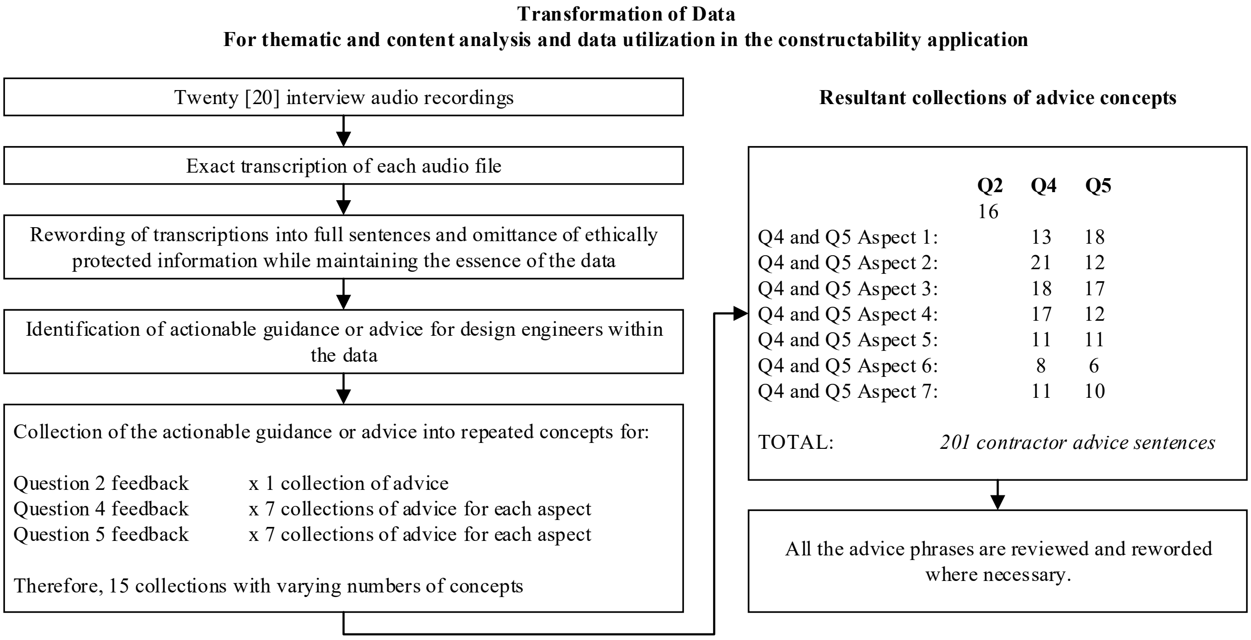


Figure 3-2: The transformation of data during the preparation process

Figure 3-2 shows the transformation of the qualitative data for data analysis and data utilization. Transformation before data analysis involved: data transcription from audio, rewording, identification of advice or lessons from the feedback and grouping of the advice or lessons into similar categories creating a collection of advice categories for each question. The transformation resulted in 201 advice phrases or phrases, referred to as "contractor advice". The 201 phrases are all included in the thematic and content analysis of the data. The collections of contractor advice phrases are provided in Appendix B.2.

3.4.2 Selection of data analysis methods

The selection of an appropriate data analysis method that aligns with the nature of the data, the objectives of data utilization and the research goals are presented in this section. Qualitative data analysis involves a systematic examination and interpretation of data to extract meaningful insights and understanding. Several methods exist for analysing qualitative data, each with its strengths and limitations. To assess their suitability, six qualitative data analysis methods were compared against the following criteria:

A The method should facilitate cross-examination between interview questions, such as correlating participant experience with advice provided

B The method should not consider the wording of the participant's responses

C The technique should primarily focus on identifying broad themes in the data, rather than examining each of the 201 individual items.

Table 3-6 provides a comparison of the six qualitative methods, including their strengths and limitations, and indicates whether each method satisfies each of the three criteria.

Table 3-6: Comparison of 6 qualitative data analysis methods (Rogelberg, 2004)

Data analysis method	Strengths	Limitations	Suitability to current research
The thematic analysis identifies patterns and themes in qualitative data by categorizing and coding recurring ideas, leading to a comprehensive understanding.	Thematic analysis is flexible, allowing for the exploration of both expected and unexpected themes.	It can be time-consuming and requires careful interpretation to ensure the accuracy of identified themes.	**A** - Yes **B** – Yes **C** - Yes
Content analysis categorizes and examines qualitative data using coding schemes to analyse frequency, distribution, and relationships between codes.	Content analysis is suitable for large datasets and can be easily replicated.	It may overlook nuanced meanings and interpretations inherent in qualitative data.	**A** - Yes **B** - Yes **C** - Yes
Grounded theory is an inductive approach where researchers develop theoretical explanations from qualitative data through constant comparison and theory refinement.	Grounded theory is valuable for generating new theories and concepts directly from the data.	It requires a high level of researcher involvement and may lack generalizability to broader populations.	**A** - Yes **B** - Yes **C** - No
Discourse analysis examines language in social contexts, exploring power dynamics and how language shapes social realities.	Strengths include uncovering hidden power structures and social processes	It requires skilled interpretation and can be subjective.	Not suitable for the data utilization goals or the current research
The narrative analysis examines stories to understand individual experiences and social contexts by identifying recurring themes and meanings.	This method allows for a deeper understanding of personal perspectives and cultural interpretations.	Narrative analysis can be subjective, requiring careful interpretation and potential biases in the researcher's understanding of narratives.	**A** - Yes **B** - No **C** - Yes
The phenomenological analysis explores the essence of lived experiences, uncovering underlying meanings by immersing in participants' subjective perspectives.	The phenomenological analysis provides rich and detailed descriptions of experiences, allowing for a deep understanding of individuals' perspectives.	It requires a skilled researcher and it may be time-intensive.	Not suitable for the data utilization goals or the current research

Based on the findings presented in Table 3-6, thematic analysis and content analysis emerged as the most suitable data analysis methods for the study. Grounded theory, while potentially applicable, would necessitate more detailed comparisons and investigations of the 201 contractor advice phrases to generate credible theoretical explanations. Given that the data has been transformed into a more readable and manageable format, conducting grounded theory analysis may not yield satisfactory results.

Narrative analysis is also feasible, as the data may reveal recurring themes that convey the contractors' opinions and experiences. However, the transformation of the data from raw audio to its final format may result in the loss of intricate details about social context and experiences. Additionally, the participants' answers were influenced by the seven constructability aspects they were prompted about, potentially shaping the narrative differently if those prompts were absent.

Conversely, thematic analysis and content analysis allow for the broader consideration of themes and patterns within the data. The data has already undergone a form of thematic and content analysis during the data preparation stage, where it was transformed into 15 collections of concepts. Each interview question was coded, organized in a spreadsheet and imported into Statistica software, which facilitated the identification of patterns, themes and outliers through methods such as cross-tabulation and histograms. However, it is important to note that the qualitative data does not lend itself to statistical analysis in Statistica, as the numerical codes are nominal and ordinal levels of measurement. Therefore, statistical analysis was not attempted. The codes for each question are presented in Appendix B.1.

3.5 Software utilization for data analysis and the constructability tool

3.5.1 Data analysis software

To support data analysis, two software options were utilized. The selection of software tools was driven by the need for effective data analysis, including the identification of themes, patterns and relationships within the provided participant answers. Specifically, the chosen software should enable coding, cross-examination and visual representation of the results. To meet these requirements, the software options considered were ATLAS.ti and Statistica.

ATLAS.ti is a qualitative data analysis software designed to facilitate the management, coding and analysis of various forms of qualitative data, such as textual, audio, video or graphical data. It offers a range of tools and features that support rigorous qualitative analysis (ATLAS.ti, 2023).

On the other hand, Statistica is a comprehensive software solution that specializes in statistical analysis, data management and data visualization. It provides a wide array of tools that facilitate data exploration and analysis (Statistica, 2023).

Table 3-7 presents a comparison of ATLAS.ti and Statistica software, considering their suitability for the research requirements and objectives.

Table 3-7: Data analysis software comparison (ATLAS.ti, 2023) (Statistica, 2023)

Software	Strengths	Limitations
ATLAS.ti	**Data management:** Enables efficient organizing capabilities for large volumes of qualitative data **Coding and analysis:** Provide robust coding tools that allow annotation, categorization and hierarchical coding systems to establish connections between codes	**The learning curve** to maximize the software's potential **Editing** imported documents containing the data is not possible, and each set of data needs to be coded in vivo
Statistica	**Extensive statistical analysis capabilities:** Including various statistical procedures to gain insights from the data **Flexibility and customization:** Allowing the user to fully customize all analysis output, settings, variables and formats **Importing and editing data:** Allows the import of data that can be edited within the software with updates to previously performed analysis **Visualization and coded data:** Provide various graphical output options for coded data such as categorized histograms and matrix plots that allow for the cross-examination of different codes	**Limited advanced features:** such as machine learning and predictive modelling

After trialling both ATLAS.ti and Statistica for data analysis, Statistica was selected as the more suitable software for several reasons. Statistica excelled in visualizing data and enabling graphical cross-examination of questions and codes (Statistica, 2023). In contrast, ATLAS.ti presented limitations, as qualitative sentences were imported and categorized within the software, which proved to be a tedious process due to the inability to view documents full screen or edit them (ATLAS.ti, 2023). Statistica allowed data to be coded in an Excel spreadsheet format with customizable numerical codes before importing into the software, providing more flexibility (Statistica, 2023).

3.5.2 Software for the creation of the constructability tool

For the development of the constructability tool features, the selection of software was based on criteria such as simplicity, Excel sheet data importing capabilities, cost, professional aesthetic and live testing capabilities on multiple devices. Visual coding software for application development, particularly platforms utilizing block-based programming, was explored. Thunkable software emerged as a viable option, offering a range of pre-built components and features (Thunkable, 2023). This aligns with the intention to present a proof-of-concept. Thunkable allows users to customize application features, data, coding and aesthetic design. Unlike traditional coding platforms, Thunkable facilitates concurrent coding, data import, application design and live testing within a single software environment. The live testing capabilities also allow for a clear demonstration to participants during the validation interviews (Thunkable, 2023).

Other viable options were BuildFire software and AppSheet software. BuildFire was found to have a lower degree of flexibility and customization options, whereas Thunkable allows for custom coding to create more diverse application features (Thunkable, 2023). AppSheet's speciality is to create data-driven applications from Excel spreadsheets. Thunkable allows for both data-driven applications and intricate user interface designs. Both BuildFire and AppSheet have live-testing capabilities, however, Thunkable is known for its seamless live-testing that instantly updates changes (AppSheet, 2023) (BuildFire, 2023).

The performance limitations of Thunkable were considered and research was conducted to assess its compatibility with the research goals. It was determined that Thunkable provides adequate capabilities to develop the constructability tool features and present the final application environment and outcomes, effectively demonstrating the proof of concept of the constructability tool (Thunkable, 2023).

3.6 Validation of research aim outcomes

Validation is an important step in establishing the acceptance and credibility of the proposed constructability tool and the prioritisation of collaboration in the mobilization phase. To enhance the credibility of the suggestions and proposals, validation from five of the construction specialists who provided the initial raw data was sought. This validation process aimed to identify potential errors and inaccuracies, thereby informing future researchers in their continuation of the study.

Five construction specialists were invited to participate in the validation interviews. The interviews included seven Likert scale questions, which served two primary goals: (1) assessing the participants' opinions regarding the usefulness of the constructability tool in facilitating better consideration of constructability during the design phase, and (2) evaluating the participants' perspectives on whether the mobilization phase is an opportune time to prioritize contractor-designer collaboration, with a focus on constructability.

Before posing the seven questions, several steps were undertaken to ensure participants were adequately informed about the constructability tool and the suggestions about a collaborative mobilization phase. These steps included an explanation of the constructability tool, a demonstration of its four features and an introduction to the mobilization phase as a valuable project phase to prioritise collaboration. The validation interview questions can be found in Appendix A.2.

3.7 Chapter summary

The methodology chapter focuses on the research design, data collection, data analysis and software selection for the study. The chapter begins with a discussion of the research approach, which employs interviews with construction specialists and obtaining qualitative data.

The data collection methods were selected to align with the research goals and the type of data. The interviews aimed to gather in-depth insights and experiences from participants to derive “contractor advice” from the feedback. Pre-interviews were conducted to refine the interview questions and ensure clarity.

Thematic analysis and content analysis emerged as the most suitable methods for analysing qualitative data. The thematic analysis focused on identifying broad themes and patterns, while content analysis involved categorizing and organizing the collected concepts. Software options such as ATLAS.ti and Statistica were considered, with Statistica ultimately chosen due to its superior data visualization capabilities and ease of use.

Additionally, the development of the constructability tool and its features required software selection. Thunkable, a visual coding platform for mobile applications, was chosen for its simplicity, data import capabilities, customization options and live testing features. Research was conducted to ensure that Thunkable's capabilities aligned with the research goals and would provide an adequate platform for the development of the tool.

Validation of the constructability tool and the proposed constructability-centred collaboration during the mobilization phase was sought through interviews with five construction specialists. The interview questions focused on the usefulness of the constructability tool and the mobilisation phase as the ideal time to prioritize contractor-designer collaboration.

This chapter lays the foundation for the subsequent analysis and discussion in the results and discussion chapter, where the findings of the data analysis are presented.

Chapter 4: Results and discussion

4.1 Chapter overview

This chapter presents and discusses the findings obtained from the interviews with constructability specialists. The participants in the study are introduced by providing relevant background information about their qualifications, roles and years of experience. A description of the allocated codes for Statistica is presented in Appendix B.1. The focal point of the chapter revolves around the following:

- The presentation and discussion of the rankings provided by the participants in question 3 for each of the seven constructability aspects.
- The introduction and discussion of the 24 most frequently mentioned advice phrases derived from questions 2, 4 and 5.
- The introduction and discussion of eight additionally identified constructability concepts from the interview data.
- The presentation and discussion of question 6 results regarding the participants' opinions on a collaborative forum involving young design engineers and experienced construction specialists.

The interview questions are presented in Appendix A.1. This chapter offers insights into the current state of constructability considerations of designers as experienced by construction specialists.

4.2 Introduction to interview participants

Table 4-1 provides an overview of the 20 interview participants, outlining their qualifications, current employment positions and years of experience in the construction industry.

Table 4-1: Interview participant information

Interview number	Qualification	Current position	Years of experience
1	BTech civil engineering	Senior project manager	19
2	MEng civil engineering	Operations director	30
3	MEng civil engineering	Project manager	10
4	BEng civil engineering	Technical office engineer	14
5	BTech civil engineering diploma	CEO Construction	27
6	BEng civil engineering PREng	Project manager	10
7	Master's Business Administration (MBA)	Construction manager	12
8	BTech mechanical engineering	MD project management	25
9	Civil engineering diploma	Project manager	8
10	BSc quantity surveying	Contracts director	30
11	BEng civil engineering	Project director	36
12	Higher diploma in architecture and building	Senior contracts manager	20
13	BSc building	Managing director	27
14	Diploma in building management	Contracts director	27
15	BTech civil engineering	Contract manager	40
16	NQF 5 in business management	Contractor	24
17	Honours in construction management and quantity surveying	Site agent	5
18	International health and safety	Director	10
19	BSc	Commercial director	30
20	NQF 6 project management	Contracts manager	8

The qualifications in column 2 are categorized into civil engineering and non-civil engineering fields, indicated by blue-highlighted and un-highlighted items respectively. The participants' current positions exhibit a wide range of roles. To facilitate effective cross-analysis and pattern identification, the employment positions in column 3 are categorized as either executive/leadership positions (unhighlighted) or project/construction management positions (grey-highlighted). This classification reveals that 55% of participants hold project and construction management positions, while the remaining 45% occupy executive and leadership roles.

In terms of years of experience, participants in executive/leadership positions have an average of 26.8 years of experience while those with project/construction management positions have an average of 15.45 years of experience.

The wide range of roles and qualifications of the interview participants is valuable for the study because it provides broader perceptions and a variety of experiences from different viewpoints, while still maintaining the scope of gaining construction expert knowledge and advice. For the constructability tool, advice from many different experiences and viewpoints could be beneficial for a young designer.

4.2.1 Results of question 3: Ranking of constructability aspects consideration by design engineers

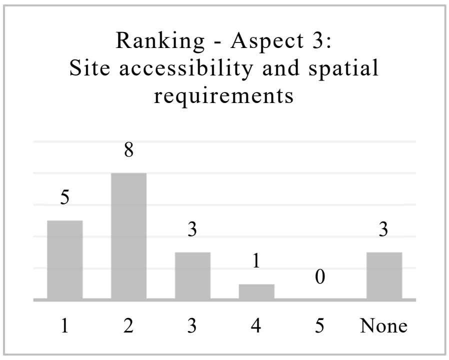
This section presents the ranking results of question 3, which assesses the extent to which each of the seven constructability aspects are considered by design engineers, as experienced by the participants. A ranking of 1 means that the aspect is not considered at all, while a ranking of 5 signifies consistent and diligent consideration of the aspect by design engineers. Three participants each did not provide a ranking on aspects 3, 6 and 7. Their reasoning varied, with some believing that these aspects fall outside the designer's responsibility during the design phase, while others felt that the design engineer could not consider the aspect and that clients or architects are the main decision-makers.

Table 4-2 shows the rankings assigned by the 20 participants to each of the seven constructability aspects (found in Table 3-3) and reveals the variations in the attention by designers to constructability aspects. The data cannot be analysed statistically; therefore, the mean scores are used merely to present the most critically ranked (aspect 3) to the least critically ranked (aspect 5) in Table 4-2. In the case of aspects 3, 6 and 7, the participants who did not provide a ranking are represented by the category code "None". To ensure consistency and to account for available data only, the means for aspects 3, 6 and 7 were calculated with a total of 17 participants, who provided rankings for these aspects.

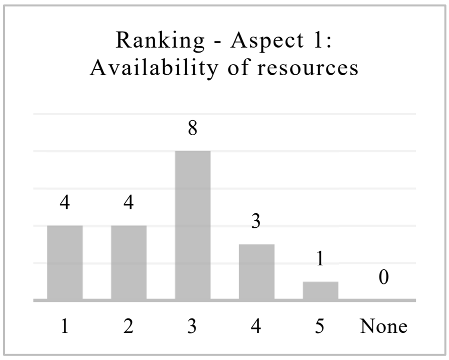
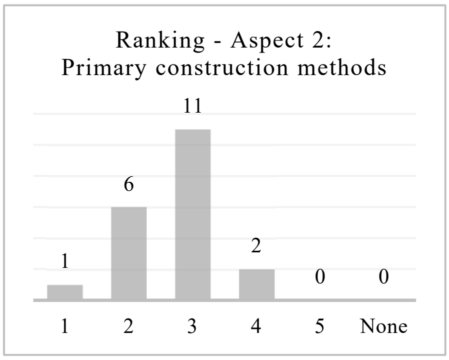
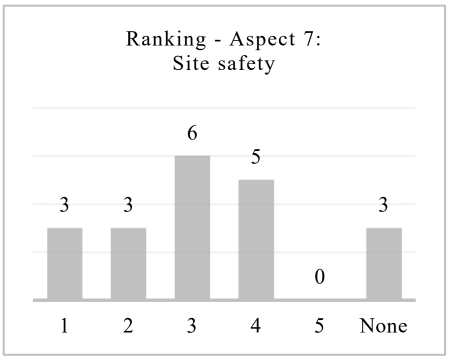
The ranking provides insights into the degree of consideration, according to the experience of construction specialists, given by design engineers to each of the constructability aspects. The ensuing discussion addresses the interpretation of these rankings, shedding more light on the reasons behind ranking decisions, as well as on their decisions not to provide rankings for certain aspects.

Table 4-2: Rank provided by the interviewees for each of the seven constructability aspects (found in Table 3-3)

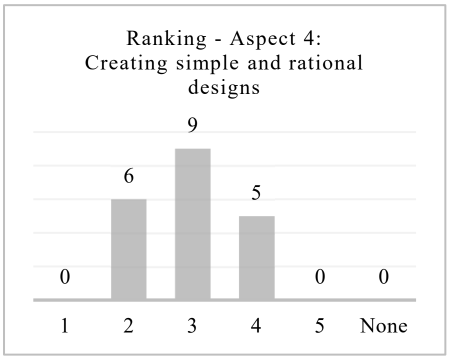
<table>
<tr><th>Aspect and mean score</th><th>Discussion</th></tr>
<tr><td>The aspect least considered by designers with a mean score of 2.03.

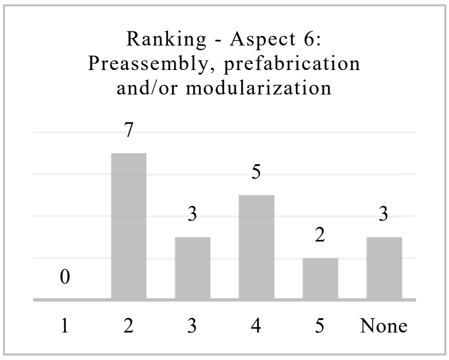


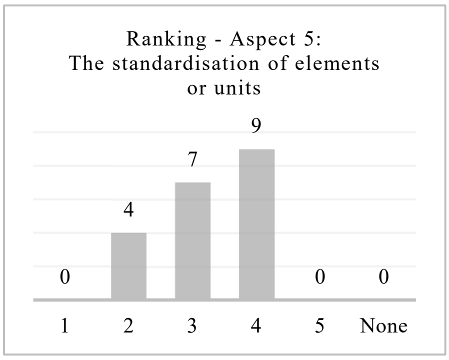
</td><td>The results for the ranking of aspect three show that participants predominantly provided rankings of 1 and 2. This suggests a general perception among construction specialists that design engineers may not adequately consider site accessibility and spatial requirements during the design phase. Participant 5 mentioned that " spatial requirements are usually an afterthought for engineers". Few participants provided higher rankings (3 and 4) and no participants ranked 5. Three participants did not give a ranking, expressing views that this aspect should not fall under the purview of design engineers. Participant 15 said that "the designer will inherit the spatial layout from the architect's design" and Participant 18 believes that "this is not the designer's problem".</td></tr>
</table>

<table>
<tr><th>Aspect and mean score</th><th>Discussion</th></tr>
<tr><td>Mean score of 2.73.

</td><td>The distribution of rankings indicates that participants were relatively evenly spread across scores 1 to 4, with the highest number of participants ranking this aspect as 3. This suggests that construction specialists perceive a moderately low to moderate level of consideration by design engineers regarding the availability of resources during the design phase. Only a single participant gave a ranking of 5. Participant 5 mentioned that “designer engineers often specify products or methods that have not been used in South Africa”. He further states that there are usually implementation and maintenance problems that follow because the required skills for the products are not available. Participant 7 emphasised that “it should not be the contractor’s responsibility to be the first individual to consider spatial requirements and access, but it does become his problem”.</td></tr>
<tr><td>Mean score of 2.78.

</td><td>The participants’ responses indicate a relatively consistent distribution across scores 2 and 4, with the highest number of participants ranking this aspect as 3. This suggests that construction specialists perceive a moderately low to moderate level of consideration by design engineers regarding primary construction methods during the design phase. Notably, no participants gave the highest ranking of 5 and the lowest score only has one participant ranking. Participant 7 mentioned that “it is not the large design aspects that designers get wrong. It is the small practical things that they miss”. Participant 18 advised designers to “think about the practical circumstances on site while designing and not only based on book knowledge”.</td></tr>
<tr><td>Mean score of 2.79.

</td><td>The highest number of participants ranked this aspect as 3 and 4. The absence of the highest score, 5, is notable. Additionally, there are varied reasons among the three participants who did not provide a ranking, such as uncertainty about the design engineer’s role in site safety. Participant 14 said that “it is not expected of design engineers by the contractor”. This suggests a middling level of perceived consideration by design engineers for site safety during the design phase, with potential ambiguities in role expectations influencing the responses. Participant 9 mentioned that “the only way designers can prevent safety hazards by design is with experience in construction processes”. On the other hand, Participant 5 stated that “safety on site remains the contractor’s responsibility, but the innovative ways that safety is ensured is costly. It would help if the designer better considers safety in the design”.</td></tr>
</table>

<table>
<tr><th>Aspect and mean score</th><th>Discussion</th></tr>
<tr><td>Mean score of 3.03.


</td><td>Responses indicate a spread across scores 2 to 4, with no participant choosing scores 1 or 5. This suggests that participants perceive design engineers to exhibit a moderate level of consideration for creating simple and rational designs. Creating simple and rational designs aligns with the responsibilities and problem-solving abilities of design engineers (Khurmi & Gupta, 2017) (Nunnally, 2001) and it is therefore understandable that design engineers are more inclined to focus on the simplicity and rationality of their designs. The absence of extreme rankings implies a consensus that design engineers do not neglect this aspect entirely, but there might be room for improvement in their consistent application of simplicity and rationality in designs.</td></tr>
<tr><td>Mean score of 3.18.


</td><td>The distribution of scores indicates a mix of considerations among participants, with no one choosing the lowest score of 1. The relatively high ranking for this aspect could be attributed to the perception that consultants consider these methods when feasible for the project and site location. However, it is important to note that the use of prefabrication in South Africa is not yet widely adopted, and its high ranking may be due to the recognition and consideration of its potential advantages rather than its extensive implementation. According to Bikitsha (2010), there is a perceived resistance to prefabrication on the part of clients in South Africa, because the cost-effectiveness of utilizing prefabrication varies depending on the project. Participant 18 mentioned that “the client should specify early on whether they want prefabrication”. The variance in scores might reflect differences in project types and expectations within the industry, indicating that design engineers’ involvement in preassembly and prefabrication is not consistently practised or required across all projects.</td></tr>
<tr><td>The aspect most considered by designers with a mean score of 3.28.


</td><td>Most participants assigned scores between 3 and 4, indicating that they perceive design engineers to put moderate to moderately high effort into considering standardization. The standardization of elements or units saves time during design. Designers can therefore streamline the design process which benefits their situation of working on concurrent projects (Khurmi & Gupta, 2017). The absence of scores 1 and 5 suggests that participants generally acknowledge some level of consideration for standardization. However, the variations in scores suggest that the extent of this consideration may vary among design engineers, possibly influenced by project-specific factors and individual design preferences.</td></tr>
</table>

Participants believed that design engineers generally prioritize the standardization of elements or units (aspect 5) during the design phase while giving comparatively less attention to aspects such as site accessibility and spatial requirements (aspect 3) and the availability of resources (aspect 1). The four lowest-ranked aspects by the participants are site accessibility and spatial requirements (aspect

3), availability of resources (aspect 1), primary construction methods (aspect 2) and site safety (aspect 7). These four aspects all require an in-depth understanding of the construction processes and hazards, whereas the considerations about standardization, prefabrication and design rationality (the less critically ranked aspects) can be considered adequately without extensive construction experience.

The participants who did not provide rankings for aspects 3, 6, and 7 argue that design engineers should not shoulder these responsibilities. They believe site accessibility and spatial requirements, as in housing projects, are only addressed by contractors during tendering after the architects maximise the number of dwellings on the site location. Similarly, they contend that preassembly and prefabrication should be determined early by clients or architects, not design engineers. Some participants suggest that design engineers lack the experience to fully comprehend safety hazards during design. However, the majority of participants express the need for design engineers to consider these aspects.

These participants' perspectives highlight differing opinions regarding the responsibilities of design engineers in considering certain constructability aspects and underscore the complexity and divergent viewpoints within the industry.

Table 4-3 shows the mean ranking scores given by executive/leadership positions and project/construction management positions for each of the constructability aspects. As is clear from the table, the executive and/or leadership participants provided a lower average ranking for all seven aspects than the project and/or construction management participants. The divergence in ranking averages between participants in executive/leadership roles and project/construction management roles can be attributed to their distinct perspectives and responsibilities within the construction industry.

Table 4-3: Mean scores of rankings for seven aspects by executive/leadership positions vs. project/construction management positions

	Executive/leadership positions	Project/construction management positions
	Mean score	**Mean score**
Aspect 1: **Availability of resources**	2.4	2.8
Aspect 2: **Primary construction methods**	2.4	2.7
Aspect 3: **Site accessibility and spatial requirements**	1.6	2.3
Aspect 4: **Creating simple and rational designs**	2.8	3.1
Aspect 5: **The standardization of elements or units**	3.2	3.3
Aspect 6: **Preassembly, prefabrication and/or modularization**	2.9	3.3
Aspect 7: **Site safety**	2.7	2.8

Executive/leadership roles often involve a more strategic and overarching focus on organizational goals and decision-making. The viewpoint of those participants may be influenced by their broader understanding of project complexities and the impact of a lack of consideration of the constructability aspects by the design engineer. They may perceive the designer's consideration of the aspects as more inadequate than project/construction management participants because of their focus on project feasibility and financial implications. At the same time, this group also has more experience, on average 26.8 years versus 14.45 years for the project/construction management group.

On the other hand, the project/construction management participant roles have more hands-on involvement. Therefore, their proximity to the work that design engineers do may provide them with more understanding of the efforts made by design engineers. The higher ranking average provided by the project/construction management participants for the seven aspects could reflect their understanding of the difficulties experienced by designers in considering the constructability aspects in the design phase.

The graphs presenting the rankings of the aspects based on the employment positions are presented in Appendix B.3.

To analyse only the most commonly occurring problems, Section 4.3 focuses on the most mentioned advice phrases instead of analysing the constructability aspects separately. The most mentioned advice by the 20 participants is assumed to be the most commonly occurring challenges that the participants experience. Therefore, the discussion will concentrate on the 24 most mentioned advice phrases, exploring the themes and categories identified.

4.3 Outcomes and discussion of advice extracted from interview feedback

4.3.1 Most mentioned advice

Construction specialists were asked for examples of instances where the constructability aspect was not considered by designers, and about the repercussions for the project (question 4 found in Appendix A.1). Additionally, participants were asked for advice on how design engineers can better consider or include each aspect in the design process (question 5 found in Appendix A.1).

This section presents and discusses the "contractor advice" that was derived from the results of questions 2, 4 and 5 of the interview. Table 4-4 shows a glossary of terms often used in this section and how they relate to one another. Figure 4-1 shows a flow diagram of subsequent tables in this chapter.

Table 4-4: Glossary of terms used in Chapter 4

Nr.	Term	Origin	Description	Location
			Relating to constructability concepts	
1	**"23 constructability concepts"**	From literature	The 23 constructability concepts by Kifokeris & Xendis (2017).	Table 2-2 Table 2-3 Table 2-4
2	**"8 additionally defined constructability concepts"**	Identified from Nr. 3	8 newly defined constructability concepts (labelled A to H) were identified from the advice provided by interview participants that do not fit into the 23 constructability concepts.	Table 4-9
			Relating to contractor advice phrases and categories	
3	**"201 advice phrases"**	From the interview participant feedback	Contractor advice phrases, of which there are 201, in the total dataset provided by the interview participants.	Appendix B.2
4	**"24 most mentioned advice"**	Identified from Nr. 3	The 24 most mentioned contractor advice phrases by the interview participants. The most mentioned phrase is mentioned by 10 participants.	Table 4-5
5	**"12 categories of the 24 most mentioned advice"**	Created from Nr. 4	Categories were identified that the 24 most mentioned pieces of advice fit into for thematic analysis. There are 12 categories.	Table 4-6
			Relating to contractor advice phrases and implementation challenges	
6	**"10 advice phrases that are challenging to implement"**	Identified from Nr. 4	Advice phrases that may be challenging to implement were identified from the 24 most mentioned advice. Ten (10) phrases were identified.	Table 4-7
7	**"More implementable advice"**	Identified from Nr. 3 and relating to the same categories from Nr. 5	More implementable, or more feasible, advice was identified from the total database (201 phrases) to replace the 10 phrases that may have implementation problems.	Table 4-8

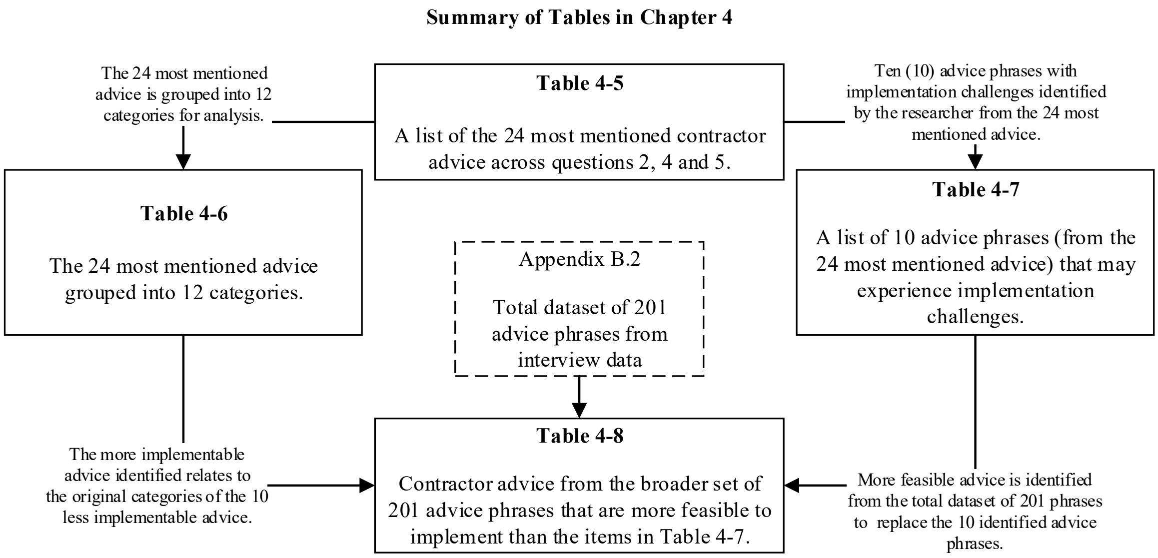


Figure 4-1: Flow diagram of subsequent tables in this chapter and how they relate

Table 4-5 lists the 24 most frequently mentioned advice phrases given by construction experts. Column 3 shows which question and aspect the advice was derived from, column 4 shows how many participants mentioned the advice and column 5 shows the number or letter of the constructability concept (CC) that relates to the advice. The numbers (1 to 23) relate to the 23 constructability concepts from the literature (Table 2-2, Table 2-3 and Table 2-4) and the letters (A to H) relate to the eight additionally defined constructability concepts (Table 4-9). The eight additional constructability concepts are discussed in Section 4.3.3.

The constructability principles (CPs), discussed in Chapter 2, are not included in this allocation because they serve as fundamental guidelines, whereas the constructability concepts (CCs) can address specific project challenges. Therefore, the constructability concepts are more suitable to allocate to the targeted contractor advice.

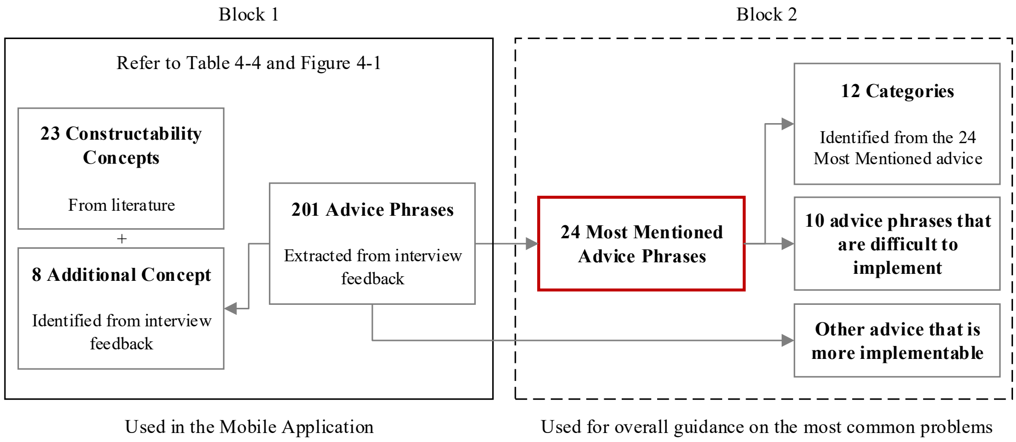


Figure 4-2: Diagram showing the process of the tables and what the information in each is used for.

The information in Block 1 from Figure 4-2 is used in the mobile application, whereas the information in Block 2 provides the most common problems identified from the interview feedback and offers guidance outside of the mobile application for design engineers to consider. Figure 4-2 shows where Table 4-5, which is discussed next, is situated in the process.

Table 4-5: The 24 most mentioned contractor advice phrases derived from questions 2, 4 and 5.

	The 24 most mentioned contractor advice phrases	**Question and Aspect**	**Number of mentions**	**CCs**
Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**
1	Have adequate site visits before design to optimally design for the specific site conditions	Question 2	10	7
2	Consider the practicality of the structure and/or finishes	Question 2	9	D
3	Ensure that proper communication and engagement occur to obtain all the necessary information that may influence the design	Question 2	8	B
4	Ensure that materials/products/technology are available in the country	Question 4, Aspect 1	8	C
5	Gain local advice from suppliers about the availability of resources	Question 5, Aspect 1	8	B
6	Do research about the resources that are best suited for the site circumstances	Question 5, Aspect 1	8	C
7	Collaborate with the contractor and discuss the design	Question 5, Aspect 2	8	B
8	Think about the sequence of events, practicality and construction methodology while designing	Question 5, Aspect 2	7	8
9	Have adequate site visits before design, as well as during construction to better understand the construction process	Question 4, Aspect 2	6	C
10	Ensure that there are no clashes between MEP services, underground water services and design elements	Question 4, Aspect 2	6	B
11	Get construction experience and go to the site more often to better understand the construction process	Question 5, Aspect 2	6	A
12	Get advice, provide suggestions and collaborate with contractors as early as possible	Question 5, Aspect 3	6	B
13	Consider the sequence of works and construction methodology during the design	Question 2	5	8
14	Consider the use of 3D modelling software and clash detection software	Question 2	5	F
15	Consider the sequence of events and construction methodology while designing	Question 4, Aspect 2	5	8
16	Learn how your design influences construction by following up during construction and soundboarding experienced individuals	Question 5, Aspect 2	5	A
17	Ensure that the specified machinery and heavy vehicles can reach the required positions on-site and operate safely	Question 4, Aspect 3	5	18
18	Consider the construction methodology and ensure that it is reasonable and practical	Question 4, Aspect 3	5	6
19	Optimize your design and avoid overdesigning structural elements	Question 4, Aspect 4	5	10
20	Consider the simplest and most cost-effective construction methodologies	Question 4, Aspect 4	5	6
21	Get mentorship and request reviews of your work	Question 5, Aspect 4	5	A
22	Get experience and exposure by spending more time on-site	Question 5, Aspect 4	5	A
23	Ensure that there is adequate space to safely construct scaffolding, provide railings and fasten harnesses	Question 4, Aspect 7	5	18
24	Identify hazards within your design and understand how your design influences safety	Question 5, Aspect 7	5	G

*CCs – Constructability concepts

Five of the advice phrases in the 24 most mentioned list were derived from question 2 feedback. This feedback was gained before introducing the participants to the seven constructability aspects (Table 3-3). The derived advice from the question 2 feedback is, therefore, notable because the participants mentioned items that are directly associated with constructability without having been introduced to it, namely, site visits for optimal design, practicality, communication and engagement, sequence of works, construction methodology and the use of 3D software and clash detection. This supports research by Othman (2011) that industry participants in South Africa are aware of constructability concepts and challenges.

Interestingly, although participants answered the questions with specific aspects in mind, the resultant contractor advice phrases include integrated concepts that are more general than expected. For instance, construction methodologies (related to primary construction methods) are mentioned in rows 18 and 20 in Table 4-5, which were derived from the aspects of site accessibility and spatial requirements and the creation of simple and rational designs, respectively. This observation implies that much of the advice provided by participants consists of general recommendations applicable in a broader context rather than exclusively to specific aspects. It also implies that many of the constructability aspects are related to one another and cannot be addressed separately. For example, Participant 5 mentioned that “you improve construction safety by first analysing the sequence of works and construction methods”.

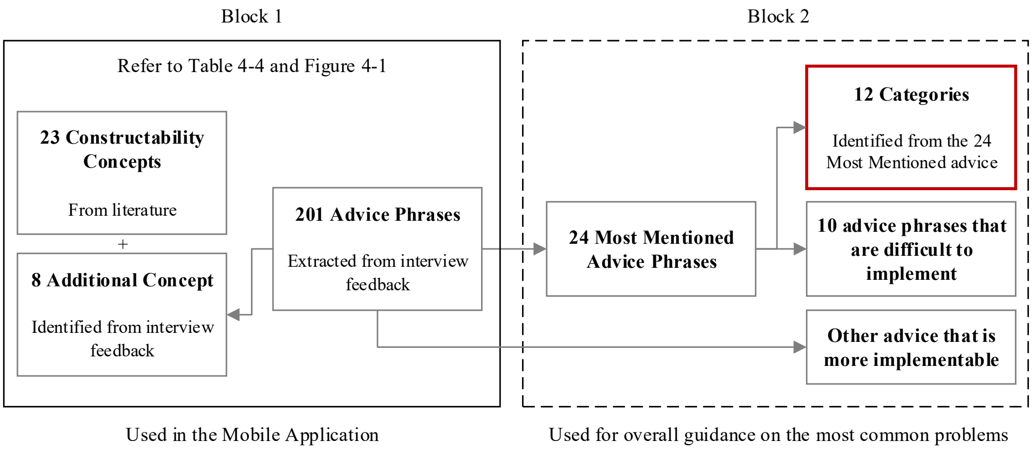
The eight additionally defined constructability concepts, which are discussed in Section 4.3.3, further support this notion, as they demonstrate a highly general and globally applicable nature. These concepts almost reflect “designer values” desired by contractors.

Advice derived from primary construction methods (aspect 2) occurs seven times in Table 4-5. Although primary construction methods are ranked less critically on average, than site accessibility and spatial requirements, low consideration of primary construction methods seems to be a more common problem experienced by the specialists. Participant 2 stated that “the basics are not followed by designers anymore”. He further emphasises that designers will have a better idea of the construction methods that are required and that are possible if they visit the site before design.

No advice feedback derived from aspect 5 and aspect 6 are on the list of the most frequently mentioned items. This is mainly because aspect 5 and 6 were the least critically ranked items and question 4 and question 5 were omitted if a favourable ranking was provided by the interviewee in question 3.

Overall, the analysis of contractor advice reveals the convergence of ideas and concepts across different constructability aspects. Participants’ recommendations transcend specific aspects, suggesting a more holistic perspective on design practices by the participants. The full collection of 201 contractor advice phrases is presented in Appendix B.2.

The 24 most frequently mentioned advice phrases from Table 4-5 can be categorized into distinct groups to facilitate analysis of the advice provided by different types of participants. It is important to note that these groupings are relatively broad and are not assigned with the aim of direct comparison. They aim to present the most common problems. The 12 categories, along with the respective advice phrases, are listed in Table 4-6.



***Repeat of Figure 4-2**

Table 4-6: The 24 most mentioned advice phrases grouped into 12 categories

	12 Categories		**The 24 contractor advice phrases from Table 4-4 are grouped into categories 1 to 12**
1	Catering to specific site conditions or circumstances	1	Have adequate site visits before design to optimally design for the specific site conditions
		6	Do research about the resources that are best suited for the site circumstances
2	The practicality of design and methodologies	2	Consider the practicality of the structure and/or finishes
		18	Consider the construction methodology and ensure that it is reasonable and practical
3	Communication to gather important information	3	Ensure that proper communication and engagement occur to obtain all the necessary information that may influence the design
		5	Gain local advice from suppliers about the availability of resources
4	Availability of materials locally	4	Ensure that materials/products/technology are available in the country
5	Contractor collaboration	7	Collaborate with the contractor and discuss the design
		12	Get advice, provide suggestions and collaborate with contractors as early as possible
6	Consideration of sequence and construction methodology during the design	8	Think about the sequence of events, practicality and construction methodology while designing
		13	Consider the sequence of works and construction methodology during the design
		15	Consider the sequence of events and construction methodology while designing
7	Understanding the construction process	9	Have adequate site visits before design, as well as during construction to better understand the construction process

12 Categories		The 24 contractor advice phrases from Table 4-4 are grouped into categories 1 to 12	
		11	Get construction experience and go to the site more often to better understand the construction process
8	Clash detection	10	Ensure that there are no clashes between MEP services, underground water services and design elements
		14	Consider the use of 3D modelling software and clash detection software
9	Learning and improvement through mentorship and exposure	16	Learn how your design influences construction by following up during construction and soundboarding experienced individuals
		21	Get mentorship and request reviews of your work
		22	Get experience and exposure by spending more time on-site
10	Elements influencing safety	17	Ensure that the specified machinery and heavy vehicles can reach the required positions on-site and operate safely
		23	Ensure that there is adequate space to safely construct scaffolding, provide railings and fasten harnesses
		24	Identify hazards within your design and understand how your design influences safety
11	Design optimization	19	Optimize your design and avoid overdesigning structural elements
12	Cost-effective methodologies	20	Consider the simplest and most cost-effective construction methodologies

The 12 categories represent the most common areas of construction challenges that design engineers can consider to create construction-sensitive designs.

Categories 1, 7 and 9 in Table 4-6 were mentioned by an equal number of participants in executive and/or leadership roles and project and/or construction management roles. This suggests a shared recognition of their significance across different positions in the construction industry. These categories address fundamental aspects that are important for the successful delivery of projects. Executive and/or leadership participants, although not active on-site, recognize the importance of understanding site-specific challenges. Similarly, project and/or construction management participants, although mainly focused on the project site activities and execution, understand the value of ongoing learning, mentorship and exposure to enhance their expertise.

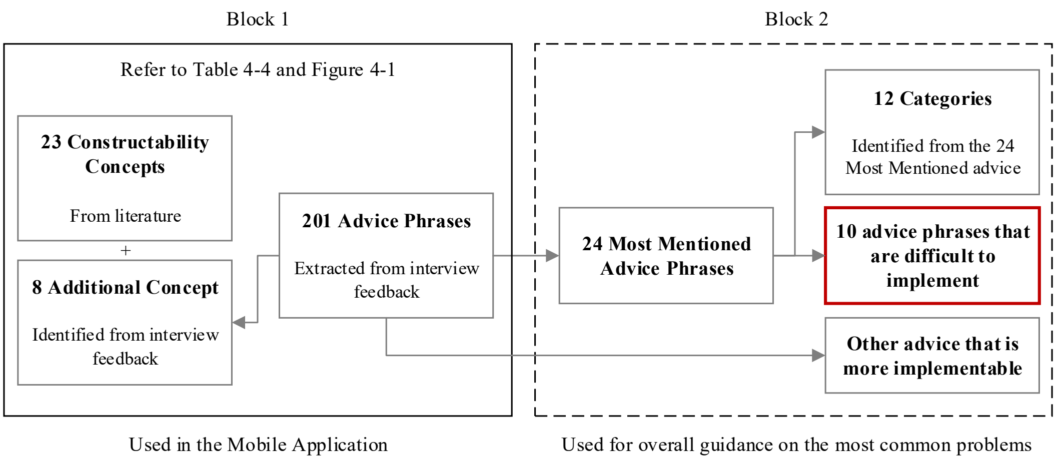
Categories 2, 3, 6, 8, 10 and 12 in Table 4-6 were predominantly mentioned by participants in project and/or construction management positions. This can be attributed to the nature of their responsibilities. Project and construction managers are actively involved in the implementation and execution of projects. Their daily tasks involve overseeing design and construction processes, ensuring practicality, coordinating communication, dealing with problems and optimizing cost-effective methodologies. Their experience and daily focus cause them to mention advice related to their direct scope of work.

On the other hand, executive and/or leadership roles typically have a broader focus on strategic planning, policy-making, decision-making and organizational management, which may explain the predominant mentions of categories 4, 5 and 11 by executive and/or leadership participants. Executive and/or leadership roles have a macro-level perspective and are responsible for ensuring efficient operations and optimizing project outcomes. Categories 4, 5 and 11 align with the strategic roles that are concerned with achieving the organizational goals.

In Appendix B.4, 12 tables are presented, showing the characteristics of the participants that mentioned advice in each of the 12 categories listed in Table 4-6.

Although the 24 items were the most frequently mentioned and most likely indicate common problems, they do not necessarily represent easily implementable advice or the most valuable recommendations from the larger set of 201 advice phrases.

Table 4-7 specifically highlights 10 items from the 24 most frequently mentioned advice that present implementation challenges or require careful consideration because they are directly related to 1) insufficient construction experience by designers, 2) insufficient time and knowledge and 3) limitations of the design-bid-build project model.



***Repeat of Figure 4-2**

Table 4-7: Most mentioned advice phrases that are difficult to implement

	Items that may have implementation challenges	Reason
1	Consider the practicality of the structure and/or finishes	Insufficient construction experience
2	Do research about the resources that are best suited for the site circumstances	Insufficient time and knowledge
3	Collaborate with the contractor and discuss the design	Limitations of the design-bid-build project model
4	Think about the sequence of events, practicality and construction methodology while designing	Insufficient construction experience
5	Get advice, provide suggestions and collaborate with contractors as early as possible	Limitations of the design-bid-build project model
6	Consider the sequence of works and construction methodology during the design	Insufficient construction experience
7	Consider the sequence of events and construction methodology while designing	Insufficient construction experience
8	Consider the construction methodology and ensure that it is reasonable and practical	Insufficient construction experience
9	Consider the simplest and most cost-effective construction methodologies	Insufficient construction experience
10	Identify hazards within your design and understand how your design influences safety	Insufficient construction experience

The items in Table 4-7 are identified based on participant insights, and their comments regarding the feasibility of implementation, as well as research by Eldin (1999) and Jadidoleslami, et al. (2018).

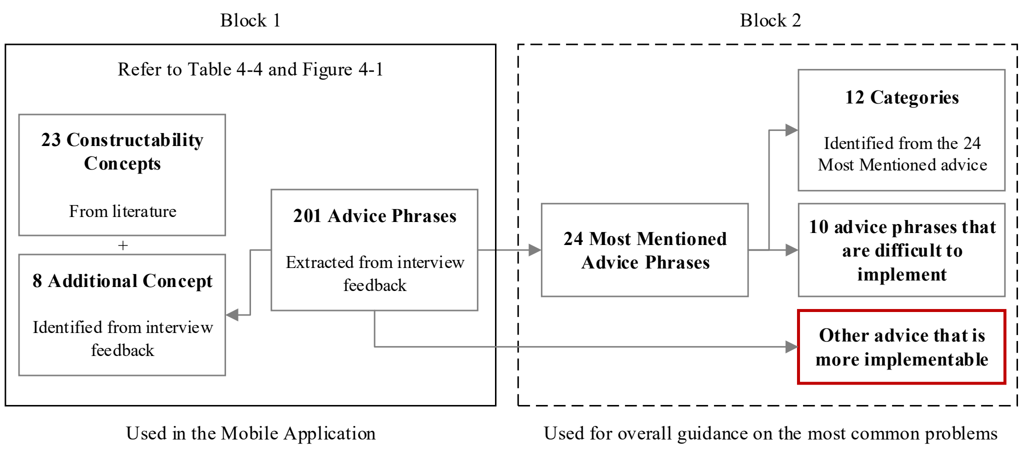
The primary implementation challenge for the 10 items is the lack of knowledge and experience in construction processes among design engineers to effectively address these requests (Eldin, 1999). Participants emphasized that identifying hazards, understanding construction processes and making decisions about resources and construction methodologies require practical experience and firsthand exposure to construction site challenges. Very little, except to address these reasons directly, could overcome these challenges in practice.

For instance, Participant 1 indicated that "being able to identify hazards comes with experience and understanding of construction processes". Participant 19 indicated that "architects and engineers would have to experience these problems first-hand to fully understand them". Jadidoleslami, et al. (2018) argue that design engineers may struggle to determine the best resources for specific site circumstances or to consider the most cost-effective construction methodologies without a comprehensive understanding of these factors. Collaboration with contractors during the design phase is also deemed a challenge due to the limitations of the design-bid-build project model. The 10 items in Table 4-7 that pose implementation challenges belong in the following categories from Table 4-6:

- Category 2: The practicality of design and methodologies
- Category 5: Contractor collaboration
- Category 6: Consideration of sequence and construction methodology during the design
- Category 10: Elements influencing safety
- Category 12: Cost-effective methodologies

Table 4-8 provides participant advice from the larger set of contractor advice data that is more feasible to implement and more practical for designers to consider. To maintain the context of the most mentioned advice, the more implementable advice identified from the broader set of 201 items must correspond with categories 2, 5, 6, 10 or 12.

By focusing on the advice phrases that are both valuable and feasible for implementation, design engineers can prioritize constructive actions that have the potential to improve constructability more consistently. If the items in Table 4-8 are considered by design engineers, they would be able to play a more active role in incorporating constructability concepts into the design phase.



***Repeat of Figure 4-2**

Table 4-8: Contractor advice from the 201 advice phrases that are more feasible to implement, specifically for categories 2, 5, 6, 10 and 12.

More implementable advice phrases from the broader set of data	The categories that they relate to
▪ Ensure that tolerances and specifications are reasonable and practical ▪ While thinking of the end product, consider the specialist skills that are required to obtain the end product	Category 2
▪ Soundboard ideas with more experienced seniors/individuals ▪ Learn from previous projects and similar designs ▪ Make a checklist for yourself containing everything that has to move on and off-site ▪ Ensure a continuous learning process during the entire project	Category 5
▪ Take accountability for the degree to which your design is construction-sensitive ▪ When methodologies are complex, ensure that potential problems are investigated and that the best solutions are found ▪ If normal concrete pouring would cause a complex start-stop methodology, consider prefabrication	Category 6
▪ Analyse whether bolting or welding is the better option regarding access and safety ▪ Take accountability for safety and research previous similarly complex projects to obtain the safest solutions ▪ Provide the contractor with as much detail as possible to allow him to mitigate hazards and add the required items to the bill of quantities	Category 10
▪ Approach design with a planning point of view ▪ Spend more time on planning, researching and defining the scope	Category 12

In contrast to the less implementable advice phrases in Table 4-7, the advice phrases in Table 4-8 are more practical for design engineers, as they can be incorporated into the design process with relative ease. The items in Table 4-8 demonstrate a shift towards more actionable recommendations for design engineers without merging the expected roles of contractors and designers. They highlight practicality, collaboration, communication, research, proper planning, proactive thinking and taking accountability for constructible designs.

However, is it too great an expectation of civil design engineers to consider construction-related challenges during design? According to Frederick Merritt in the Standard Handbook for Civil Engineers (2004), "Civil Engineering is that field of engineering concerned with planning, design and construction". Design engineers are highly skilled problem solvers, trained to address complex design challenges that relate to all aspects of a construction project. Therefore, it is worth exploring whether the design engineer's role has evolved to a more specific and limited design scope or whether they do not consider construction feasibility because they face limitations and time constraints.

4.3.2 Considerations from literature about the role of design engineers

This discussion aims to foster a better understanding of the role of design engineers in integrating constructability considerations into their design processes while acknowledging the complexities and constraints they may encounter. The following list presents the roles of civil design engineers as discussed by several researchers.

- Khurmi & Gupta (2017) argue that design engineers are responsible for developing design solutions that meet project requirements, and consider factors such as functionality, safety, aesthetics, and constructability.
- Nunnally (2001) states that design engineers should ensure that the proposed solutions are practical and cost-effective. He further states that design engineers should work closely with the contractor during construction to resolve design-related issues and facilitate smooth execution.
- Design engineers should choose appropriate materials by considering availability and cost (Pekelnicky & Rosen, 2021).
- Fewings and Henjewele (2019) argue that design engineers should collaborate closely with architects and other stakeholders to ensure a cohesive and coordinated approach.
- Designers should contribute to cost estimation by providing inputs about the resources required for construction, helping to establish accurate project budgets (Oloke & Okunade, 2019).
- Ching (2014) mentions that designers should prepare detailed information to guide contractors during the construction phase.

The roles of a civil design engineer may differ depending on the size, complexity and contractual arrangements of a project. However, the interview participants provided advice to design engineers about actions and considerations that should be attended to by designers according to the literature, namely:

- Functionality and safety
- Practicality and cost-effective solutions
- Collaboration with the contractor
- Adjusting designs if necessary
- Choosing readily available materials
- Collaboration with architects
- Providing enough detail to ensure accurate project budgets

Although these responsibilities seem to be clearly defined in a civil engineer's scope of work, the participants of the study have, in their experience, found that these roles are not executed by all designers. For example, one of the advice phrases extracted from the feedback is "Optimise your design and avoid overdesigning structural elements". This observation suggests a disconnect between the expected role of design engineers and their actual roles in practice.

Several factors could contribute to this situation. Design engineers may face constraints or challenges that prevent them from fully carrying out their roles, such as time pressure or competing priorities. Designers may face challenges in keeping up with industry advancements. Additionally, they may encounter difficulties in integrating functionality, safety, practicality and cost-effectiveness into their designs due to the complexity of balancing these factors. These challenges cement the importance of collaboration between design engineers and contractors to achieve optimal designs. Promoting a culture of multidisciplinary teamwork, when possible, in a design-bid-build project can enable the integration of expert knowledge and a broader consideration of constructability concepts. Participant 2 advises to "use the network of people around you". The recognised 23 constructability concepts by Kifokeris & Xendis (2017) do not provide an adequate framework for a multidisciplinary culture in design-bid-build projects. The eight additionally identified concepts aim to address this gap.

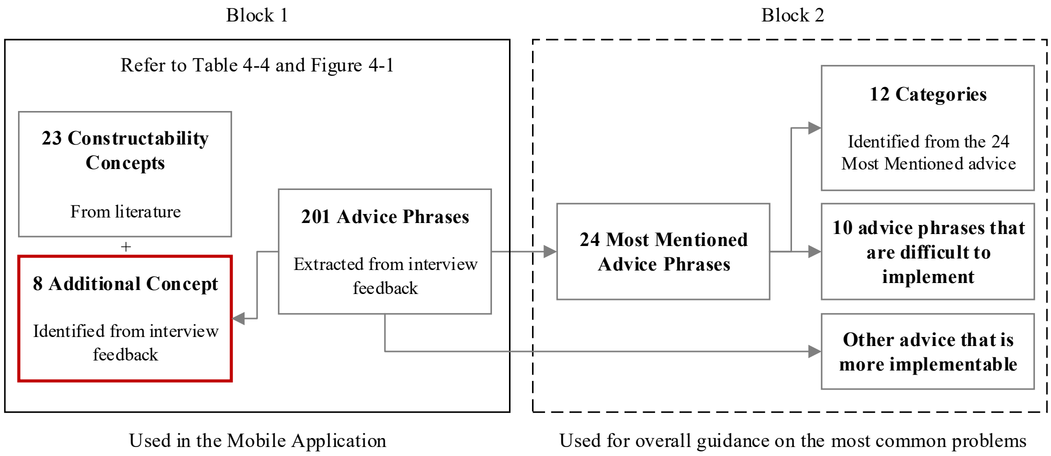
4.3.3 Eight additionally defined constructability concepts

It is noteworthy that out of the 24 items in Table 4-5, only 10 advice phrases align with the 23 constructability concepts by Kifokeris & Xendis (2017). The constructability concepts by Kifokeris & Xendis (2017) are presented in Table 2-2, Table 2-3 and Table 2-4. Specifically, constructability concepts 6, 7, 8, 10, 16 and 18 correspond with some of the most frequently mentioned advice phrases as shown in Table 4-5. These concepts are categorized into the initiation, execution and delivery phases of a construction project as presented by Kifokeris & Xendis (2017). Concepts 6 and 7 fall under the initiation phase, concepts 8 and 10 belong to the execution phase, while concepts 16 and 18 are associated with the delivery phase.

The interview participants were requested to provide suggestions that primarily focus on the design phase of a design-bid-build project. However, their responses relate to the execution and delivery phase as well. This could imply a significant expectation of design engineers to broaden their scope of responsibility and considerations. It could also signify that the current constructability concept framework is not suitable to account for the considerations necessary from design engineers in design-bid-build projects.

Out of the total 201 advice phrases offered by the participants, 100 phrases did not align with the 23 constructability concepts. These 100 phrases were allocated to eight additional constructability concepts, labelled A to H. For example, the advice phrase, "Ensure a continuous learning process during the entire project" is more suitable to the new constructability concept, labelled A: Mentorship and supervision, than any of the 23 constructability concepts by Kifokeris & Xendis (2017).

Table 4-9 provides the definitions of the newly introduced constructability concepts. The advice phrases categorized into each of the additionally created constructability concepts are presented in Appendix D.



***Repeat of Figure 4-2**

Table 4-9: Eight additional constructability concepts to better represent the 100 advice phrases

Label	Eight additional constructability concept definitions	Number of advice phrases allocated
A	**Mentorship and supervision** Mentorship and supervision by more senior engineers or individuals should be encouraged for all levels of experience, as well as continuous learning about the impact that your design has on construction.	15
B	**Communication and collaboration:** Effective and continuous communication, interaction and collaboration with all project participants should be prioritized.	23
C	**Continuous learning** Continuous research, gaining of new information and enthusiastic learning about all aspects of construction should be encouraged for all levels of experience.	19
D	**Practical design decisions** Careful consideration of the practicality of design decisions in terms of their impact on construction activities.	9
E	**Clarity about scope and specification** Clarity about the scope and specifications should be ensured to enable efficient and optimal planning.	8
F	**Design and software** Design-specific details should be carefully considered through the use of appropriate software solutions.	15
G	**Safety** The safety of construction staff should be prioritized and the identified safety hazards should be addressed during design.	10
H	**Continuous monitoring** For lengthy construction projects, the changes to site conditions should be monitored as construction advances.	1
Total		**100**

The introduction of these new constructability concepts reflects the participants' valuable input, indicating the need to expand the existing constructability framework to include additional dimensions that were not previously addressed. These new concepts capture important aspects and contribute to a more holistic understanding of constructability considerations from the perspective of construction specialists. These new constructability concepts reflect the "designer values" that contractors believe would improve construction feasibility and efficiency.

The new constructability concept B, which emphasizes communication and collaboration, received the highest allocation of advice phrases, with 23 advice phrases. This highlights the participants' strong emphasis on the value of effective communication, interaction and collaboration among project participants. It signifies their belief that close collaboration fosters better constructability outcomes. Kuo & Wium (2014), in their research, found that contractors are more actively involved in collaboration with stakeholders during project close-out meetings, whereas partaking in close-out meetings by consultants is insubstantial. Close-out meetings are often attended by project managers, site managers, directors and quantity surveyors, while the design engineers miss out on valuable collaborative engagement with various project stakeholders (Kuo & Wium, 2014). The advice feedback from interview participants indicated that the trend of limited collaboration by consultants, as identified by Kuo & Wium (2014) in close-out meetings, occurs in other project phases as well.

Furthermore, new constructability concept A, focusing on mentorship and supervision, received 15 advice phrases. For example, "If you are unsure about construction methods, talk to your more experienced colleagues". The 15 advice phrases reflect the participant's recognition of the importance of mentorship, continuous development and guidance from more experienced professionals. They acknowledge the significance of understanding the impact of their design decisions on construction and of support and guidance to improve knowledge and skills.

Constructability concepts C (continuous learning) and F (design and software) have 19 and 15 allocated advice phrases, respectively. An advice phrase categorized under concept C, for example, is "Gain knowledge on the standard dimension of scaffolding, formwork, pipes, windows, doors and bricks". An advice phrase categorized under concept F, for example, is "Ensure that all services and design element dimensions are correctly indicated in the drawings". This indicates the participants' emphasis on the importance of ongoing learning, research and the use of appropriate software tools to optimize design decisions and enhance constructability.

In design-bid-build projects, contractors compete through a tender. The winning bid is selected partly on the grounds of cost, experience and technical competence (CIDB, 2021). Innovative methods to reduce cost, the ability to keep up with new technologies that save time during construction, and the availability of equipment and experience are all used by contractors to gain a competitive advantage and win tenders. It is, therefore, understandable that early contractor involvement in design-bid-build projects is difficult to achieve because contractors would be wary of losing a competitive edge by sharing their knowledge and insights before contract award. The procurement rules also limit engagement between design engineers and contractors before and during the bid preparation period. Moreover, it is understandable that construction specialists emphasize mentorship, continuous learning and innovative software because these concepts are the cornerstone of their competitive edge.

Design engineers, on the other hand, are often selected through a qualifications-based selection with cost not being the primary determinant of the selection and negotiations on cost being possible at a later stage (CIDB, 2021). Designers may, therefore, not prioritise mentorship, learning and innovation in the same way as contractors.

4.4 Question 6 results: Opinions on a collaborative forum

This section focuses on the findings of question 6, which aimed to gather participants' opinions on a collaborative forum involving young design engineers and experienced construction specialists (Appendix A.1).

The construction industry is widely acknowledged for its fragmented nature, posing challenges to effective collaboration between the design and construction phases. In complex projects with multiple stakeholders, teamwork and collaboration are essential for success. However, traditional procurement approaches often lack a strong emphasis on collaboration, despite the well-known benefits. Negative incentives that prioritize error avoidance rather than rewarding successful teamwork, communication and collaboration are prevalent. This is particularly true in traditional contract and procurement methods, where financial risk takes precedence over value engineering and collaboration, even though these factors are essential for project success (O'Connor, 2009).

Participant 8 astutely highlighted the prevailing "them" versus "us" mindset in the industry, emphasizing the urgent need for greater respect, support and collaboration.

A collaborative forum has the potential to deepen the understanding of challenges faced by design and construction parties. Participant 10 emphasised that designers and architects must experience these challenges first-hand to truly comprehend them. Similarly, contractors must understand the designer's circumstances, which necessitates close collaboration with the architect and client, concurrent involvement in other projects and the ability to navigate external barriers that prevent effective decision-making.

Table 4-10 provides an overview of the 16 result clusters derived from question 6 responses, shedding light on participants' perspectives on a collaborative forum.

Table 4-10: Question 6 collection of results

	Question 6 Opinions on a collaborative forum between young design engineers and retired construction specialists	
	Collection of repeated answers	**Number of mentions**
1	Good idea / support the idea / it would be beneficial to the industry	16
2	Informal and more general implementation would be better	3
3	Internal use within the project or company would be best	6
4	Such a collaborative forum will remove the “authoritative “or “hierarchy “relationship	2
5	There will be many challenges for such a collaborative forum (e.g., willing involvement and the industry culture)	3
6	It depends on the implementation of the forum	4
7	A “frequently asked questions” section would be ideal for an easier search	2
8	The interviewee would be willing to participate	7
9	Such a collaborative forum has to be driven by the learner or mentee	1
10	Such a collaborative forum should be implemented by the engineering councils and they should motivate the use of it for continuous professional development	2
11	Design engineers will be able to use the forum as a “soundboarding” platform	1
12	Not all professionals want to remain involved in the industry after retirement	1
13	The culture of the industry will have an impact on the usage of such a forum	2
14	The younger generation may use such a forum more willingly	2
15	Include subcontractors, foremen and artisans in this forum	1
16	This would help design engineers to be less likely to design in isolation	1

The participants expressed a unanimous agreement regarding the benefits of implementing a collaborative forum in the construction industry. Participant 1 stated that “it would be helpful to young designers that lessons be taught on construction problems, what causes delays and what makes construction more effective.” Participant 16 mentioned: “I have been thinking about this for years. It would be an invaluable tool to bring to the industry”. However, they also identified specific conditions that should be considered for such a forum’s success.

Firstly, several participants emphasized the preference for an informal or more generalized implementation of a collaborative forum. They highlighted the potential risks of sharing detailed project-specific information with external parties, which could compromise confidentiality and prevent the contractor’s ability to protect intellectual property within their organization.

Secondly, participants suggested that the collaborative forum should primarily be utilized internally within a project team or company. This internal implementation would facilitate the transparent sharing of ideas, lessons learned and challenges encountered, thereby enhancing communication and knowledge exchange among team members.

Thirdly, it should be noted that such collaboration may experience significant challenges. These should be understood and acknowledged and strategies developed to deal with them.

The willingness of all participants to actively engage and cultivate a collaborative culture within the industry is identified as a significant challenge. All stakeholders must have a genuine desire to learn from one another. Participant 7 mentioned that "the learning process has to be driven by the person that wants to learn. Unfortunately, design engineers do not seem to deem learning from the contractor as valuable". Overcoming the prevailing adversarial relationships and fragmented culture within the industry will undoubtedly pose a considerable challenge in establishing an effective collaborative forum. Other challenges include removing the authoritative hierarchy between participants, adapting the industry culture, the forum to be driven by the learner and not the mentor and the lack of respect that different participants have for one another's specialisations.

Some opportunities to consider are that the engineering councils can drive collaborative forums as continuous professional development, the younger generation is more inclined to gravitate towards new technology and online communication platforms and the potential of including a wider audience such as subcontractors, artisans and foremen.

By considering the participants' suggestions and tailoring the implementation to align with industry culture, such a forum can serve as a platform for fostering collaboration, knowledge sharing and a deeper understanding of the challenges faced by different parties.

4.5 Summary of results

This chapter presents an analysis of the findings from interview responses to questions related to constructability considerations and collaboration in design-bid-build projects.

The findings reveal that the most critically ranked aspects are site accessibility and spatial requirements (aspect 3), availability of resources (aspect 1), primary construction methods (aspect 2) and site safety (aspect 7). To consider these aspects, designers require an in-depth understanding of the construction processes and hazards.

Executive and/or leadership interview participants ranked all seven aspects more critically, on average than the project and/or construction management participants. This may be because of their focus on financial implications, whereas project and/or construction management participants may be more partial to the challenges faced by design engineers.

The 24 most frequently mentioned advice (found in Table 4-5) is presented in this chapter, of which the five most mentioned are 1) have adequate site visits before design to optimally design for the specific site conditions, 2) consider the practicality of the structure and/or finishes, 3) ensure that proper communication and engagement occur to obtain all the necessary information that may influence the design, 4) ensure that materials/products/technology are available in the country and 5) gain local advice from suppliers about the availability of resources.

The most mentioned advice that relates to practicality, communication and cost-effective methodologies was mentioned mostly by project and/or construction management participants, likely because these relate to their daily tasks. The advice relating to the availability of materials, contractor collaboration and design optimization was mentioned mostly by executive and/or leadership participants, likely because of their focus on strategic planning and decision-making.

Ten of the 24 most frequently mentioned advice were identified to have implementation challenges relating to inadequate knowledge about construction processes, limited design time and limitations to early contractor involvement in design-bid-build projects. More practical advice, falling into the same context as the less feasible advice, include:

- Learn from previous projects and similar designs
- Make a checklist for yourself containing everything that has to move on and off-site
- Ensure a continuous learning process during the entire project
- Provide the contractor with as much detail as possible to allow him to mitigate hazards and add the required items to the bill of quantities.

Furthermore, the 201 advice phrases were each allocated a constructability concept, but the recognized 23 constructability concepts by Kifokeris and Xendis (2017) do not adequately suit 100 of the 201 advice phrases. Eight additional constructability concepts were, therefore, identified to address the gap and to provide a better framework for a multidisciplinary culture in design-bid-build projects. The eight additional constructability concepts are presented in Table 4-9.

Furthermore, the participants expressed a consensus on the benefits of implementing a collaborative forum between design engineers and experienced construction specialists. They emphasized the need for enhanced collaboration, deeper comprehension of challenges faced by both parties and the establishment of a collaborative culture within the industry. Specific conditions for the success of such a forum were identified, including the preference for an informal implementation and internal use within projects or companies to protect intellectual property.

The findings provide a valuable foundation for developing strategies and tools to enhance constructability and promote collaboration between designers and contractors.

It was found that increased collaboration and understanding between designers and construction specialists is of utmost importance. Although design engineers are mostly under pressure, have concurrent projects, are pressed for time and concentrate on their design role only, they should consider construction constraints for the benefit of the project and all the stakeholders.

Designers should be required to do continuous research, engage in conferences and adopt innovative methodologies. These actions mirror the proactive approach demonstrated by contractors to gain a competitive edge. Designers should stay the course, engage with contractors as soon as possible, go to the site more often, learn from the project and participate in close-out meetings.

Chapter 5: Constructability-centred collaboration during the mobilization phase

5.1 Chapter overview

This chapter addresses constructability in design-bid-build projects, emphasizing the significance of designer consideration of construction constraints and intentional collaboration between designers and contractors during the mobilization phase. While the mobilization phase is typically associated with furnishing the construction site with essential resources, this chapter explores its potential for enhancing project outcomes through collaborative efforts. The proposed approach, inspired by Integrated Project Delivery (IPD) principles and stakeholder feedback, aims to shed light on how intentional collaboration can drive constructability and cost-effectiveness.

The chapter begins by explaining how the constructability concepts (found in Table 2-2, Table 2-3, Table 2-4 and Table 4-9) were allocated to 11 design-bid-build phases. Next, practical implementation methods for project managers, contractors and designers are explored to foster a culture of engagement and effective communication during the mobilization phase. Drawing on the insights from validation interviews with key industry participants, the chapter finally unveils valuable perspectives of interview participants on the feasibility of the proposed approach, along with the potential challenges and responsibilities faced in driving collaboration.

5.2 Allocation of constructability concepts to design-bid-build phases

The 23 constructability concepts by Kifokeris & Xendis (2017) (found in Table 2-2, Table 2-3 and Table 2-4) are categorized into three phases: initiation, execution and delivery. The activities in these phases, as discussed in Section 2.2.3, are more suited to design-build projects and would be challenging to relate to design-bid-build, mainly because of the emphasis on early contractor involvement in the initiation phase. Dykstra (2018) presents a framework consisting of 11 design-bid-build phases, according to which the 23 constructability concepts and the eight additionally defined constructability concepts can be appropriately allocated. Figure 5-1 shows the allocation process for the advice phrases and the constructability concepts. The descriptions of the 11 design-bid-build phases are presented in Appendix C.

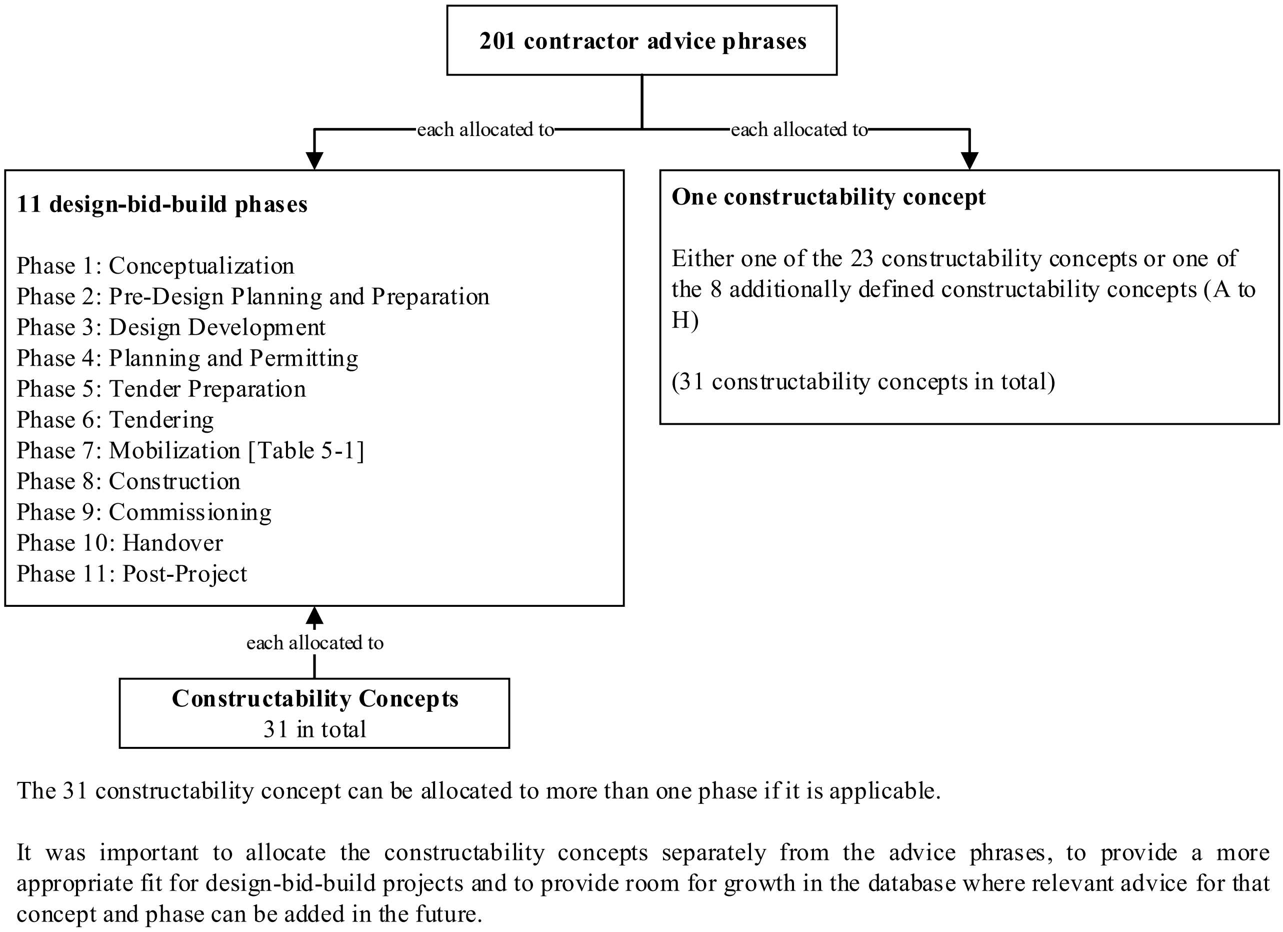


Figure 5-1: The allocation of advice phrases and constructability concepts to the 11 design-bid-build phases

The 23 constructability concepts by Kifokeris & Xendis (2017), listed in Table 2-2, Table 2-3 and Table 2-4, as well as the eight additionally defined concepts, listed in Table 4-9, were each allocated to the 11 design-bid-build phases based on their feasibility and relevance to the phase. In instances where a concept could be relevant in several phases or addressed by different project participants at different stages, it was assigned to those phases as well. For example, for constructability concept 9, *the cooperation of all specialists should be facilitated through advanced information technologies, thus overcoming the fragmentation of specialized roles during the project lifecycle,* remains relevant throughout the entire project lifecycle and was, therefore, allocated to all phases.

Each of the 201 contractor advice phrases, however, was exclusively assigned to the most relevant phase to avoid repeating advice to the designer in the constructability tool application.

Phase 7, the mobilization phase, emerged as the recipient of 14 contractor advice phrases, predominantly focusing on pre-construction collaboration between the design engineer and the contractor. Table 5-1 shows the 14 phrases that were allocated to the mobilization phase, along with their allocated constructability concepts. The specific allocations of design-bid-build phases and constructability concepts to each of the 201 contractor advice phrases are presented in Appendix B.2.

Table 5-1: Contractor advice phrases allocated to Phase 7 - Mobilization phase

	Phase 7: Mobilization Phase	
	Contractor advice phrases allocated to Phase 7	**The constructability concept allocated to the advice**
1	Consider that the placement of the parking area can be used for storage, offices and/or staff parking before paving commences	16
2	Consider innovative ways to ease the construction process	17
3	Consider areas in your design that would cause construction workers and other staff to have poor natural light while working	18
4	Consider the safety hazards of bushy sites and ensure that roads are cleared for construction vehicles to avoid the wheels getting clogged by grass	18
5	Prioritise value engineering and collaboration exercises before construction commencement	B
6	Attempt to involve the contractor as early on in the project as possible	B
7	Ask the contractor for advice on accessibility and spatial requirement decisions	B
8	Discuss complex methodologies with the project team and the contractor	B
9	Ask a contractor or subcontractor about their knowledge of available resources on the market	B
10	Set up a team for a pre-construction design meeting to discuss the construction methods	B
11	Collaborate with the contractor and discuss the design	B
12	Obtain advice, provide suggestions and collaborate with the contractor as early as possible	B
13	Gain advice from contractors and collaborate on the required changes to be made	B
14	Share the hazards identified with the entire project team and determine how to mitigate the safety risk	G

The 14 advice phrases in Table 5-1 underscore the importance of early collaboration and concerted efforts to ensure that the design is attuned to construction considerations. Section 5.3 further discusses the mobilization phase and explores potential adjustments that can be made to prioritize and enhance designer-contractor collaboration.

5.3 Designer-contractor collaboration during the mobilization phase

The mobilization phase, as described by Singh & Arora (2018), involves the preparatory stage where the contractor arranges essential resources for the construction site. The contractor, besides tendering, only becomes involved in the project in this phase. While many of the mobilization activities are managed by the construction manager and involve equipment deployment and site readiness, Singh & Arora (2018) present a more comprehensive perspective by elaborating on various activities. These activities are:

1	Project setup
2	Site preparation
3	Mobilizing resources
4	**Project scheduling**
5	Permits and approvals
6	Safety planning
7	**Contract coordination**
8	**Stakeholder engagement**
9	Procurement management
10	Pre-construction surveys

* **collaborative mobilization activities**

Most of these activities can and should be attended to by the contractor without a need for collaboration. However, project scheduling, contract coordination and stakeholder engagement are identified as inherently collaborative activities. Project scheduling necessitates close coordination with diverse stakeholders to establish key milestones and comprehensive timelines for construction activities (Sears, et al., 2008). Contract coordination involves resolving ambiguities and discrepancies while clarifying obligations, roles and responsibilities (Phillips, 1999). Stakeholder engagement requires active involvement and cooperation among clients, architects, engineers, contractors and the community to address concerns and ensure alignment among all parties involved (Richardson, 2015) (Singh & Arora, 2018).

The 14 advice phrases allocated to the mobilization phase (Table 5-1) indicate that designer-contractor collaboration is infrequent and rarely prioritised during the mobilization phase, in the experience of the participants. This stands in contrast to the definitions of project scheduling, contract coordination and stakeholder engagement as presented by Singh & Arora (2018). Figure 5-2 presents ten of the 14 advisory items allocated to the mobilization phase, showing the contrast with the three collaborative mobilization activities.

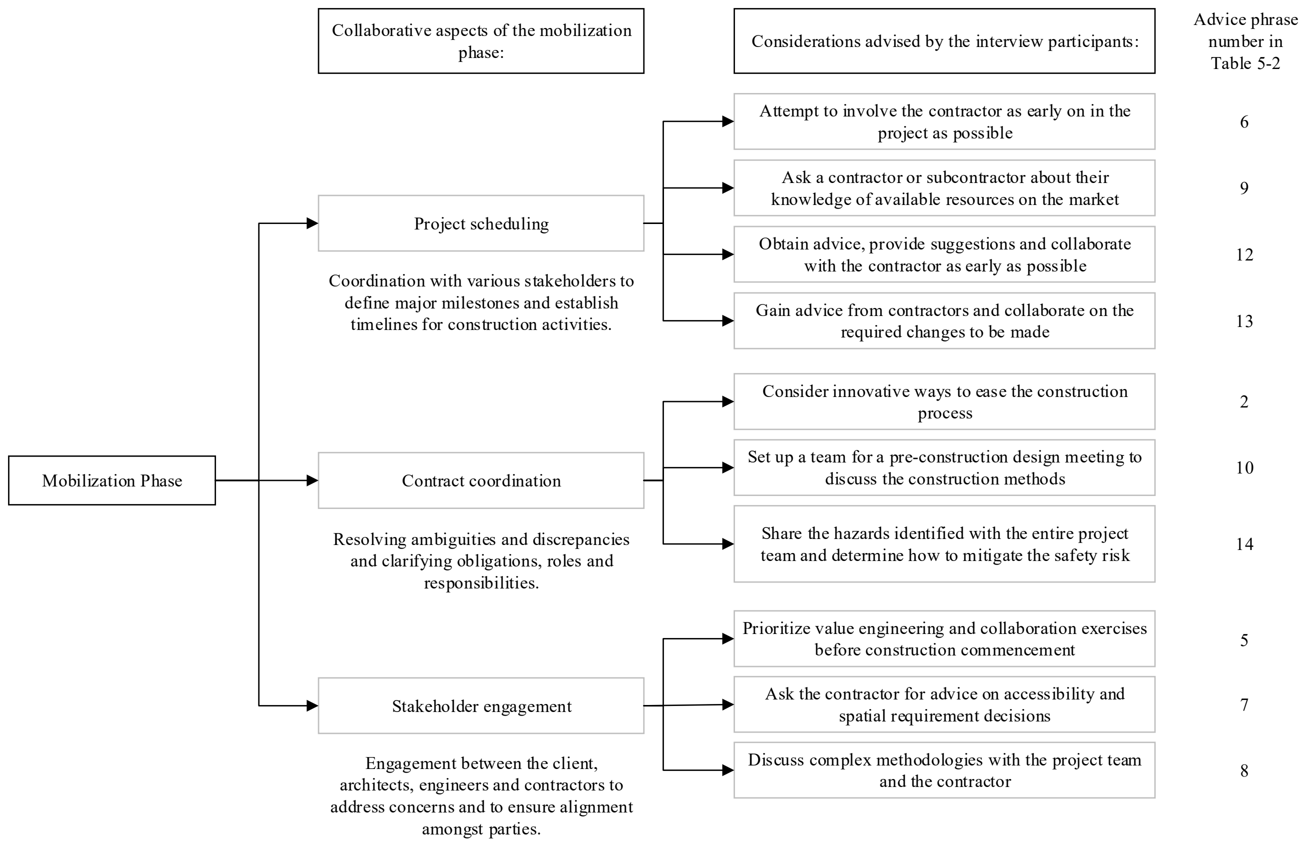


Figure 5-2: Collaborative mobilization activities versus the advice provided by interview participants

The three activities – project scheduling, contract coordination and stakeholder engagement – inherently require collaboration and are explicitly stated as pre-construction endeavours. Paradoxically, participants' accounts reveal a deficiency in such practices. Participant 9 noted that the project management process is followed until the contractor is selected, and then the approach becomes “Go go go!”. He mentions that “everyone misses out on the opportunity to have a value engineering exercise and to collaborate”. Participant 1 advised to “sit with the contractor and let him go through the basic principles of the constructability of the design”. He further states that this collaboration is starting to occur in the industry, but that it is infrequent. Participant 7 mentions that “different design teams design different aspects of the structure, but those aspects end up clashing because they do not communicate with one another”.

While project scheduling, contract coordination and stakeholder engagement may be present in design-bid-build projects, they are often reduced to mere procedural obligations, neglecting their potential to significantly enhance project quality, cost-efficiency and timely delivery.

To rectify this lack of collaboration, a shift in mindset regarding these collaborative activities during the mobilization phase may be needed. Rather than completing them perfunctorily for compliance, project stakeholders should strive to foster a culture of engagement and collaboration with the contractor. Embracing this approach can lead to a plethora of positive outcomes. Research by Rahman et al (2014) demonstrates that collaborative practices result in improved project performance, including improved quality, cost control and timely completion. Additionally, the findings of Hwang & Ng (2013) underscore the pivotal role of contract coordination in ensuring transparent communication, shared understanding and effective resolution of ambiguities.

Moreover, genuine stakeholder engagement holds significant potential for benefits. Establishing an environment that actively involves the contractor alongside the client, architects and engineers allows for the integration of diverse perspectives, knowledge and expertise. Such collaborative efforts, supported by studies conducted by Boton & Forgues (2017), Rahman et al (2014) and Erdogan et al (2008), foster creative problem-solving, proactive risk management and informed decision-making.

While the interview participants' observations shed light on inadequate collaboration during the mobilization phase of design-bid-build projects, proactive efforts to prioritize and foster collaboration remain infrequent. By reorienting the approach and embracing the true spirit of collaboration, project stakeholders can harness the full potential of project scheduling, contract coordination and stakeholder engagement.

The duration of the mobilization phase can vary depending on the project's scope, ranging from two weeks to 6 months. During this important phase, design-bid-build projects should strategically seek collaborative endeavours to facilitate construction operations, optimize construction planning and explore possibilities for cost and time savings (Singh & Arora, 2018).

A significant aspect of the advice provided by the interview participants revolves around rationalizing the design and making practical design decisions that are feasible for construction. Participant 9 emphasised that "you have to have a pre-construction meeting. The designer should present the design and the contractor should check the practicality of it. Let the contractor help you rationalize your design".

Regarding project scheduling, Participant 12 notes that "the design team will make schedule decisions based on limited understanding and experience" and emphasises that they can be inaccurate with their schedules by up to four months. Participant 16 raises concerns that "design engineers determine the schedule before wayleaves are granted. When the site finally can be accessed, many aspects of the schedule need drastic changes when site challenges are identified". He further alludes to the lack of due diligence and that the schedule is seldom reviewed after the tender award with the consultation of the contractor. Designers may struggle to be accurate with scheduling that involves construction activities because of inadequate knowledge and experience. To address this, the involvement of the contractor as early as possible is important to consult feasibility, practicality and the accuracy of material acquisition and construction activity schedules.

Regarding contract coordination, Participant 2 explains that designers may lack the experience to make timely and cost-effective design decisions, resulting in a hesitancy to finalize changes requested by the contractor. This highlights the need for mutual trust and respect between parties to analyse problems and approve variation orders when necessary. It was also stressed by Participant 9 that "there needs to be communication between the parties, as well as a bit of leeway and understanding between the two".

Participant 4 suggests that a high-level method statement created by the designer could prevent many problems, but acknowledges that designers might not possess the necessary expertise in construction processes. This reinforces the importance of relying on specialist knowledge and prioritising collaboration during mobilization.

Regarding stakeholder engagement, Participant 9 raised concerns that collaboration often diminishes after the contractor selection, leading to potential problems on-site. Participant 20 suggests that effective project management and coordination are important to ensure that communication reaches the contractor promptly for timely problem-solving.

The lack of effective and intentional collaboration in design-bid-build projects presents many problems. O'Connor (2009) identified four systemic problems with traditional procurement methods: 1) good ideas are held back, 2) contracting limits cooperation and innovation, 3) an inability to coordinate and 4) pressure for local optimization at the expense of the project as a whole. These problems are echoed in the observations of interview participants.

While integrated project delivery (IPD) differs significantly from design-bid-build, some lessons from IPD could be considered to prioritise designer-contractor collaboration during feasible periods. Although full implementation of IPD may not be possible, identifying collaborative priorities from IPD that can benefit the design-bid-build approach is important. By emphasising collaboration during relevant stages, design-bid-build projects can reap the benefits of improved efficiency and involvement of all stakeholders.

5.3.1 A proposed approach to improve constructability in design-bid-build projects

Research by Boton & Forgues (2017), Rahman et al. (2014) and Erdogan et al. (2008) underscores the transformative potential of deliberate collaboration between designers and contractors in construction projects. This section introduces an approach for design-bid-build projects that emphasises deliberate collaboration during the mobilization phase while drawing inspiration from integrated project delivery (IPD) principles and feedback from interview participants.

Integrated project delivery (IPD) is a collaborative delivery method that aims to foster close cooperation among key stakeholders, including the client, architects, engineers and contractors. These stakeholders enter into a single contractual agreement early in the project's development stage, enabling them to work as a cohesive team from the outset. The primary goal of IPD is to optimize efficiency by promoting a collective decision-making process, shared risk and rewards and a focus on shared project goals (O'Connor, 2009)

Early involvement of the contractor is essential, but merely considering it as one professional commenting on another's work might not yield true collaboration or real benefits. IPD, primarily fostered by collaboration, can be implemented, for example, by the known "construction management" delivery method that is infused with collaborative or team-based processes (O'Connor, 2009). The approach to design-bid-build delivery would be similar. The familiar framework can be infused with collaborative processes that are driven by key participants and incentivised in the contract. Although an early contract with the contractor is not feasible in design-bid-build projects, the ideals of collective problem-solving and value-driven decision-making through intentional collaboration can be integrated into the framework.

The goal of collaboration should be to increase value and explore options that best serve the client and project outcomes. If efforts by participants to serve the interest of the project are not incentivised, the result of engagement in the project is an "every person for themselves" approach. According to O'Conner (2009), "traditional contracts rigidly delineate responsibilities with much elaboration on the consequences of failure. These contracting approaches reinforce self-protective behaviour and instil mistrust". O'Connor mentions "intelligently crafted incentives" that decrease the tendency of participants to protect themselves financially, at the expense of the project and other participants. These incentives can include bonuses for achieving milestones ahead of schedule, cost savings that result from value engineering or shared benefits resulting from successful constructability improvements.

Negative incentives often involve the use of penalties or punishments in the event of failure, whereas positive incentives involve rewards or economic benefits in the event of positive outcomes. IPD contracts, as for traditional contracts, define the processes, services, products and desired results, but through positive incentives, they also describe the desired project team culture (O'Connor, 2009).

The interview participant feedback suggests the desire for a particular culture. The 15 advice phrases allocated to the new constructability concept "Mentorship and supervision", the 23 advice phrases allocated to "Communication and collaboration" and the 19 advice phrases allocated to "Continuous learning" show a trend of an enthusiastic and collaborative culture desired by the participants. The 14 advice phrases that are allocated to the mobilization phase, of which 10 items pertain to collaborative activities between designers and other project stakeholders, show that intentional collaboration with the designer is sought-after by the interviewees. The 158 advice phrases that are allocated to all phases before the mobilization phase show the need for an alternative tool or communication framework to support design engineers in the consideration of constructability concepts while they do not have the option of contractor collaboration.

The inspiration drawn from IPD methods, literature and the valuable feedback provided by the participants have led to the formulation of six considerations:

(O'Connor, 2009) (Singh & Arora, 2018)

1 Incorporating positive incentives in contracts to promote good performance and intentional collaboration among stakeholders.
2 Implementation of the proposed constructability tool, or similar, during the design phase to proactively address constructability challenges.
3 Infusing intentional collaboration into the mobilization phase, particularly within the activities of a) project scheduling, b) contract coordination and c) stakeholder engagement.
4 Creating opportunities for contractors and designers to gain a deeper understanding of each other’s challenges and perspectives during the mobilization phase.
5 Enabling designers to enhance their understanding of constructability and construction processes while the project is underway on-site.
6 Facilitating the active participation of consultants in project close-out meetings to encourage knowledge sharing and collaboration.

Figure 5-3 illustrates the distinctions between the traditional approach and the proposed approach, emphasising (in blue) the phases most significantly influenced by the new approach. Each of these six considerations holds complexity and warrants individual in-depth exploration. Therefore, in this approach, particular attention will be given to collaboration during the mobilisation phase, as this study identified it as a concern based on the participant's feedback. The constructability tool mentioned in Figure 5-3 is presented in Chapter 6.

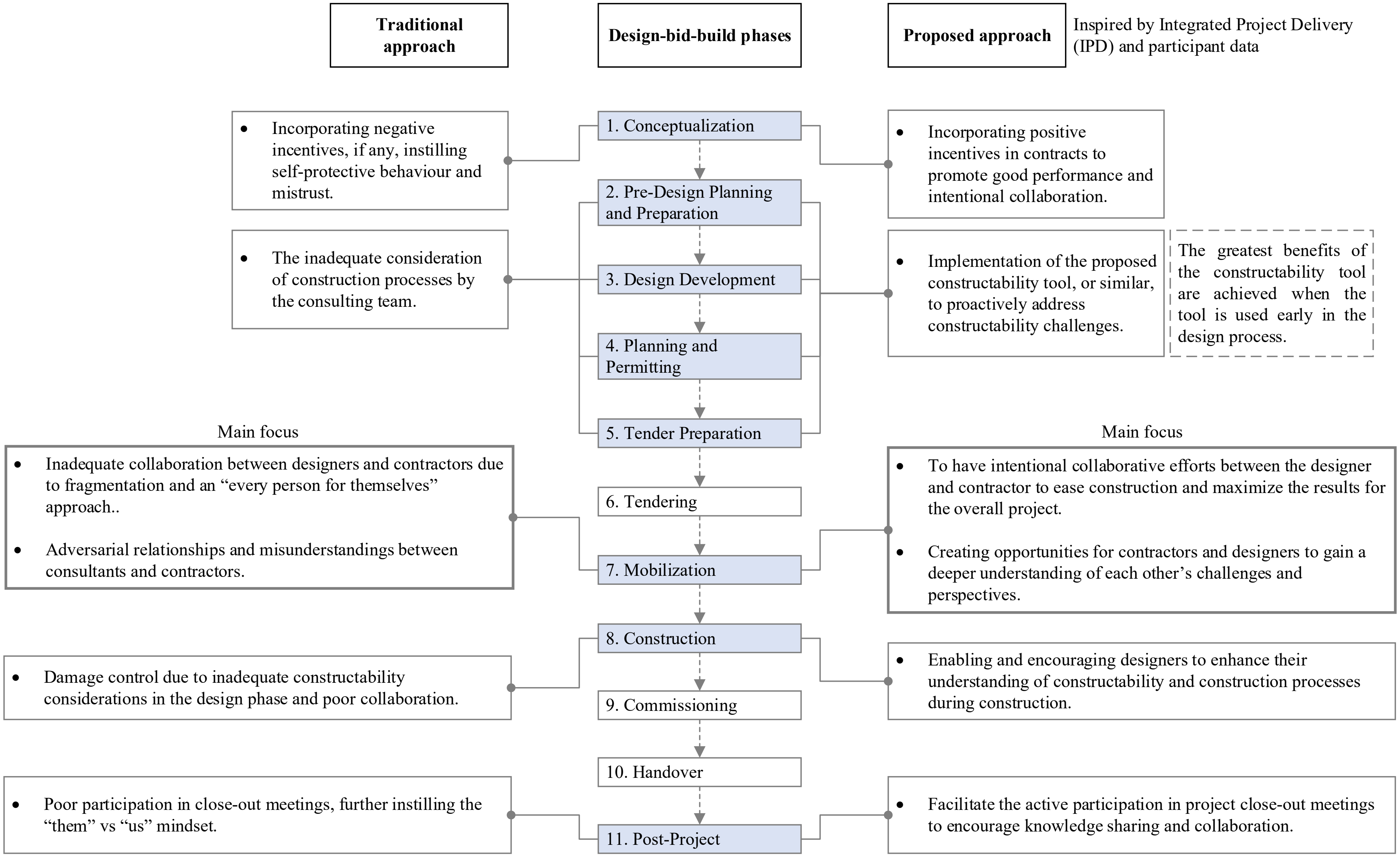


Figure 5-3: A suggested new approach, inspired by IPD and participant data

Given the varying size and complexity of projects, the mobilization phase can span from two weeks to six months. Consequently, mobilization activities and the approach adopted during this period must be meticulously planned, with specific objectives to be achieved within the expected timeframe. Central roles in coordinating and planning activities during the mobilization phase are played by the project manager and the contractor. Additionally, designers should be encouraged or incentivised to actively engage in intentional collaboration with the contractor to explore constructability improvements. Table 5-2 presents six activities included in the mobilization phase, along with the suggested intentional collaboration that should be integrated into these existing activities. These activities are discussed here below.

Table 5-2: Collaborative approaches for the mobilization phase activities

Activity	Definition	Collaborative approach
Project setup	In the initial phase of the project, the project team is assembled, objectives and constraints are identified, and the scope, budget and schedule are defined (Dykstra, 2018).	To initiate an integrated planning process, designers, contractors and other stakeholders should collaboratively work together to establish clear project goals, define roles and responsibilities and set expectations from the very beginning.
Site preparation	Activities before construction commence, such as clearing, grading and arranging utilities and infrastructure. (Sears, et al., 2008).	Conduct a collaborative site assessment involving both designers and contractors to identify potential challenges, opportunities, and constraints. This assessment will inform the overall project strategy.
Project scheduling	This involves systematic planning and sequencing of a detailed construction schedule, defining major milestones, and establishing start and finish times for tasks, guiding timely project execution (Sears, et al., 2008).	Develop a joint project schedule with inputs from both designers and contractors, ensuring that constructability considerations are thoughtfully integrated into the timeline.
Safety planning	This includes developing a comprehensive safety plan with protocols for maintaining a secure construction work environment. It involves conducting safety assessments, creating safety plans, and implementing appropriate safety training programs (Hill, 2014).	Collaboratively develop a safety plan that addresses the specific construction site and project requirements. This collaborative effort fosters a shared commitment to safety among all stakeholders.
Contract coordination	Contract coordination entails aligning and clarifying contracts, reviewing contractual obligations, defining roles and responsibilities, and resolving any ambiguities or discrepancies while ensuring compliance (Phillips, 1999).	To promote a collaborative approach and mutual understanding of project objectives, align contract provisions between designers and contractors.
Stakeholder engagement	Stakeholder engagement involves actively involving key stakeholders, such as the client, architects, engineers, consultants and the community, in regular meetings to discuss project progress, address concerns and ensure alignment among all parties involved (Richardson, 2015).	Engage stakeholders, particularly designers and contractors, in collaborative sessions to gather feedback, address concerns and foster inclusive decision-making processes.

By incorporating these actionable steps and practical implementations, project managers, contractors and designers can significantly improve constructability, cost-effectiveness and overall project success.

5.4 Validation interview results

The proposed approach in section 5.3 was subjected to validation through interviews with five of the original 20 selected participants. The aim was to establish the feasibility of the approach, identify potential challenges and clarify which participants have the greatest role in driving constructability considerations during design and constructability-focused collaboration during mobilization.

Table 5-3 shows the qualifications, current employment position and years of experience of the five validation interview participants.

Table 5-3: Introduction to the validation interview participants

Interview participants (from Table 4-1)	**Qualification**	**Current position**	**Years of experience**
1	BTech Civil Engineering	Senior Project Manager	19
8	BTech Mechanical Engineering	MD Project Management	25
4	BEng Civil Engineering	Technical Office Engineer	14
11	BEng Civil Engineering	Project Director	36
18	International Health and Safety	Director	10

Table 5-4, Table 5-5, Table 5-6 and Table 5-7 present the results of specific validation interview questions (questions 4, 5, 6 and 7, respectively). The preceding questions 1, 2 and 3 relate to the constructability tool and are discussed in Chapter 6, Section 6.4.

Table 5-4: The most suitable time for designer-contractor collaboration.

Question 4
Statement: The mobilization phase is the most suitable time for contractor-designer collaboration in design-bid-build projects.
1 – strongly disagree
5 – strongly agree

Interview participant	**Likert scale rank**	**A more ideal time to initiate collaboration**
1	5	No answer
8	4	Collaboration with the top three bids one-on-one, during pre-qualification, would be ideal.
4	5	No answer
11	5	No answer
18	4	No answer
Average rank	**4.6**	

Table 5-5: Design changes that are still possible to make during the mobilization phase.

Question 5
Which of the 5 changes are still possible during the mobilization phase?

Interview participant	1 Changes to selected resources and materials	2 Changes to primary construction methods	3 Changes to design layout (Spacing between buildings or pipes, amendments to above-ceiling space requirements for MEP services)	4 Changes that involve standardizing elements or units that were not previously standardized	5 Changes from an in-situ design to prefabrication
1	It depends	It depends	Yes	Yes	Yes
8	Yes, but an influence on the time	Yes, but an influence on the time	Yes, but an influence on the time	Yes, but an influence on the time	Yes, but an influence on the time
4	Yes	Yes	Yes	Yes	No
11	Yes	Yes, but an influence on the time	Yes	Yes	No
18	Yes	Yes	Yes	Yes	Yes

Table 5-6: Challenge(s) that are prevalent in a) the attempt to prioritise constructability implementation during the design phase and b) the attempt to have intentional collaboration in the mobilization phase

Question 6
What challenge(s) will be prevalent?

Interview participant	a) in the attempt to prioritise constructability implementation during the design phase by designers?	b) in the attempt to have intentional collaboration in the mobilization phase in design-bid-build projects?
1	Designers may exhibit bias and resistance to change.	Contractors might raise concerns about cost, leading to potential arguments and strained relationships.
8	Lack of maturity, openness, and user-friendliness of the tool/application can impede the implementation of constructability.	Designers may resist making design changes and including the contractors in planning and management.
4	Limited time availability for designers to prioritize constructability during the design phase.	Negative attitudes, feeling attacked, and anti-competitive behaviour can affect collaboration.
11	Designers may be resistant to implementing constructability, requiring a plan to accommodate the change.	Ego-driven conflicts and resistance to accommodating new ideas can arise among engineers.
18	Designers' competence and accountability play an important role in successfully prioritizing constructability.	Unaddressed aspects in the collaboration that were not included in the tender and variation orders can strain relationships, and designers may struggle with acknowledging their shortcomings.

Table 5-7: The participant to take responsibility for implementing constructability and to prioritise intentional collaboration

Question 7
Rank the following participants in order of responsibility to drive the implementation of constructability and intentional collaboration.
1 – most responsibility
5 – least responsibility

Interview participant	Client	Project manager	Engineer	Architect	Other
1	1	2	3	4	None
8	5	1	2	3	4 (Contractor)
4	1	2	3	4	None
11	5	2	3	4	1 (Principal-agent)
18	2	3	1	4	5 (SHEQ advisor)
Average	**2.8**	**2**	**2.4**	**3.8**	

Table 5-4 reveals that the majority of the participants expressed a positive view towards collaboration during the mobilization phase, considering it suitable for contractor-designer collaboration in design-bid-build projects.

Table 5-5 highlights that most participants responded positively to the proposed changes to design resulting from designer-contractor collaboration during the mobilization phase. According to Wuni & Shen (2020), the success of prefabrication is largely determined by the decisions made as early as during the conceptualization phase. Therefore, changing an in-situ design to prefabrication as late as the mobilization phase is likely to affect schedule and cost and may have a higher risk of failure, depending on the complexity of the design. Nonetheless, the results affirm that the mobilization phase offers an opportune time to implement various changes, provided there is thorough planning and consideration of the impact that the change will have on the project schedule and cost.

Table 5-6 presents the challenges reported by participants concerning two aspects of the design-bid-build process: a) the attempt to prioritise constructability implementation during the design phase by designers and b) the attempt to have intentional collaboration in the mobilization phase. For a), challenges included biases and resistance to change, time constraints and limitations in the tool/application's usability, affecting the seamless integration of constructability into the design process. The constructability tool application is made to be user-friendly and utilized during the design phase to support the designer with constructability considerations. Regarding b), concerns were raised about resistance to change and difficulties in incorporating different perspectives, highlighting the importance of effective communication and trust-building for successful intentional collaboration.

Participant 1 mentioned that the contractor may raise concerns about cost. If design changes result from the designer-contractor collaboration, there will be cost implications. One option is for the designer and the contractor to share the cost savings that the changes will bring. A mitigation option is to develop a clear change order process that outlines how design changes will be identified, assessed and approved during the mobilization phase collaboration. This topic should be investigated in a further research study.

Table 5-7 ranks the stakeholders based on their responsibility to drive the implementation of constructability and intentional collaboration. The project manager and engineer received mean rankings of 2 and 2.4, respectively, indicating that they are perceived as key participants in fostering constructability and collaboration due to their organizational and communication skills. The project manager is best suited, being the only unbiased participant, and can drive collaboration during the design, mobilization and construction phases. The client's rankings varied, with some interviewees viewing the client as the primary driver of constructability and collaboration, while other interviewees ranked the architect and engineer as more suitable candidates. Interestingly, the architect, often the principal agent, is not expected to bear the responsibility of driving collaboration and constructability implementation.

Overall, the validation results support the proposed approach's feasibility, while also highlighting the importance of addressing challenges and defining clear roles for participants to drive intentional collaboration during the mobilization phase.

5.5 Chapter summary

The chapter focuses on finding ways to improve constructability in design-bid-build projects through intentional collaboration between designers and contractors during the mobilization phase. The mobilization phase is an important phase for furnishing the construction site with essential resources and optimizing construction planning. However, it is often underutilized for intentional collaboration, leading to missed opportunities for improved project outcomes. To address this issue, a proposed approach is introduced, influenced by the principles of Integrated Project Delivery (IPD) and participant feedback.

The proposed approach emphasizes collaborative efforts during the mobilization phase to foster a culture of genuine engagement and effective communication. Project managers, contractors and designers play central roles in driving intentional collaboration. Practical implementations include initiating and integrating a planning process during project setup, conducting a collaborative site assessment and developing a joint project schedule that incorporates constructability considerations.

Validation interviews with key stakeholders validated the approach's feasibility. Participants expressed positive views towards collaboration during the mobilization phase, with a consensus that it is an opportune time for contractor-designer collaboration. They acknowledged the potential for changes resulting from such collaboration.

However, participants also identified challenges, such as biases, resistance to change, limited time availability and communication issues, that hindered the seamless integration of constructability considerations into the design process. Overcoming these challenges necessitates effective communication, trust-building and a cooperative mindset.

Given the difficulties of the design-bid-build procurement method and low BIM maturity, the constructability tool is a useful tool to empower young designers with a better grasp of the actions and considerations that will decrease construction challenges. The tool makes expert advice available during the design phase, which traditionally is only available once the contractor is appointed.

The industry's prevailing culture significantly influences the reception and implementation of novel concepts, such as the mobile application and the idea of collaboration during phases traditionally devoid of such interaction.

The responsibilities for driving constructability and intentional collaboration were ranked by participants, with project managers and engineers deemed most suited due to their organizational and communication skills. The client's role varied, with some participants viewing them as key drivers, while others saw the client as least equipped to foster collaboration.

Numerous challenges impede this collaboration, including potential cost fluctuations in the design that stem from the collaboration and conflict with procurement regulations, attitudes towards redesigning, conflicts from differing perspectives and resistance to change. The project manager has a pivotal role in fostering collaborative dynamics due to his relative impartiality. Suggestions for fostering collaboration include incorporating financial incentives into contracts, predetermining acceptable design changes resulting from collaboration and sharing the benefits of cost savings.

Chapter 6: Constructability tool proposal

6.1 Chapter overview

This chapter introduces a proposal for a constructability tool, which can serve as an aid for design engineers, or other consultants, in enhancing project outcomes, particularly through improved constructability. To improve constructability considerations and promote knowledge exchange, the proposed tool takes the form of an intuitive mobile application.

The chapter commences with the objectives and framework of the constructability tool. By emphasizing the importance of early constructability considerations, providing expert advice and documenting project insights, the tool endeavours to improve project outcomes and bridges the gap between design engineers and construction specialists.

The chapter further presents an overview of the four core features implemented as a proof of concept using the Thunkable software. These features showcase the user-friendly nature of the tool and its capacity to improve constructability awareness, receive contractor advice, enable effective data filtering and enable the user to add personal lessons learned to the advice database.

To validate the tool's efficacy, interviews were conducted with five participants, who shared their feedback on its potential benefits.

6.2 Proposed constructability tool desirables and framework

The proposed constructability tool envisioned as a mobile application, should ideally offer a range of features that enable design engineers to utilise it as a continuous development platform. The tool should also provide construction specialist advice to design engineers on aspects to consider and ways to improve the constructability of their designs. Furthermore, it should facilitate easy access to contractor advice, project documentation, incorporation of lessons learnt and seamless communication with other professionals in their project team or organization to exchange ideas.

It was noted by one of the interview participants that design can often be an isolated experience, and therefore, the constructability tool aims to mitigate this isolation by encouraging greater consideration of constructability during design and greater collaboration via a forum, even when early contractor involvement during design is not possible, as is the case in design-bid-build projects.

The desired outcomes for this constructability tool are as follows:

- Foster an increased consideration of constructability by the design engineer.
- Enhance awareness and understanding of constructability concepts.
- Provide a platform for personal development to the design engineer.
- Facilitate the documentation of lessons learnt by the design engineer.
- Establish a collaborative forum that allows participants to gain insights into the challenges faced by others involved in the project.
- Improve the designer's ability to think holistically and achieve the best outcome for the project.

The primary target audience for this tool is design engineers. However, the platform can be adapted for use by any participant involved in construction. The forum, for instance, should be open to all participants who wish to pose questions, exchange ideas and learn from one another.

Figure 6-1 presents the framework for the constructability tool. The figure highlights four features that have been implemented in the form of a mobile application to demonstrate the proof of concept.

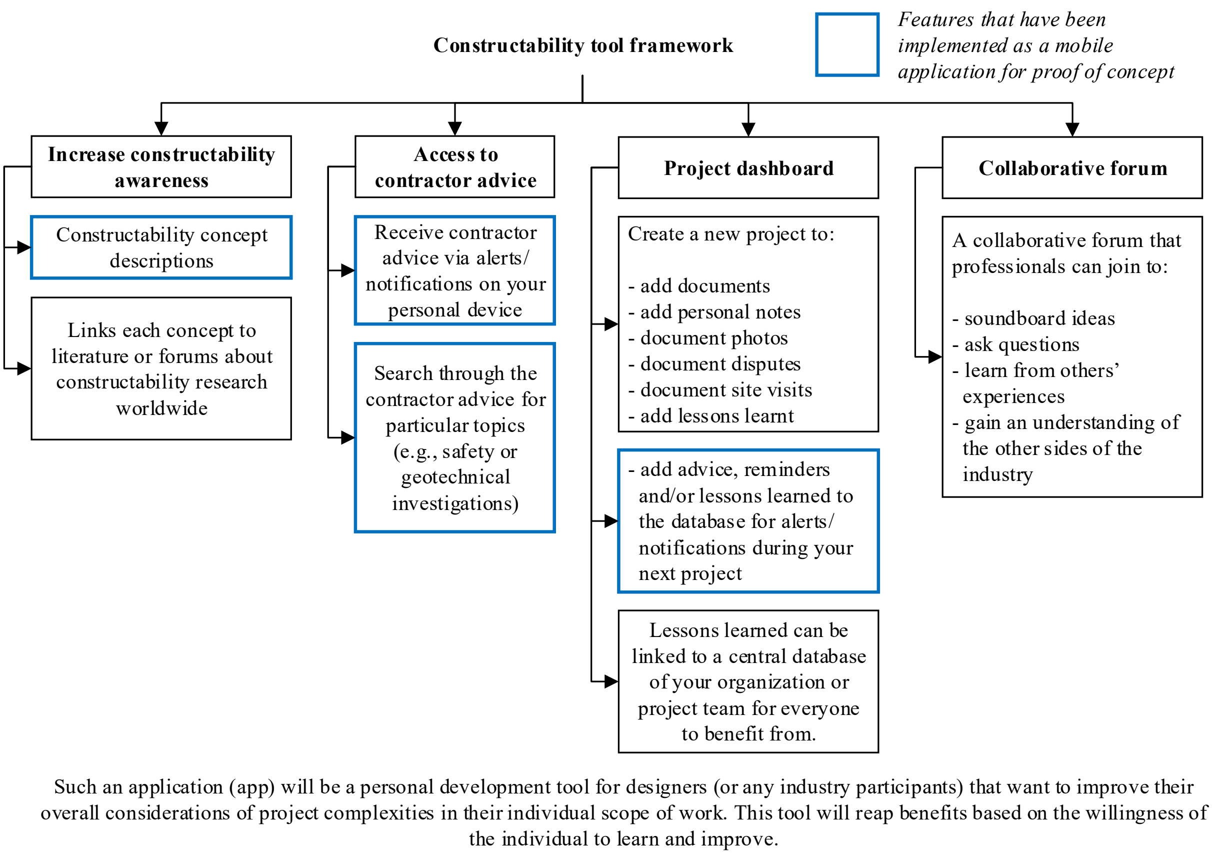


Figure 6-1: Constructability tool framework

As demonstrated in section 5.3.1 and depicted in Figure 5-3, the constructability tool proves to be most advantageous when implemented during the early stages of the design process. Delaying the adoption of this tool diminishes its benefits, particularly in terms of constructability improvement. To maximize its effectiveness, the tool should ideally be employed consistently throughout the entire project lifecycle, and all knowledge and documented lessons learned should be used to benefit future projects with similar characteristics.

Implementing the constructability tool from the early design stages and combining it with intentional collaboration during mobilization between the designer, project manager and contractor, can lead to the following benefits:

- **Improved constructability considerations:** Design engineers can proactively assess and incorporate constructability into their designs by utilizing specialist construction advice and, through close collaboration with the contractor during mobilization, ensure that construction-related challenges are addressed from the outset.
- **Improved project efficiency:** Early considerations of construction challenges and sharing of information and insights between the designer and contractor during mobilization can streamline the decision-making process and facilitate prompt resolution of constructability problems that arise.
- **Minimize rework and delays:** Through early evaluation of constructability by the designer and problem-solving with the contractor during mobilization, potential clashes between design intent and construction feasibility can be identified and resolved promptly.
- **Optimal resource allocation:** The consideration of constructability during the design, as well as the collaboration with the contractor during mobilization, improves the understanding of project requirements, available resources and potential constraints. This leads to effective resource allocation, the minimization of wastage and the optimization of the use of labour and equipment.
- **Enhanced quality and safety:** The constructability tool and collaborative approach facilitate discussions on constructability challenges, safety considerations and quality standards. By addressing these aspects early on, the project team can implement appropriate measures to improve project quality and safety on site.

For this study, a fully functional version of the application was not developed. Instead, four distinct features of the application were individually implemented using Thunkable software. These features were enhanced with the incorporation of contractor advice from the interview participant feedback and with constructability concepts. The four highlighted features, as presented in Figure 6-1, are as follows:

1 Viewing the constructability concepts and definitions, which include the eight additionally created concepts.
2 Providing the user with contractor advice through alerts on their device.
3 Implementing a search function to allow users to filter through the available contractor advice phrases.
4 Allowing users to add reminders, lessons learned or personal advice to the contractor advice database. These additions can then be included in future alerts and be accessible through future filtered searches.

The constructability tool is demonstrated in section 6.3 and focuses on the four core features.

6.3 The mobile application proof of concept objectives and outcome

The four features incorporated into the Thunkable software were selected as fundamental aspects, as they directly involve the contractor advice provided by the interview participants as well as the constructability concepts related to each advice item. Consequently, these features serve as the primary focal points of the proof of concept implementation.

The main objective of the proof of concept is to demonstrate the ease with which contractor advice can be utilized within a user-friendly tool. Figure 6-2 outlines the specific objectives of the proof of concept for each of these four features.

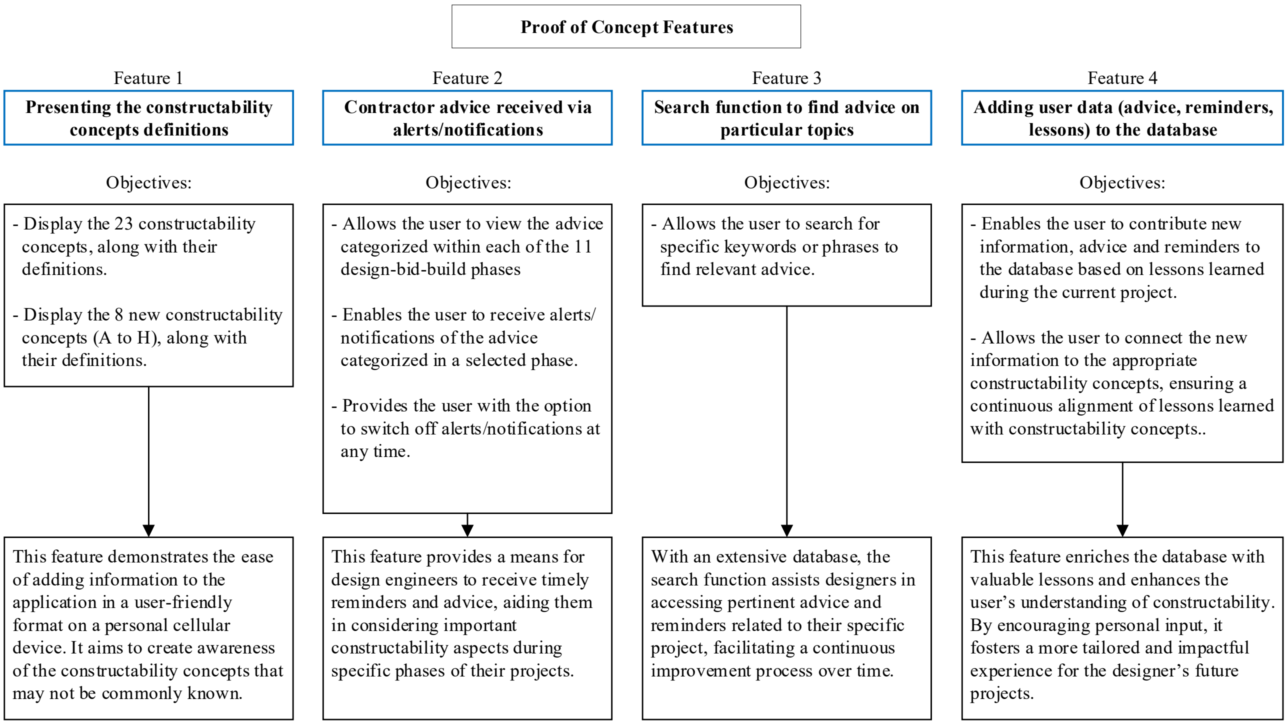


Figure 6-2: Features that have been implemented as a proof of concept, along with their respective objectives

The demonstration screens of the four features are presented. An explanation of the visual coding for these features can be found in Appendix E.

Figure 6-3 shows the screens for feature 1: "User viewing constructability concepts and definitions". The screens include:

- Screen 1: The initial screen where feature 1 can be selected.
- Screen 2: A description screen features a button to access the constructability concept list.
- Screen 3: The constructability concept list

Figure 6-4 presents the screens for feature 2: "User receiving contractor advice as alerts". The screens include:

- Screen 1: The starting point where feature 2 is selected.
- Screen 2: An illustration of the 11 design-bid-build phases; an example showing phase 2 being selected.
- Screen 3: The contractor advice phrases listed for phase 2, with the allocated constructability concepts serving as the title for each item.
- Screen 2: Upon selecting the back button in screen 3, users can again access screen 2, where a switch is available to enable the contractor advice alerts for phase 2. The alerts will start immediately after the switch has been activated and will provide the contractor advice in order

of constructability concepts (1 to 23 and then A to H). The next alert will only display when the user selects the confirm button of the current alert.

- Screen 2: An example of the first contractor advice item for phase 2 is displayed on the screen, with subsequent advice phrases being presented upon user confirmation.

Figure 6-5 exhibits the screens for feature 3: "Search function for filtering contractor advice data". The screens include:

- Screen 1: The starting screen where feature 3 can be selected.
- Screen 2: A search bar is presented, with the user entering "site visits" as an example.
- Screen 2: An alert confirming that a result was found in the contractor advice database.
- Screen 2: The search results for "site visits" are displayed below the search bar.

Figure 6-6 demonstrates the screens for feature 4: "User data addition to the contractor advice database" (specifically for phase 2 in this example). The screens include:

- Screen 1: The starting screen where feature 4 is selected.
- Screen 2: A text box allows users to input information, while another text box enables the inclusion of the relevant constructability concept. Users can check the constructability concepts by selecting the "Check constructability concept list" button.
- Screen 3: The updated contractor advice for phase 2 is shown, with the newly added user data displayed alongside appropriate constructability concepts 5 (The scheduling goals should be construction-driven and assigned as early as possible) and B (Effective and continuous communication, interaction and collaboration with all project participants should be prioritized).

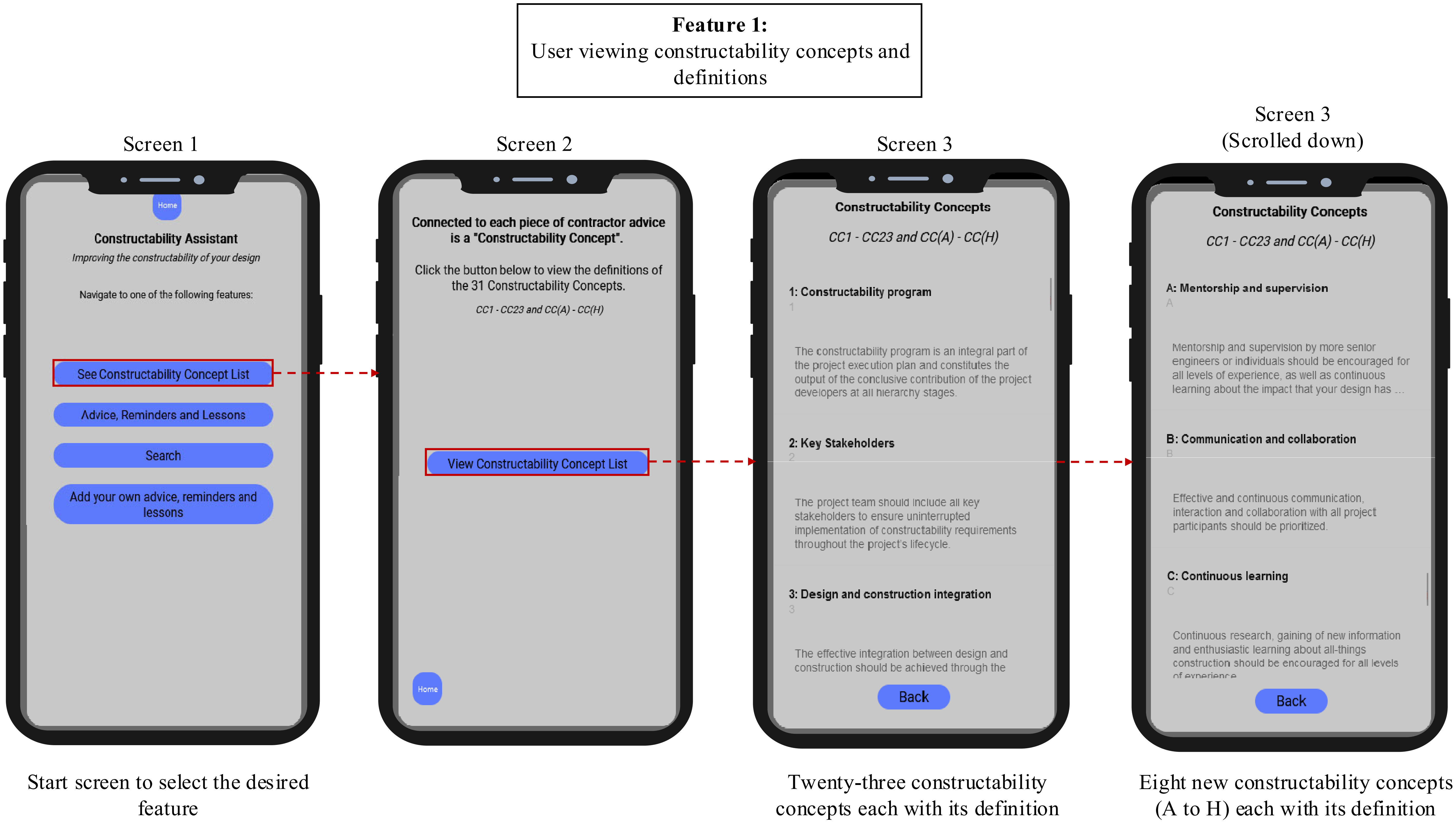


Figure 6-3: Feature 1 – User viewing the constructability concepts and definitions

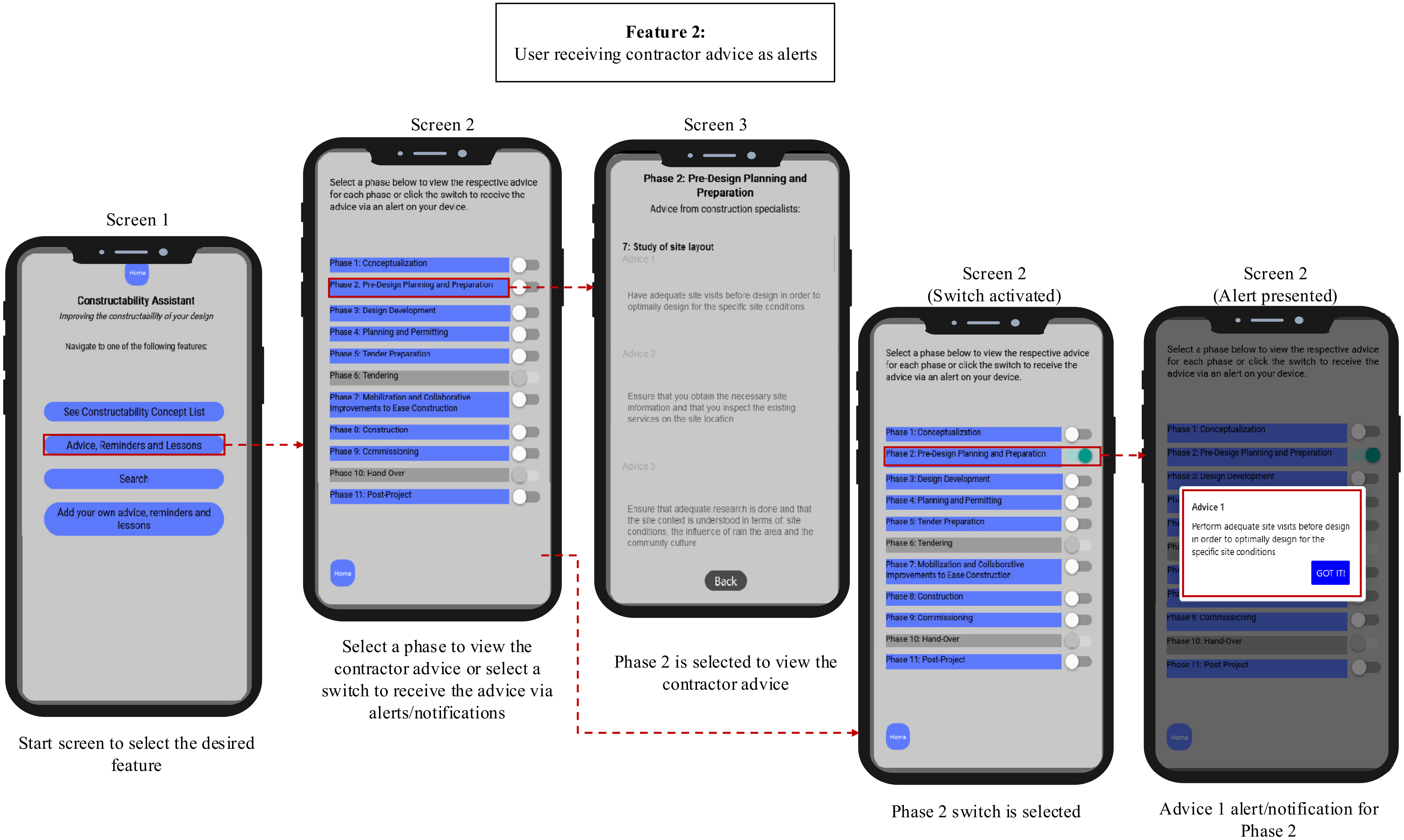


Figure 6-4: Feature 2 - User viewing and receiving data as alerts/notifications

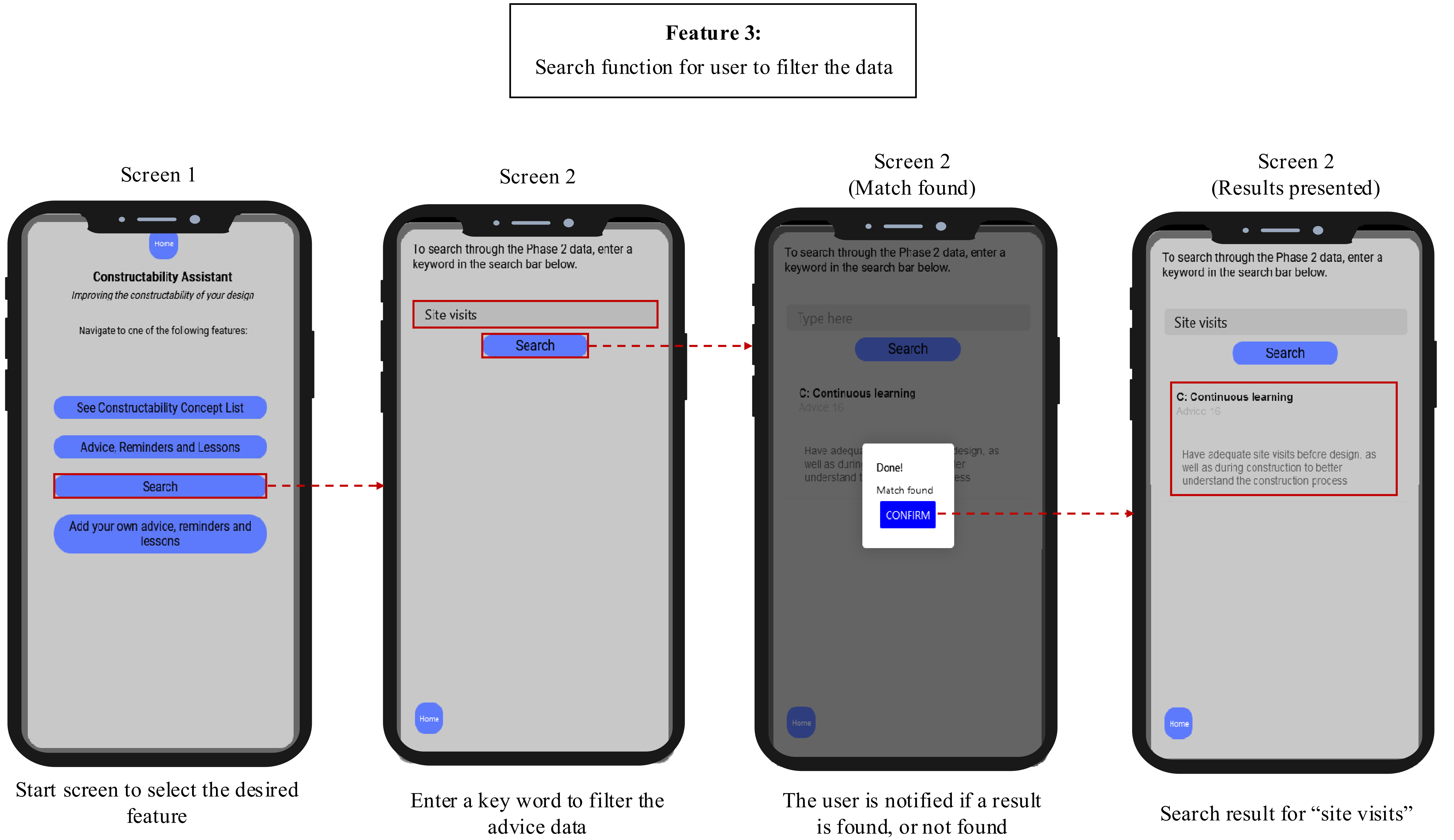


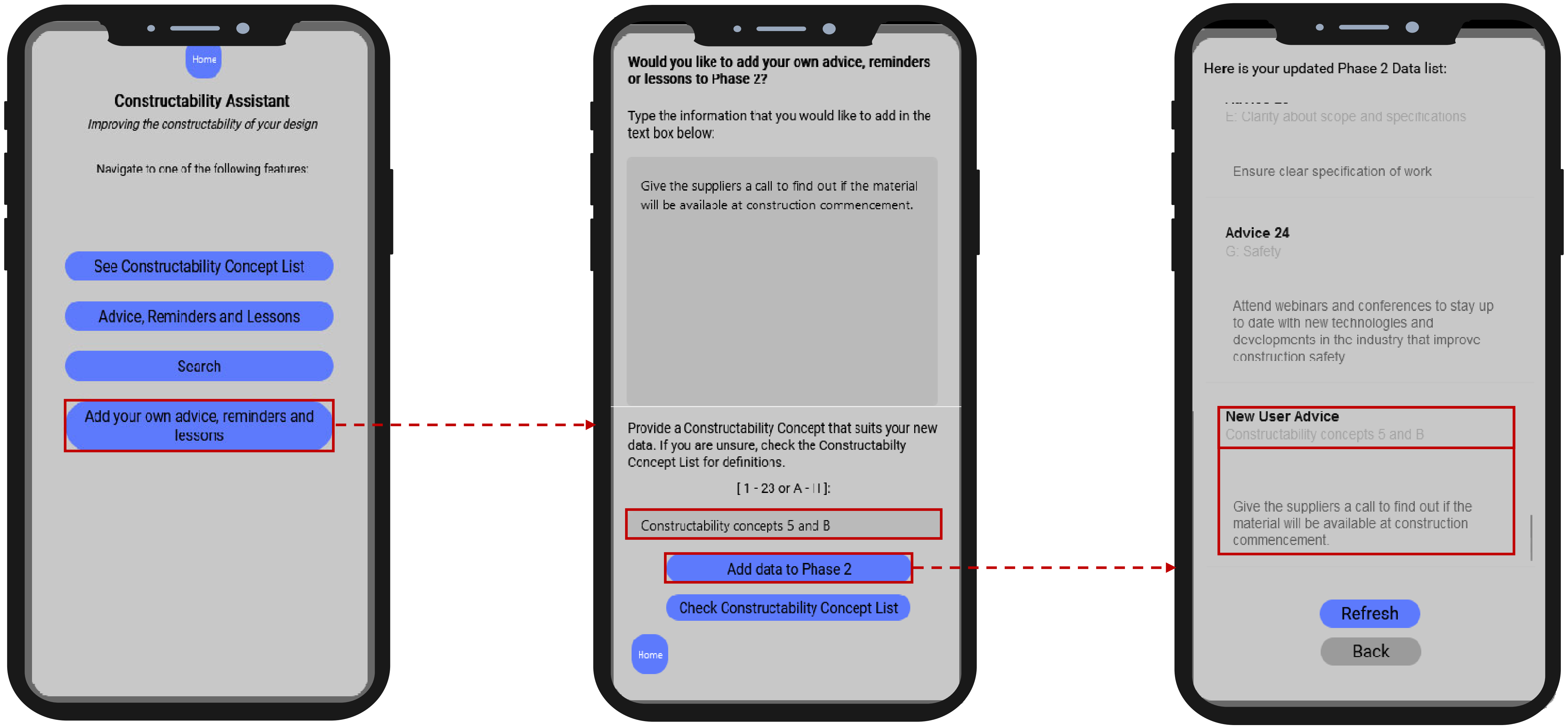
Figure 6-5: Feature 3 - Search function to filter the advice data

Feature 4:
User data added to the contractor advice database

Screen 1

Screen 2

Screen 3
(Scrolled to the last data item)



Start screen to select the desired feature

User input to be added to the contractor advice database for Phase 2 as an example. If the user is not sure which constructability concept to select, he/she can view the concept list again.

User input added as the latest data item and will also be included in the alerts/ notifications and search filter

Figure 6-6: Feature 4 - User data added to the contractor advice database

6.4 Validation interview results

The proposed constructability tool presented in section 6.3 was validated through interviews with five selected participants. Table 5-3 in Section 5.4 shows the qualifications, current employment position and years of experience of the five validation interview participants.

The constructability tool was demonstrated to the participants live on a video call or face-to-face. The objective was to gauge the participants' opinions about the tool and determine the ideal future functionalities of the tool. Their responses were obtained using a Likert scale ranging from (1) strongly disagree to (5) strongly agree. The specific validation interview results (Questions 1, 2 and 3) are presented in Table 6-1. Questions 1, 2 and 3 are:

- **Question 1:** This tool will aid design engineers to better consider constructability during the design phase.
- **Question 2:** I would suggest this tool to young designers.

  Question 3: Would you prefer the tool to have the following goals?
- **Question 3.1:** A tool to help inexperienced designers.
- **Question 3.2**: A tool for mentors and supervisors to verify the work of their subordinates.
- **Question 3.3**: A tool to keep a record of lessons learned.
- **Question 3.4**: All of the above.

Table 6-1: Validation interview results for questions 1, 2 and 3

Questions 1, 2 and 3 responses for the validation interview

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Interview participants (from Table 4-1)	Q1	Q2	Q3.1	Q3.2	Q3.3	Q3.4
1	4	4	5	4	3	4
8	4	5	5	4	5	5
4	4	4	3	4	5	4
11	4	5	4	4	5	4
18	5	5	5	4	5	5
Average	**4.2**	**4.6**	**4.4**	**4**	**4.6**	**4.4**

Overall, the participants agreed that the tool is beneficial to design engineers and that it should be employed to aid inexperienced designers, provide supervisors and mentors with means to verify their subordinates' work and keep a record of lessons learned. Notably, the majority of "strongly agree" feedback was received for question 3.3: “A tool to keep a record of lessons learned”. This indicates that participants highly value proper documentation and utilisation of lessons learned.

Research by Eken, et al (2015) mentions that lessons learned knowledge is important to achieve optimal efficiency, competitiveness and organizational growth in construction companies. However, Eken, et al (2015) further state that construction knowledge is mostly tacit knowledge and that the adequate codification of the lessons learned is an important aspect of successfully utilizing the information. The constructability application can be a useful tool in extracting lessons learned data. Further investigation into this subject is warranted for future research endeavours.

Two instances of “neutral” feedback are observed, both for question 3.1: “A tool to help inexperienced designers” and question 3.3: “A tool to keep a record of lessons learned”. Interestingly, the participant who responded neutrally to question 3.1 provided an “agree” response for question 2: “I would suggest this tool to young designers”. This implies that while they would recommend the tool to young designers, they harbour some reservations regarding its effectiveness in assisting inexperienced designers to better consider constructability.

Participant 13 mentioned that “young engineers rely too much on software and spend too little time on site”. The constructability application could make young engineers aware of constructability challenges early in their careers. Making the value of construction expert knowledge clear to young engineers, could increase their interest and willingness to engage more in site activities. Participant 20 said that “designers can study the building process independently and they should take pride in gaining an understanding of the industry they work in”. If a young engineer uses the constructability application, there could be an increase in understanding and accountability for the constructability of their design.

However, Participant 19 emphasises that “design engineers do not have the practical experience to understand constructability” and Participant 20 states that “architects and engineers would have to experience these problems first-hand to fully understand them”. The constructability tool could increase awareness and understanding of constructability and could improve the considerations of constructability aspects by providing expert advice. However, the application cannot replace practical experience. Participant 1 states that “the opinion is shared by many people in the industry that designers need to be onsite for at least 3 years”.

6.5 Chapter summary

This chapter presents a proposal for a constructability tool designed to assist design engineers in considering the constructability of their designs and better understanding the constructability concepts. The proposed tool, developed as a user-friendly mobile application, aims to foster collaboration among project and organizational team members while improving constructability considerations during the design phase.

As the proof of concept, Thunkable software was employed to realize four features of the constructability tool. These features illustrate the tool's ease of use and practicality, demonstrating its potential to help design engineers better understand constructability concepts and receive valuable advice throughout the project lifecycle. The four features are 1) the user viewing constructability concepts and definitions, 2) the user receiving contractor advice as alerts on a mobile device, 3) a search function for filtering contractor advice data and 4) the addition of user data (lessons learned, advice or reminders) to the contractor advice database.

The validation interviews on the constructability tool application yielded insightful results. The participants predominantly agreed, with many providing "agree" and "strongly agree" responses to all questions. The consensus emerged that the tool is indeed beneficial for design engineers, with a utility in assisting less experienced designers, facilitating supervisory oversight of tasks and facilitating the documentation of lessons learned. The participants could not test the application on their mobile devices themselves, therefore feedback concerning the application's convenience and ease of use was not obtained in the validation interviews.

Presently, the arrangement of contractor advice is organized around 11 design-bid-build phases and the order in which the advice is presented is based on the constructability concepts that are linked to each advice item. To improve the tool's efficacy and practicality, a suggestion is made to align advice with the chronological design process. This adjustment could ensure the timely receipt of advice and mitigate the risk of it reaching the design engineer too late in the project timeline.

Chapter 7: Conclusions and recommendations

This chapter concludes the study by presenting the fulfilment of the research objectives, summarising the key research findings and discussing the value and contribution thereof. It also reviews the limitations of the study and proposes opportunities for future research.

7.1 Conclusions

The work in this study was devoted to the development of a constructability tool to support design engineers in considering the constructability of their designs and being mindful of construction constraints. The focus was on design-bid-build projects in which the designer did not have the opportunity to collaborate with a contractor during the design phase. Therefore, a mobile application was developed that provides a design engineer with advice from construction specialists, information on constructability concepts and the ability to contribute their insights for future reference.

The 23 constructability concepts by Kifokeris & Xendis (2017) are more suited to design-build project frameworks. In adapting these concepts to suit design-bid-build projects, each of the 23 concepts was allocated to the relevant design-bid-build phases to enable practical consideration by designers. The designers can then receive project-phase-specific advice, paired with the appropriate constructability concept, facilitating an increased awareness and comprehension of constructability considerations.

Drawing from interviews with construction specialists, the study found a gap between the 23 constructability concepts from the literature and the advice provided by experts. To accurately reflect expert insights on constructability, eight additional constructability concepts were formulated. In addition, an avenue for future research emerged: the importance of collaboration between designers and contractors. The mobilization phase was pinpointed as an optimal opportunity for this collaboration, enabling focused constructability discussions.

7.1.1 Achievement of objectives

An intuitive mobile application tailored to design engineers was developed and successfully aligned with the outlined objectives.

Firstly, it was found that there is a high level of agreement that design engineers do not have adequate practical construction knowledge and experience to fully consider the constructability of their designs or be mindful of construction constraints. This is especially the case in design-bid-build projects where collaboration with the contractor is only possible after tender award.

Secondly, the 23 constructability concepts by Kifokeris & Xendis (Kifokeris & Xendis, 2017) are more applicable to design-build or turnkey procurement where the contractor becomes involved early in the project. While they categorized these concepts into the initiation phase, the execution phase and the delivery phase, the activities occurring in these phases do not align with the design-bid-build process. With design-bid-build procurement being used most often in government projects, it is all the more important to find a way to incorporate constructability concepts into the design-bid-build format.

Thirdly, in countries where there is low BIM maturity, the readiness for change is lower and it is more difficult to align innovative constructability tools with the industry’s needs. Should one want to develop a tool to incorporate constructability into design-bid-build projects it should be simple and easily adoptable by organizations, teams or individuals.

Objective 1: Seek input from contractors and experts in the construction field

Interviews were conducted with 20 construction specialists and 201 qualitative advice phrases emerged from the data. The extensive database of advice gained from the interviews is suitable to guide design engineers and offers opportunities for future researchers to expand on the specialist advice. The contributions by the construction experts provided clarity on the disconnect between designs and the eventual practical construction. They reinforced the notion that a means needs to be found to improve collaboration between designers and contractors, all in the interest of executing projects better and more effectively.

Objective 2: Systematically and contextually examine the gathered data to attain a more profound understanding of the dataset.

Addressing the challenge of the misalignment between the 23 constructability concepts by Kifokeris & Xendis (2017) and the design-bid-build phases and activities, the 23 constructability concepts are allocated to the relevant design-bid-build phases where the project participants could practically consider the concepts. From the interview feedback, 201 advice phrases emerged of which 100 phrases do not align with the 23 constructability concepts.

To address the gap illuminated by the expert advice, eight additional constructability concepts were defined to suitably encapsulate the content of the advice.

These eight additional concepts are, A. Mentorship and supervision, B. Communication and collaboration, C. Continuous learning, D. Practical design decisions, E. Clarity about scope and specifications, F. Design and software, G. Safety and H. Continuous monitoring. These newly defined concepts serve to complement and expand upon the existing constructability framework and broaden the understanding of the complex dynamics within the construction process in general, and the design-bid-build process in particular.

The participant feedback and findings supported the literature. From the participant feedback it was found that 1) constructability, although widely researched, is not implemented intentionally in design-bid-build construction projects, 2) design engineers often lack or have a limited understanding of construction processes and often fail to adequately address constructability challenges in their designs and 3) the adoption of innovative 3D software is rare.

It was further found that some of the advice related directly to the defined roles and responsibilities of design engineers, while other advice phrases were found to be a challenge for designers to consider because of limitations to their understanding and experience, as well as the challenge of collaboration with contractors at an early stage.

Research aim: Develop a constructability tool in the form of a mobile application to support designers in considering the constructability of their designs and being mindful of construction constraints.

A simple and easily adoptable mobile application was successfully developed. The expert advice gained from the interviews was incorporated into four proof-of-concept features of the mobile application and was allocated to the appropriate design-bid-build phases where the advice can best be considered. Each advice phrase is also connected to a constructability concept to improve the understanding of constructability and help with its incorporation in design. The four application features are capable of the following:

Feature 1 - Presenting the constructability concept definitions: This feature displays constructability concepts, along with their definitions to increase the designer's awareness and understanding of constructability.

Feature 2 - Contractor advice received via alerts/notifications: This feature allows the user to view the contractor advice for design-bid-build phases and enables the user to receive alerts/notifications on constructability considerations on a mobile device for any selected phase.

Feature 3 - A search function to find advice on particular topics: This feature allows the user to search for specific keywords or phrases to find relevant advice within the database.

Feature 4 - Adding user data to the database in the form of advice, reminders or lessons learned: This feature enables the user to contribute new information to the database in the forms of advice, reminders or lessons learned. The user can indicate the relevant constructability concept(s) to the newly added information to continuously approach design with constructability in mind.

Figure 4-2 shows which information is presented in the mobile application and which information can provide general guidance to designers on the most common challenges. In the case where the constructability tool is not used, the most common challenges (Table 4-6) and advice that is easier to implement by designers (Table 4-8) can provide overall recommendations on what aspects to consider to increase the constructability of designs.

In the pursuit of achieving the research aim, an important aspect was identified for future research. Addressing the lack of early contractor involvement in design-bid-build projects, the mobilization phase is identified as the ideal phase for constructability-centred collaboration between the designer and the contractor and is also the earliest opportunity for this collaboration.

However, some challenges emerged concerning the design changes that may result from such collaboration. Modifying the design during mobilization, which could lead to cost changes, may pose questions about the fairness stipulations in the Procurement Act and the Competition Act of South Africa. Other challenges relate to the conflict between participants, biases, resistance to change and time limitations. Additional research could further investigate these challenges and propose novel means to try and address them.

Objective 3: Verify the efficiency of the suggested constructability tool by utilizing feedback from contractors and/or construction specialists and pinpoint opportunities for improvement.

The effectiveness and acceptability of the constructability tool were verified through subsequent discussions with 5 construction experts to pinpoint opportunities for improvement. The interviewees were also probed on the suggestion of constructability-centred collaboration during the mobilization phase to determine the practicality and possibility of such collaboration.

Regarding the constructability tool, the interviewees agreed strongly that the mobile application should be used to keep a record of lessons learned and there was substantial agreement that this tool could help inexperienced designers. The challenges identified by the participants included biases, resistance to change and time constraints due to concurrent projects.

Regarding collaboration during the mobilization phase, the interviewees agreed that the mobilization phase is the most suitable opportunity for contractor-designer collaboration in a design-bid-build project and indicated that it is often possible to make changes to the design resulting from the collaboration. Challenges identified by the participants included potential resistance to change and difficulties in incorporating different perspectives during the collaboration. The participants best suited to take responsibility to drive the collaboration during the mobilization phase are identified as, firstly the project manager, secondly the engineer and third the client.

7.1.2 Relevance of the study

The study addresses the need to improve constructability in traditional procurement methods and offers practical solutions for including constructability considerations during the design phase and promoting collaboration and knowledge exchange between designers and contractors during the mobilization phase. These solutions allow for early identification and resolution of constructability challenges, minimizing rework, improving project efficiency and enhancing project quality and safety. Since there is limited research on the implementation of constructability considerations in design-bid-build projects, the study fills a knowledge gap in the existing literature.

Firstly, the study contributes to the construction industry by presenting valuable advice and feedback on constructability considerations provided by industry professionals. The contractor's advice, incorporated into a user-friendly mobile application, is a practical resource for young design engineers to better understand the value of being mindful of construction constraints. Beyond the mobile application, common constructability challenges (Table 4-6) and feasible advice (Table 4-8) are also provided as general recommendations for designers to consider.

Additionally, the study contributes to the industry by identifying the mobilization phase as the ideal phase in a design-bid-build project for collaboration. The practical implementation of constructability-centred collaboration during mobilization should be investigated further.

7.1.3 Applications in the construction industry

The findings from this study can be applied by project managers, designers and contractors to enhance constructability, improve project efficiency and foster a collaborative culture. The study's findings have practical applications in construction project execution.

During project planning and set-up, project managers can use the findings to initiate an integrated planning process during project setup in the mobilization phase. By encouraging intentional collaboration between designers and contractors from the early stages of mobilization, more construction-sensitive decisions can be made, construction efficiency can be improved and costly design changes during construction can be avoided. The mobile application can be deployed in organizations or teams or can be adopted by individual designers who seek to improve the constructability of their designs. Design engineers can use the tool to access contractor advice and to add their lessons learned to the database to be utilized by the organization team or individual for improvements on future projects.

7.2 Recommendations for future work

In this section, the recommendation for future work is discussed. The limitations of the study are related to the qualitative nature of the data, the small sample size, the emphasis on particular types of structures, the partial development of the constructability tool and related software and insufficient integration of industry standards and codes into the mobile application.

Each of these limitations applies to 1) the contractor advice feedback, 2) the proposed constructability tool or 3) the collaboration within the mobilization phase, as presented in sections 7.2.1, 7.2.2 and 7.2.3 respectively.

7.2.1 Building on the contractor's advice and findings from the data

The limitations that are relevant to the contractor advice findings are the small sample size, the qualitative nature of the data, the scope being limited to low-medium rise structures and the limited specificity about particular project circumstances. Based on the limitations, some specific areas for further exploration and development are:

Expand the sample size: Future researchers should aim to increase the sample size to include a more diverse range of participants. A larger sample would improve the generalizability of the findings and provide a more comprehensive understanding of the various perspectives and experiences in the construction industry.

Include different project types: While the data collection for this study focussed on low to medium-rise structures, future researchers can explore contractor advice in other types of construction projects. Comparing and contrasting advice across different project types would offer valuable insights into how constructability considerations vary.

Incorporate project-specific context: To enhance the applicability of the findings, future research should consider incorporating project-specific contextual factors that may influence constructability considerations. Factors such as project size, complexity and location could play a role in shaping contractor advice, as well as the strategy for designer-contractor collaboration.

Qualitative and quantitative approaches: Combining qualitative insights from interviews with quantitative data could offer a more robust analysis of the impact of contractor advice on project performance. By gathering both qualitative feedback and quantitative performance metrics, researchers can establish stronger correlations.

By building on these aspects and expanding the research scope, future researchers can contribute to a more comprehensive understanding of the role of contractor advice in enhancing constructability in design-bid-build projects.

7.2.2 Reassessing and building on the framework and theory of the constructability tool

Some areas for further investigation for the development of the software application are:

Full-scale implementation of the mobile application: The current study presented a proof-of-concept of the constructability tool using Thunkable software. Future researchers can develop a fully functional version of the tool and conduct field tests to evaluate its usability, effectiveness and impact on construction projects.

Logical order of contractor advice notifications: The current contractor advice database for each phase does not provide advice in order of design steps or priorities. Future research can organize the data for the application to effectively provide the most important advice to the designer first or chronologically based on the design sequence.

Mobile application software: The Thunkable software used in this study is not entirely suitable for the effective use of large databases. Future researchers can explore more suitable software that can implement the desired features and accommodate a growing database.

Expand on the constructability concept feature to improve awareness: Future researchers can enrich the awareness of constructability concepts by linking the implementation of each concept to real-world examples and research.

Industry standards and guidelines: Future researchers can incorporate local standards, guidelines and best practices into the tool to provide a more comprehensive resource for young design engineers.

7.2.3 Reassessing and building on the framework and theory of collaboration in the mobilization phase in design-bid-build projects

Limited previous research is available on the implementation of constructability concepts (which includes collaboration between all stakeholders) in design-bid-build projects. A key finding in this study is that the mobilization phase, by definition, includes collaborative activities between designers and contractors. However, the interview participants do not often experience such collaboration in their design-bid-build projects. Future research can investigate specific ways in which the project manager and the client can incorporate constructability-centred collaboration into the mobilization phase of design-bid-build projects.

Improved collaboration between designers and contractors has the potential to be beneficial for all the role players in a project. This seems to be acknowledged by all stakeholders consulted in this study. However, the opportunities for such collaboration, especially in the design-bid-build procurement framework, seem to be undeveloped and viewed with scepticism. This study contributes new ideas and methods that could be considered to make progress towards a model where the incorporation of expert construction knowledge in design decisions (through the mobile application), together with meaningful consultation between role players during mobilization, can improve how we design and execute construction projects.

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Appendix A: Interview sheets

A.1 Interview sheet for construction specialist interviews

This appendix section shows the interview sheet for the interviews with 20 construction specialists. The interview sheet includes the project summary and the six interview questions.

Project summary

The main topics involved in the proposed research paper are "Constructability" and "Early Contractor Involvement (ECI)". ECI is an ideal way to improve the constructability of engineering designs. When construction specialists are involved during the design phase, they can offer expert knowledge of construction processes and warn against potential difficulties that may occur during construction. This collaboration provides the design engineer with valuable knowledge that can aid in the creation of construction-sensitive designs and, in turn, mitigate constructability problems early in the project life cycle.

For the proposed research paper, it will be assumed that design-bid-build procurement is the traditional method that is most widely used and that early contractor involvement is not possible during the design phase. For a proposed collaborative constructability tool, this interview aims to collect data for the content and framework of the proposed tool.

Interview goals

Goal 1: To determine which aspects, according to construction specialists, increase the difficulty of the construction process the most, concerning the design decisions that design engineers make (or do not make).

Goal 2: To determine what advice construction specialists would provide to design engineers during the design phase to aid designers in creating construction-sensitive designs. (Based on 7 constructability aspects as inspiration)

Goal 3: To determine the willingness of construction specialists to participate in a collaborative constructability discussion forum.

Interview approximate length

The interview will have a time length of approximately 60 minutes to 90 minutes.

Interview Questions

Question 1	a) What is your highest level of education? b) What is your current position? c) How many years of experience do you have in construction?
Question 2	In your experience, which **2 aspects** increase the difficulty of the construction process the most concerning the design decisions that design engineers make (or do not make)?
Question 3	In your experience, how actively do design engineers consider **the constructability aspect** during the design phase, on a scale from 1 to 5? 1: "Not considering it at all" 5: "Always making a great effort to consider it" *1. *availability of resources** *2. *primary construction methods** *3. *site accessibility and spatial requirements** *4. *creating simple and rational designs** *5. *the standardization of elements or units** *6. *preassembly, prefabrication and/or modularization** *7. *site safety**
	Answer: 1, 2 or 3: Ask Questions 4 and 5 **Answer: 4 or 5:** Skip Questions 4 and 5
Question 4	Could you provide an example of a case where the design engineer did NOT consider **the constructability aspect**, which resulted in problems during construction?
Question 5	If you could advise a design engineer on what he/she should focus on during the design phase regarding *t*he constructability aspect** to create a more construction-sensitive design, what advice would you give?
	Repeat Questions 3, 4 and 5 for each of the 7 constructability concepts
Question 6	If there were a collaborative forum for young design engineers and retired construction specialists where young engineers could ask questions regarding the constructability of a design, would you be willing to provide advice via the forum as a retired construction specialist (or even now)?

A.2 Interview sheet for validation interviews

This appendix section shows the interview sheet for the validation interviews with 5 construction specialists. The interview sheet includes the interview goals, the seven interview questions and Figure A-1 which demonstrates the constructability-centred mobilization phase.

Additional interview goals for interviews with five participants:

Goal 1: To determine the opinion of the participant on whether the constructability tool is a useful tool to help designers better consider constructability during the design phase.

Goal 2: To determine the opinion of the participant on whether the mobilization phase is the ideal time to prioritise contractor-designer collaboration.

Interview approximate length

The interview will have a time length of approximately 40 minutes.

Disclaimer

The interviewee's personal information, as well as their company details, will **NOT** be shared in the research paper.

No recording of the meeting is necessary, since Likert scales are mostly used and the few open-ended questions require a short answer that the interviewer can simply write down.

Validation interview questions for five previous participants:

Interview Type: Zoom meeting or Teams meeting

Interview Set-up: The participant will be presented with the proposed constructability tool, as well as the proposal about constructability-centered collaboration during the mobilization phase. Thereafter, the participant will be asked the following 7 questions.

Question 1

Statement:
This tool will aid design engineers to better consider constructability during the design phase.

Please select 1 of the 5 Likert scale options:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Question 2

Statement:
I would suggest this tool to young designers.

Please select 1 of the 5 Likert scale options:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Question 3

Would you prefer the tool to have one of the following goals:

1. A tool to help inexperienced designers.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

2. A tool for mentors and supervisors to verify the work of their subordinates.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

3. A tool to keep a record of lessons learnt.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

4. All of the above.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Question 4

Statement:
The mobilization phase is the most suitable time for contractor-designer collaboration in a design-bid-build procurement project.

Please select 1 of the 5 Likert scale options:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

If a 1 or a 2 is answered, please provide a time/phase within a design-bid-build project that you believe is most suitable for contractor-designer collaboration.

Answer if applicable: ____

Question 5

Collaboration during the mobilization phase may lead to changes. Will the following changes be possible to make after the tender award?

Select all changes that will be possible:

- ☐ Changes to selected resources and materials
- ☐ Changes to primary construction methods
- ☐ Changes to design layout (spacing between buildings or pipes, amendments to above-ceiling space requirements for MEP services)
- ☐ Changes that involve standardizing elements or units that were not previously standardized
- ☐ Changes from an in-situ design to prefabrication

Question 6

Implementing the constructability concepts in a design-bid-build project could be a challenge because:
1) It expects larger responsibility on the side of the designers to consider the ease of construction.
2) Collaboration after tender awards, and requests for variation orders, could increase adversarial relationships between participants instead of improving them.

In your opinion, what other challenge(s) will be prevalent in the attempt to:

a) prioritise constructability implementation during the design phase by designers?
Answer: ____

b) prioritise collaboration during the mobilization phase in a design-bid-build project?
Answer: ____

Question 7

Please rank the following participants in order of responsibility to drive the implementation of constructability in the design phase and drive collaboration during the mobilization phase.

Provide each participant with either a 1, 2, 3 or 4 ranking. If there is another participant that you have in mind, please specify.

- ☐ Client
- ☐ Project Manager
- ☐ Architect
- ☐ Engineer
- ☐ *Other: [Please specify]*

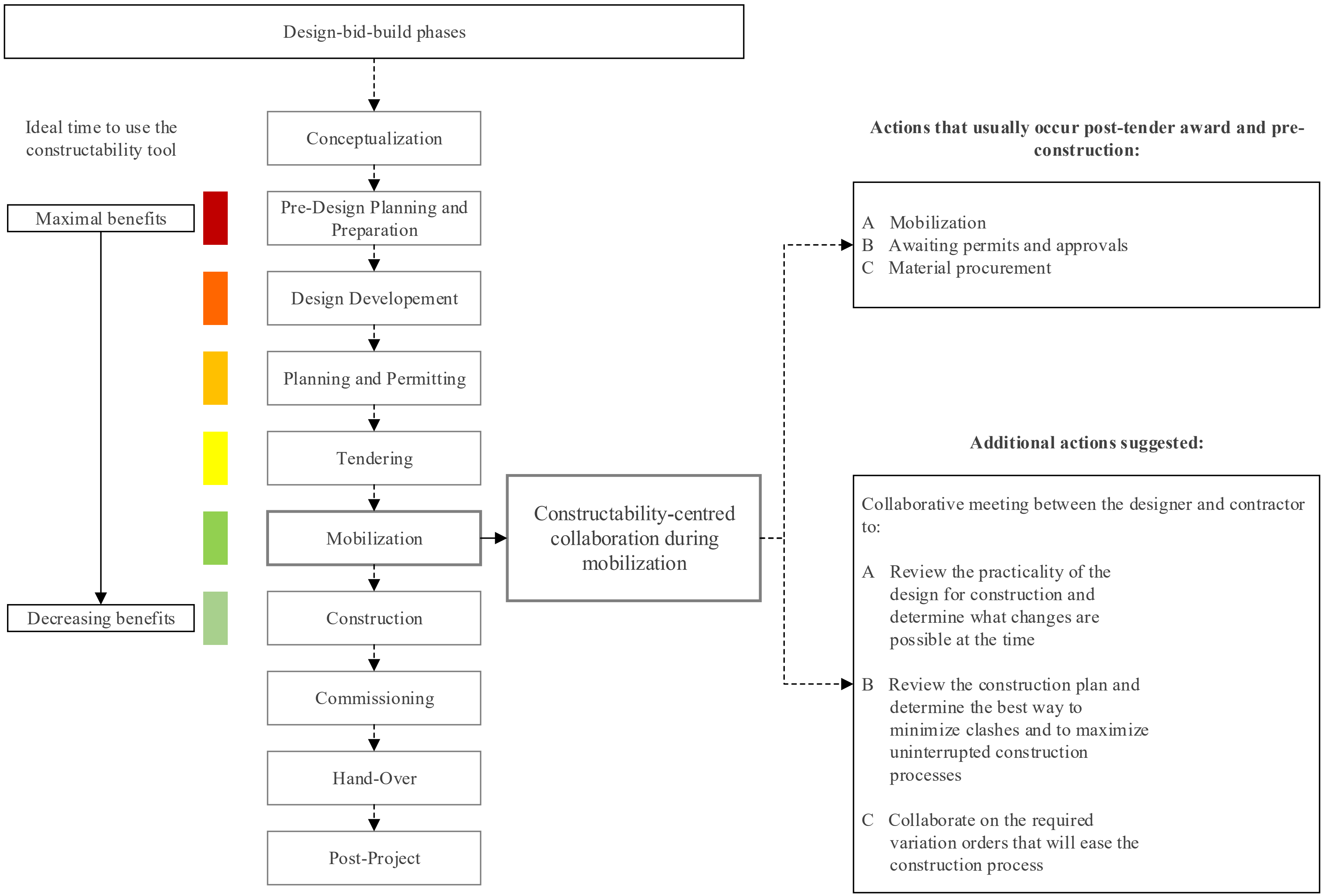


Figure A-1: Design-bid-build phases showing the constructability-centred mobilization phase

Appendix B: Interview data

B.1 Code allocations for use in Statistica software

Figure B-1 shows the variables (Var) from the interview questions and their respective codes used in the spreadsheet for Statistica analysis.

Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Variables 6–12	Variables 13–19	Variables 20–27	Variable 28
	Qualification	Current Position	Years of Experience		Aspect Ranking			
Interview Number	Question 1 a)	Question 1 b)	Question 1 c)	Question 2	Question 3	Question 4	Question 5	Question 6
1 - 20	1: Civil Engineering 2: Non-Civil Engineering	1: Executive and Leadership Positions 2: Construction and Project Management Positions	1: < 10 2: 11 - 20 3: 21 - 30 4: > 30	1 - 17	1: Rank 1 2: Rank 2 3: Rank 3 4: Rank 4 5: Rank 5 6: No Answer	1 - 13 1 - 21 1 - 18 1 - 17 1 - 11 1 - 8 1 - 11	1 - 18 1 - 12 1 - 17 1 - 12 1 - 11 1 - 6 1 - 10	1 - 16
				Corresponding with 17 participant answer groupings	Rank 1: Design engineers do not consider the aspect at all. Rank 2: Design engineers make a great effort to consider the aspect.	Corresponding with contractor advice groupings for each of the 7 aspects	Corresponding with contractor advice groupings for each of the 7 aspects	Corresponding with 16 participant answer groupings
				Appendix B-2 Table B-1		Appendix B-2 Table B-2 to B-8	Appendix B-2 Table B-9 to B-15	Table 4-10

Figure B-1: Codes for 28 variables relating to questions 1 to 6.

B.2 Collection of advice concepts from interview data

The 15 tables in this appendix section present the contractor advice phrases for each question and aspect of the interview process.

Table B-1: Contractor advice derived from Question 2

	Question 2: Design decisions that increase the difficulty of construction		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Consider access and space on the site during the design	4	14
2	Consider the sequence of works and construction methodology during the design	3	8
3	Have adequate site visits before design to optimally design for the specific site conditions	2	7
4	Do not send young engineers to the site before design without an experienced engineer present	2	A
5	Consider the practicality of the structure and/or finishes	3	D
6	Ensure that proper communication and engagement occur to obtain all the necessary information that may influence the design	2	B
7	Consider the availability of all resources required for the design to be realised	4	8
8	Prioritise value engineering and collaboration exercises before construction commencement	7	B
9	Consider the use of 3D modelling software and clash detection software	3	F
10	Attempt to involve the contractor as early on in the project as possible	7	B
11	Ensure that you provide timeframes based on a good understanding of construction processes and material acquisition and do the necessary research to provide accurate timeframes	4	5
12	Do not specify materials/products that cannot be used in conjunction with one another	3	16
13	Do not bind yourself to software results and rather prioritize optimizing the design	4	10
14	Ensure that you obtain the necessary site information and that you inspect the existing services on the site location	2	7
15	Do not finalize the project schedule before having all the necessary information and approval that will influence that schedule	4	5
16	Ensure that adequate research is done and that the site context is understood in terms of site conditions, the influence of rain on the area and the community culture	2	7
17	Take accountability for the degree to which your design is construction-sensitive	3	F

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-2: Contractor advice derived from Question 4, Aspect 1

	Question 4 **Aspect 1: Availability of resources**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ensure that materials/products/technology are available in the country	3	C
2	If the specified material/product/technology is difficult to procure in the country, research and consider other options	3	C
3	Avoid custom-made dimensions for steel and ensure that steel sections are available at the time of the project	3	12
4	Ensure that specifications and method statements are reasonable and practical to implement	3	6
5	Think practically about the contractor's limitations	3	D
6	Think practically about material transportation to the site	3	D
7	Reconsider using methods/materials/technologies that have not been used often in the country or require specialised skills	3	C
8	Ensure that maintenance of the materials/products will be available in the future	3	D
9	Be reasonable concerning the timeframe of acquiring materials/products/technologies	4	5
10	Ensure that the quarry can yield the correct amount of material	2	7
11	Ensure that the geotechnical analysis and exploration of works are done thoroughly to know what material is available on site and what resources are required for the site preparation	2	7
12	If a product or material is not available due to unforeseen circumstances, ensure that this is communicated to the whole project team regarding schedule and cost changes	8	B
13	If the designer does not specify the exact material/product to use, the designer should research the options that will be available to the contractor on the market and determine whether those options suit the specifications	5	C

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-3: Contractor advice derived from Question 4, Aspect 2

	Question 4 Aspect 2: Primary construction methods		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ensure that the concrete aggregate can fit in between the rebar and that the rebar is adequately encased in concrete	3	F
2	Ensure that the transport of materials to a site is possible and practical	3	D
3	Ensure that the geotechnical analysis is done thoroughly and that the report includes ground-level boulders	2	7
4	Ensure that the number of trees is correctly specified	2	7
5	Have adequate site visits before design, as well as during construction to better understand the construction process	2	C
6	Ensure that there are no clashes between MEP services, underground water services and design elements	3	B
7	Consider the sequence of events and construction methodology while designing	3	8
8	Ensure that machinery and heavy vehicles can enter and exit the site and reach the required position	3	18
9	Gain an understanding of the complexity of installing multiple services on site: MEP and underground water services	8	C
10	Ensure that there is enough space for cranes and that the ground or structure they stand on can support the weight of the crane	3	F
11	Ensure that tolerances and specifications are reasonable and practical	3	12
12	Ensure that structure front door heights are high enough to prevent water from flowing in and that slopes are correctly calculated for efficient water runoff	4	F
13	If services are specified to be added to the roof, ensure that this does not add significant weight to the roof and require a redesign	4	F
14	Analyse whether bolting or welding is the better option regarding access and safety	4	18
15	Ensure that all services and design elements' dimensions are correctly indicated in drawings	4	F
16	Ensure that emergency services (e.g., fire, health) can easily and practically reach fire taps and have adequate space to operate	4	F
17	Ensure that the inside of the structure has adequate ventilation to avoid reaching the dew point	4	F
18	When methodologies are complex, ensure that potential problems are investigated and that the best solutions are found	3	6
19	Ensure that soil conditions are known to avoid inadvertent under-designing	2	7
20	For a lengthy construction project, monitor changes in the site conditions as construction advances	8	H
21	Ensure that the fixing details of aesthetic specifications are considered thoroughly and that they are practically possible	3	12

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-4: Contractor advice derived from Question 4, Aspect 3

	Question 4 Aspect 3: Site accessibility and spatial requirements		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ensure that there is adequate space to install formwork and scaffolding safely and that there is space for workers to install it	3	6
2	Ensure that MEP (Mechanical, Electrical and Plumbing) services are well coordinated and that pipes do not clash with design elements like boundary walls and foundations	3	F
3	Consider the location on site of the contractor's offices	3	D
4	Ensure that the specified machinery and heavy vehicles can reach the required positions on-site and operate safely	3	18
5	Negotiate with the architect about spatial requirements	3	B
6	Ensure that you have a good understanding of the location of trees and existing services like manholes, water pipes and electrical installations	2	7
7	If spatial requirements cannot be considered, provide suggestions to the contractor and include the risk in the tender	5	B
8	Ensure that the soil stability is adequate and specify if strutting is required	3	12
9	Ensure that you have a good understanding of standard scaffolding, formwork and crane dimensions	3	C
10	Consider the construction methodology and ensure that it is reasonable and practical	3	6
11	If large steel or concrete elements are specified, ensure that there is space on site to place them before installation	3	14
12	Consider the use of cranes in windy areas and ensure that the loss of time due to the wind is considered	4	15
13	Discuss complex methodologies with the project team and the contractor	7	B
14	Consider continuous site activities like outside paving, and suggest methodologies that prevent interruption of work on-site	4	8
15	Ask the contractor for advice on accessibility and spatial requirement decisions	7	B
16	Consider that the placement of the parking area can be used for storage, offices and/or staff parking before paving commences	7	16
17	Consider the turning radii of the heavy vehicles that will be required during construction	3	D
18	Attempt to provide the contractor with as much space as possible	4	18

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-5: Contractor advice derived from Question 4, Aspect 4

	Question 4 **Aspect 4: Creating simple and rational designs**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ensure that no clashes occur with rebar, steel beams or MEP (Mechanical, Electrical and Plumbing) services	3	12
2	Optimize your design and avoid overdesigning structural elements	4	10
3	Ensure that concrete can fit in between the rebar and that the rebar is adequately encased in concrete	3	F
4	Ensure a good understanding of the client's scope and that you collaborate with your project team	2	E
5	Gain more site experience and go to the site as often as possible during the project	8	C
6	Ensure that the specified time frames are reasonable and practical	4	5
7	Ensure the correct interpretation of building codes	3	E
8	Consider the use of as many 90-degree angles and straight lines in your design as possible to ease construction	3	D
9	Ensure that load-bearing walls do not include large doors or sliding doors to avoid extra structural support requirements	3	F
10	Ensure that service shafts are placed in practical positions and that services connect practically to the service shaft	4	D
11	Consider the simplest and most cost-effective construction methodologies	3	6
12	Consider whether insulation is required to prevent the doming of floors	4	F
13	Do not design in isolation	3	A
14	Consider the importance of fast decision-making	8	B
15	Do not compartmentalize your design elements and risk them not being practical to construct in conjunction with one another	3	16
16	Ensure that you do not under-design due to the soil conditions having not been investigated thoroughly	2	7
17	Ensure a good understanding of the type of structure you are designing and rationalize according to the infrastructure type	3	10

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-6: Contractor advice derived from Question 4, Aspect 5

	Question 4 **Aspect 5: Standardization of elements or units**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	If normal concrete pouring would cause a complex start-stop methodology, consider prefabrication	3	13
2	Gain knowledge of the standard dimensions of scaffolding, formwork, pipes, windows, doors and bricks	3	C
3	When standardizing formwork, ensure the consideration of shape (e.g., cone-shaped columns of different heights will require custom formwork for each column)	3	11
4	Avoid custom formwork or custom steel elements if possible	3	11
5	Duplicate and standardize as many sections and elements as possible to ease construction	3	16
6	Consider the use of Maxi bricks instead of ROK bricks	4	D
7	When designing elements of the structure, consider the construction methodology of construction activities that will occur simultaneously and close to one another	3	6
8	When using a standard material or product, ensure that it is adequate for the unique project circumstances and consider whether it will require modification	3	19
9	Ensure that the elements that are specified to be custom-designed or manufactured are truly required and consider whether there are alternatives	4	12
10	Gain an understanding of the complex manufacturing process	3	C
11	If custom finishes for architectural aspects are required, ensure that the time-frames and schedules for acquiring the finishes are well managed in advance	4	5

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-7: Contractor advice derived from Question 4, Aspect 6

	Question 4 **Aspect 6: Pre-assembly, prefabrication and/or modularization**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	If pipes are to be cast in concrete, consider using precast pipes instead to avoid the impracticality of pipes wanting to float in the concrete	3	12
2	Consider prefabrication w.r.t time and cost	3	13
3	Ensure a good understanding of the processes and requirements of prefabrication	3	C
4	If prefabrication is considered, ensure that the design corresponds with standard prefabrication formwork to avoid custom formwork requirements	3	13
5	To fully consider prefabrication as an option, first ensure a good understanding of the project scope and specifications	2	E
6	Do research about the developments of prefabrication and modularization in your country	3	C
7	Consider innovative ways to ease the construction process	7	17
8	Analyse the feasibility of prefabrication w.r.t the benefits of using it (e.g., repetition and quality)	3	13

**DBB Phase: Design-bid-build phase (Number 1 to 11)* *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-8: Contractor advice derived from Question 4, Aspect 7

	Question 4 **Aspect 7: Site Safety**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ensure that the slopes of ditches are safe by providing enough space for more gradual slope walls on either side	3	18
2	Ensure that there is adequate space to safely construct scaffolding, provide railings and fasten harnesses	3	18
3	Ensure a good understanding of construction sequencing and methodologies so that you can identify safety hazards within your design	4	C
4	Go to the site more often to gain experience in identifying safety hazards in your design	8	A
5	Provide as much detail as possible to the contractor and, if possible, suggest safety measures specific to hazardous activities	5	G
6	Ensure that you do not create safety hazards by under-designing due to the soil conditions having not been investigated thoroughly	2	7
7	Consider the uniqueness of the infrastructure type and identify hazards that may occur during the operational phase of the project	3	G
8	Consider areas in your design that would cause construction workers and other staff to have poor natural light while working	7	18
9	Consider the safety hazards of bushy sites and ensure that roads are cleared for construction vehicles to avoid the wheels getting clogged by grass	7	18
10	If the construction methodology is high in complexity and hazardous activities, reconsider the design and look for safer alternatives	4	G
11	Consider the soil type w.r.t the safety of a ditch slope in rainy weather conditions	3	18

**DBB Phase: Design-bid-build phase (Number 1 to 11)* *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-9: Contractor advice derived from Question 5, Aspect 1

	Question 5 **Aspect 1: Availability of resources**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Gain local advice from suppliers about the availability of resources	3	B
2	Gain local knowledge about availability in the country	3	C
3	Negotiate with the client and/or architect about the choice of resources	3	B
4	Soundboard ideas with more experienced seniors/individuals	3	A
5	Ask a contractor or subcontractor about their knowledge of available resources on the market	7	B
6	Create a construction method statement to better understand what resources are required	3	8
7	Think about the practicality of the chosen resources	3	D
8	Get site experience to better understand the practical implementation and negative effects of the chosen materials and resources	8	A
9	Do research about the resources that are best suited for the site circumstances	3	C
10	Prioritise geotechnical investigations to know what materials are available on-site and what resources are required during construction	2	7
11	Get a trusted sales representative and obtain guarantees, if possible	4	B
12	Do not proceed with assumptions	3	A
13	Approach design with a planning point of view	3	5
14	Attempt to specify the simplest and most accessible resources possible	3	12
15	Gain a better commercial awareness	3	C
16	Obtain a detailed scope to identify the key skills required for the specified resources and ensure that those skills are readily available	3	19
17	Provide alternative materials or products to mitigate material acquisition risk	5	E
18	Consider the time frame for acquiring materials	4	5

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-10: Contractor advice derived from Question 5, Aspect 2

	Question 5 Aspect 2: Primary construction methods		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Get construction experience and go to the site more often to better understand the construction process	8	A
2	Collaborate with the contractor and discuss the design	7	B
3	Set up a team for a pre-construction design meeting to discuss the construction methods	7	B
4	Do not allow students to do work unchecked or go to the site alone as they do not have enough experience to adequately consider construction methods	2	A
5	Learn how your design influences construction by following up during construction and soundboarding experienced individuals	8	A
6	Think about the sequence of events, practicality and construction methodology while designing	3	8
7	Determine the most efficient design in terms of construction methods and optimise your design	3	10
8	If you are unsure about construction methods, talk to your more experienced colleagues	3	A
9	Do not proceed with assumptions	3	A
10	Spend more time on planning, researching and defining the scope	2	E
11	While thinking of the end product, consider the specialist skills that are required to obtain the end product	3	D
12	Ensure clear and constant communication to all parties about sudden changes to the design	8	B

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-11: Contractor advice derived from Question 5, Aspect 3

	Question 5 Aspect 3: Site accessibility and spatial requirements		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Get advice, provide suggestions and collaborate with contractors as early as possible	7	B
2	Use 3D modelling software and clash detection capabilities	3	F
3	Learn from previous projects and similar designs	3	A
4	Make a checklist for yourself containing everything that has to move on and off-site	3	D
5	Consider whether your design is practical to build within the provided space and visit the site to make sure	2	7
6	Put yourself in the contractor's shoes	3	B
7	Negotiate with the architect about spatial requirements	3	B
8	Create a high-level method statement	3	6
9	Ensure that the scope is clear and gain a good understanding of the project requirements	2	E
10	Do your research and identify potential problems regarding accessibility and space	2	C
11	Take accountability for ensuring that there is adequate space for site activities	3	18
12	Be creative and utilize opportunities to obtain the best solutions	4	17
13	Visit the site often to better understand how spatial problems hinder efficient construction	8	A
14	Ensure continuity of work by providing sequencing suggestions	5	16
15	Do research about the standard turning radii of commonly used heavy construction vehicles	3	C
16	Consider that trucks can get stuck in muddy areas during the rainy season	3	15
17	Do not let junior engineers do documentation and site checks alone because they do not have adequate knowledge to consider the necessary aspects	2	A

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-12: Contractor advice derived from Question 5, Aspect 4

	Question 5 Aspect 4: Creating simple and rational designs		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Ask for advice from more experienced individuals	3	A
2	Gain advice from contractors and collaborate on the required changes to be made	7	B
3	Use BIM (Building Information Models) and 3D modelling software	3	F
4	Get mentorship and request reviews of your work	4	A
5	Get experience and exposure by spending more time on-site	2	A
6	Thoroughly check your design and keep it simple	4	12
7	Ensure a continuous learning process during the entire project	8	A
8	Instead of working in isolation, share information and request support from the project team	3	A
9	Spend enough time planning, doing research and reviewing similar past projects	2	E
10	Optimise the design w.r.t cost and available skills	4	10
11	When providing alternatives to elements in a design, also analyse which of the alternatives is the best option and communicate that to the contractor	5	B
12	Put yourself in the contractor's shoes	3	B

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-13: Contractor advice derived from Question 5, Aspect 5

	Question 5 Aspect 5: Standardization of elements or units		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Do research on prefabrication and new technology	3	C
2	Determine whether repetition and identical manufacturing of elements is possible within the scope and specifications	3	13
3	Think practically about what the contractor would need for the formwork process	3	D
4	Make yourself aware of standard sizing and dimensions and know how to calculate them	3	C
5	Stay informed about available products and read the supplier brochures	3	C
6	Negotiate with the architects about the potential standardization of elements	3	11
7	Ensure clear specification of work	2	E
8	When using innovative methods, tailor them to the unique project circumstances and type	4	19
9	Clearly and constantly communicate changes to all project parties to avoid problems later on in the construction process	8	B
10	Get different perspectives from seniors and other project participants to obtain the best solutions	3	B
11	If custom manufacturing is required, adapt the specification to what is available within the specified time frame and with the available skills	3	12

Table B-14: Contractor advice derived from Question 5, Aspect 6

	Question 5 Aspect 6: Preassembly, prefabrication and/or modularization		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Do research on prefabrication and consider new technologies	3	C
2	Look at what other countries are doing and evaluate the benefits from another perspective	3	C
3	Keep up with changes and developments in the industry	3	C
4	Encourage involvement in R&D, academic institutions and innovation competitions	8	C
5	Consider prefabrication for smaller sections of the design if a larger scale of prefabrication is not possible	4	20
6	When prefabrication is considered, ensure that the benefits of prefabrication are maximised w.r.t repetition, cost and time	3	13

**DBB Phase: Design-bid-build phase (Number 1 to 11)* *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* *Tables 2-2, 2-3. 2-4 and 4-9*

Table B-15: Contractor advice derived from Question 5, Aspect 7

	Question 5 **Aspect 7: Site Safety**		
	Collection of grouped answers	**DBB Phase***	**CC****
1	Identify hazards within your design and understand how your design influences safety	3	G
2	Gain site experience to better understand construction methodologies and can then more effectively identify safety hazards	8	A
3	Take accountability for safety and research previous similarly complex projects to obtain the safest solutions	3	G
4	Have a close-down meeting to discuss the safety hazards that were identified and not addressed early enough	11	G
5	Share the hazards identified with the entire project team and determine how to mitigate the safety risk	7	G
6	Make suggestions about construction methods that may reduce safety hazards	5	G
7	Consider that the construction workers need to work in adequate light to work safely	7	18
8	Consider the uniqueness of the project and identify hazards associated with the unique aspects	3	G
9	Provide the contractor with as much detail as possible to allow him to mitigate hazards and add the required items to the bill of quantities	5	G
10	Attend webinars and conferences to stay up to date with new technologies and developments in the industry that improve construction safety	2	G

**DBB Phase: Design-bid-build phase (Number 1 to 11)* — *Appendix C.1*

***CC: Constructability concepts (Numbers: 1 to 23 Constructability concepts from literature - Letters: A to H additionally defined constructability concepts)* — *Tables 2-2, 2-3. 2-4 and 4-9*

B.3 Ranking results with the current employment position comparison

The seven figures in this appendix section present the employment position comparison for the ranking results of the seven constructability aspects by the interview participants.

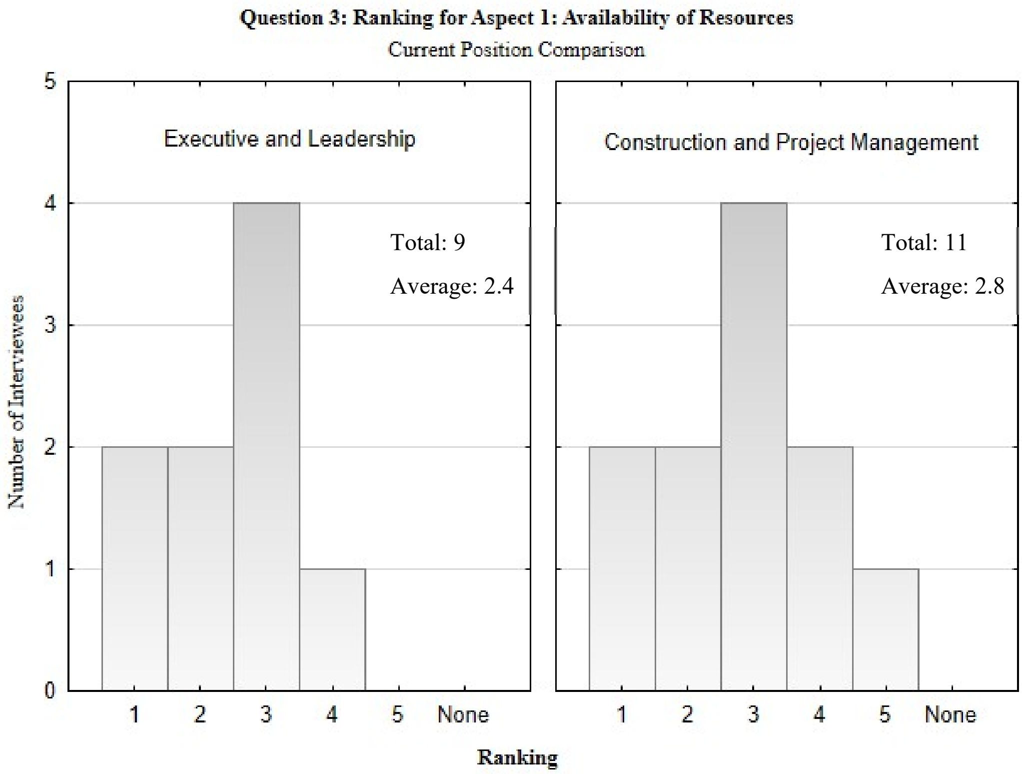


Figure B-2: Question 3 Aspect 1 Employment position comparison

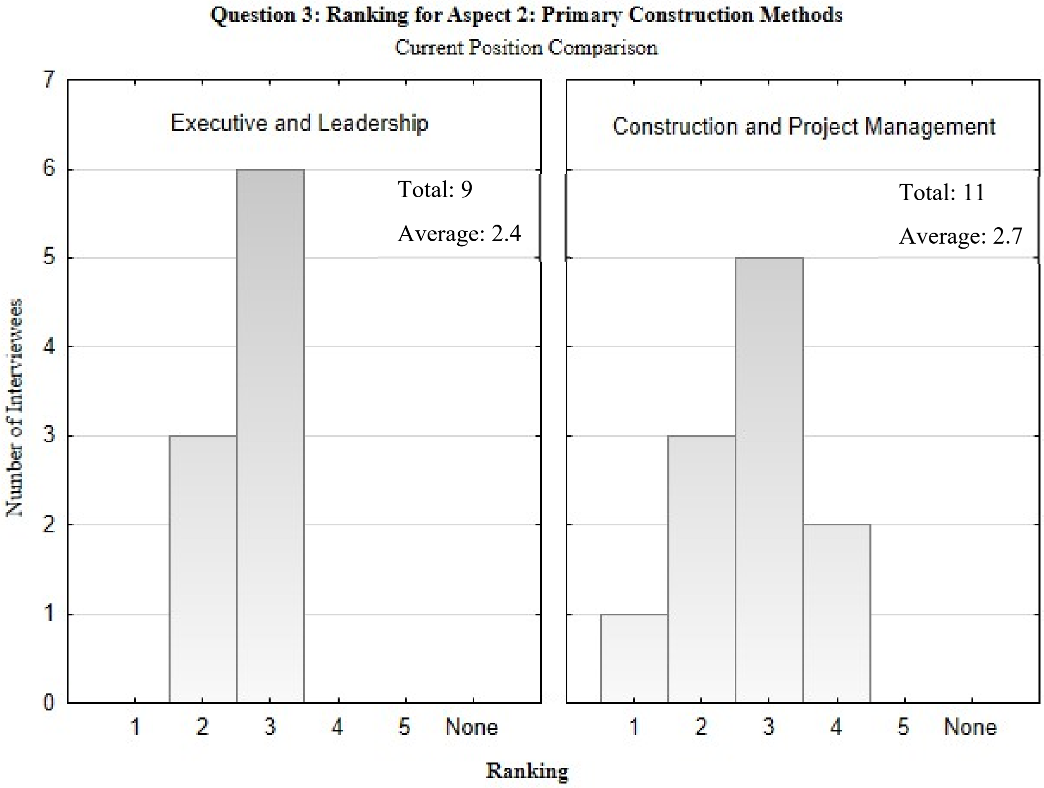


Figure B-3: Question 3 Aspect 2 Employment position comparison

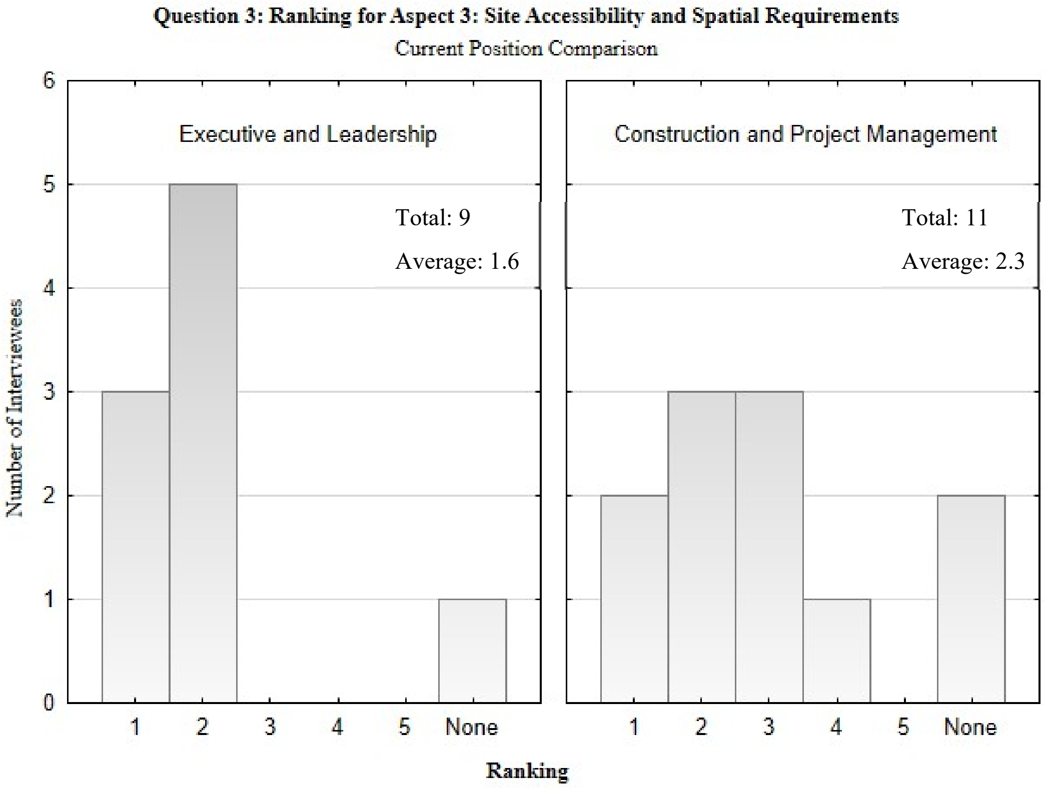


Figure B-4: Question 3 Aspect 3 Employment position comparison

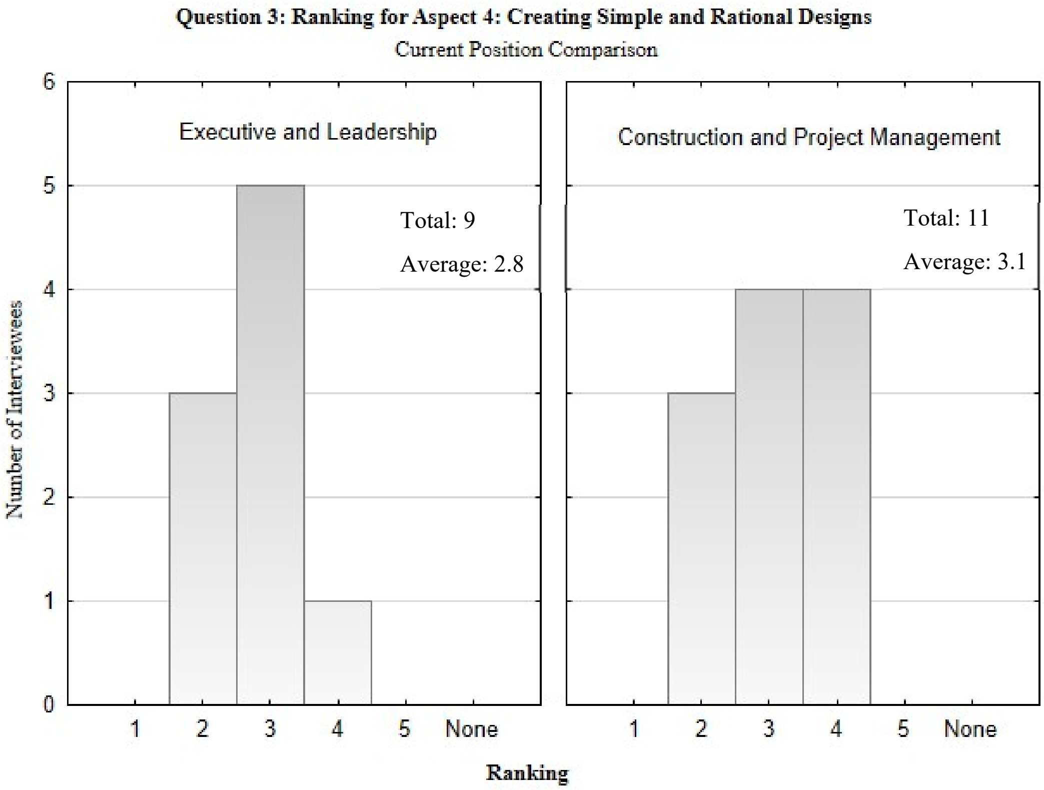


Figure B-5: Question 3 Aspect 4 Employment position comparison

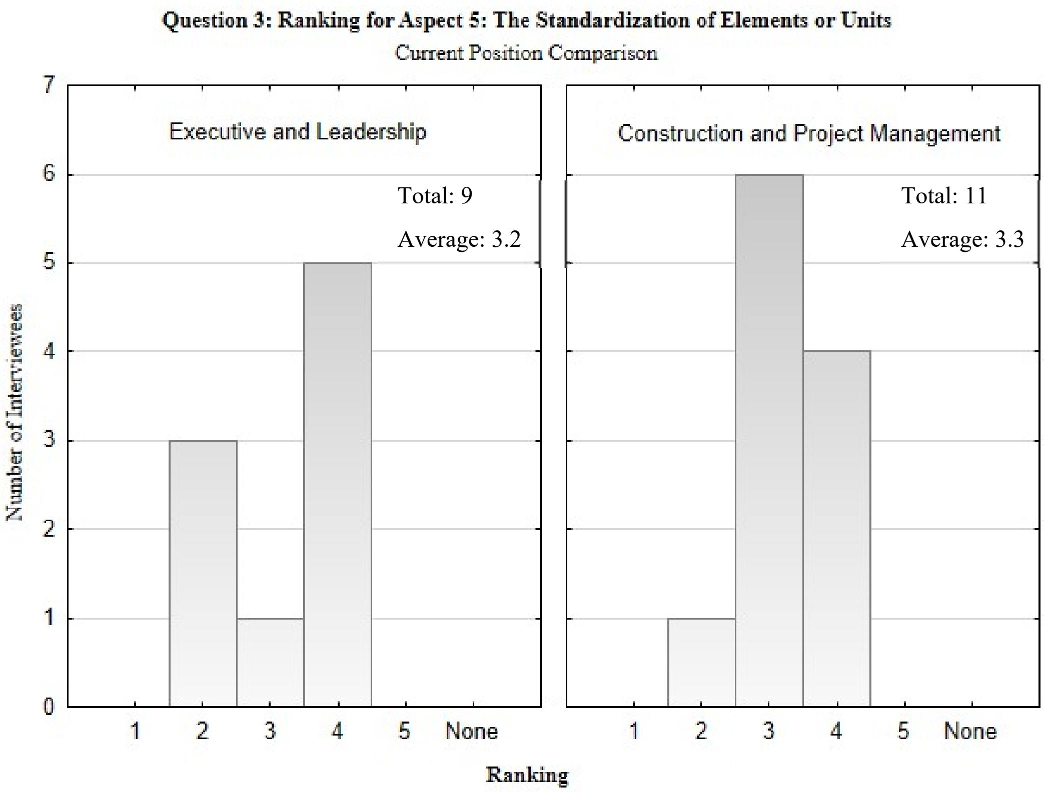


Figure B-6: Question 3 Aspect 5 Employment position comparison

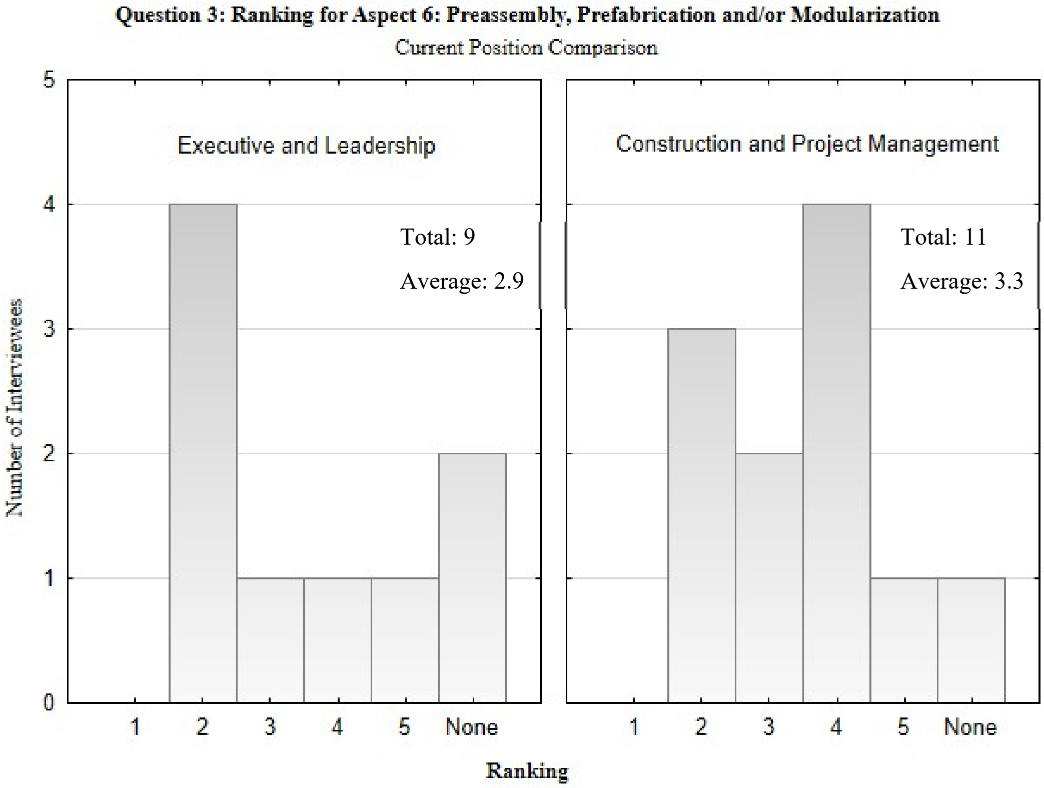


Figure B-7: Question 3 Aspect 6 Employment position comparison

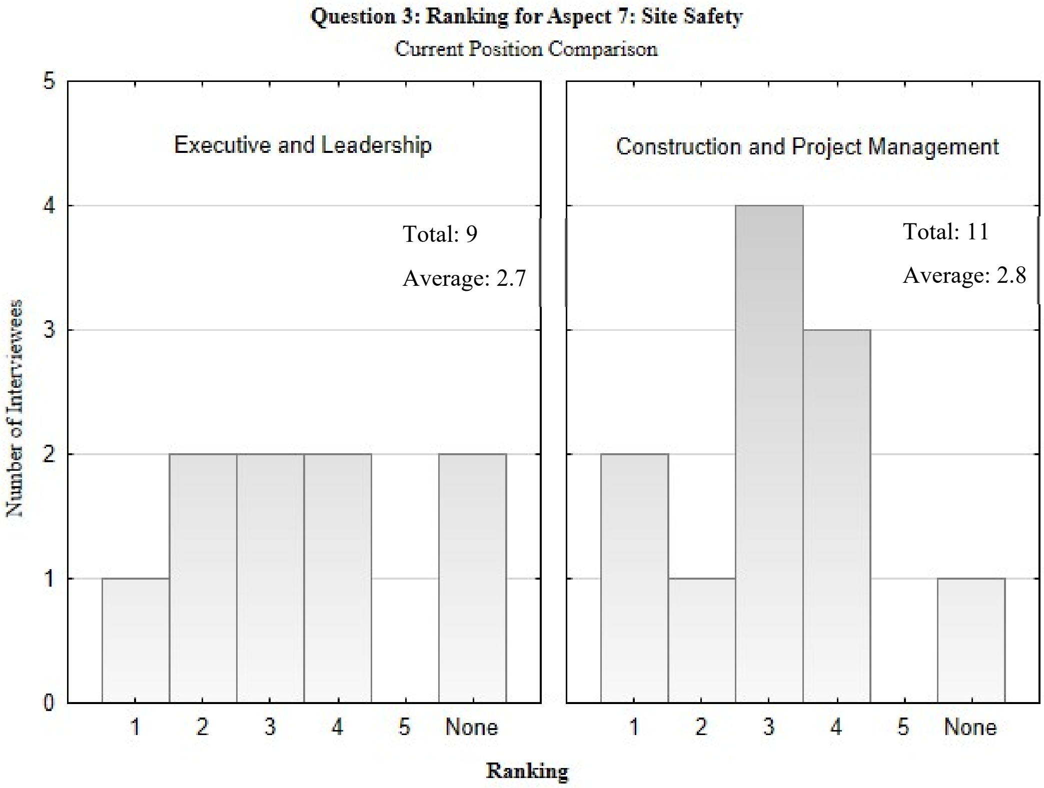


Figure B-8: Question 3 Aspect 7 Employment position comparison

B.4 Participant information for the 12 categories of the most frequently mentioned advice phrases

The 12 tables presented in this appendix section are each for categories 1 to 12 into which the 24 most frequently mentioned advice was categorized in Chapter 4.4.1. Each table shows the characteristics of the participants who mentioned the advice within the category.

Table B-16: Characteristics of participants that mentioned advice in Category 1

Category Grouping 1: Catering to the specific site conditions or circumstances						
Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
2		x	x		x	
4	x		x			x
5		x	x		x	
6	x		x			x
7	x			x		x
8		x		x	x	
9	x		x			x
12	x			x		x
13		x		x	x	
14		x		x	x	
16		x		x		x
18	x			x	x	
19		x		x	x	
20	x			x		x
TOTALS	7	7	5	9	7	7

Table B-17: Characteristics of participants that mentioned advice in Category 2

Category Grouping 2: The practicality of design and methodologies						
Participants	0 - 20 years	21 - 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
4	x		x			x
6	x		x			x
7	x			x		x
8		x		x	x	
9	x		x			x
10		x		x	x	
11		x	x		x	
12	x			x		x
14		x		x	x	
15		x	x			x
17	x			x		x
19		x		x	x	
TOTALS	6	6	5	7	5	7

Table B-18: Characteristics of participants that mentioned advice in Category 3

Category Grouping 3: Communication to gain important information

Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
1	x		x			x
2		x	x		x	
3	x		x			x
4	x		x			x
5		x	x		x	
6	x		x			x
8		x		x	x	
9	x		x			x
12	x			x		x
14		x		x	x	
15		x	x			x
16		x		x		x
17	x			x		x
19		x		x	x	
20	x			x		x
TOTALS	8	7	8	7	5	10

Table B-19: Characteristics of participants that mentioned advice in Category 4

Category Grouping 4: Local availability of materials

Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
1	x		x			x
2		x	x		x	
4	x		x			x
5		x	x		x	
8		x		x	x	
11		x	x		x	
14		x		x	x	
20	x			x		x
TOTALS	3	5	5	3	5	3

Table B-20: Characteristics of participants that mentioned advice in Category 5

Category Grouping 5: Contractor collaboration

Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
1	x		x			x
4	x		x			x
5		x	x		x	
6	x		x			x
7	x			x		x
8		x		x	x	
9	x		x			x
10		x		x	x	
11		x	x		x	
13		x		x	x	
14		x		x	x	
TOTALS	5	6	6	5	6	5

Table B-21: Characteristics of participants that mentioned advice in Category 6

Participants	0 – 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
Category Grouping 6: Considering construction sequence and methodologies during the design						
1	x		x			x
4	x		x			x
5		x	x		x	
8		x		x	x	
9	x		x			x
10		x		x	x	
13		x		x	x	
14		x		x	x	
15		x	x			x
16		x		x		x
17	x			x		x
18	x			x	x	
20	x			x		x
TOTALS	6	7	5	8	6	7

Table B-22: Characteristics of participants that mentioned advice in Category 7

Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
Category Grouping 7: Gain an understanding of the construction process						
1	x		x			x
2		x	x		x	
3	x		x			x
7	x			x		x
8		x		x	x	
10		x		x	x	
17	x			x		x
18	x			x	x	
19		x		x	x	
20	x			x		x
TOTALS	6	4	3	7	5	5

Table B-23: Characteristics of participants that mentioned advice in Category 8

Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
Category Grouping 8: Clash detection						
3	x		x			x
4	x		x			x
9	x		x			x
10		x		x	x	
12	x			x		x
15		x	x			x
16		x		x		x
19		x		x	x	
20	x			x		x
TOTALS	5	4	4	5	2	7

Table B-24: Characteristics of participants that mentioned advice in Category 9

Category Grouping 9: Learn and improve with mentorship and exposure						
Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
2		x	x		x	
3	x		x			x
4	x		x			x
5		x	x		x	
7	x			x		x
8		x		x	x	
9	x		x			x
11		x	x		x	
14		x		x	x	
16		x		x		x
TOTALS	4	6	6	4	5	5

Table B-25: Characteristics of participants that mentioned advice in Category 10

Category Grouping 10: Considering elements that influence safety						
Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
1	x		x			x
2		x	x		x	
4	x		x			x
5		x	x		x	
6	x		x			x
9	x		x			x
11		x	x		x	
14		x		x	x	
15		x	x			x
16		x		x		x
17	x			x		x
19		x		x	x	
TOTALS	5	7	8	4	5	7

Table B-26: Characteristics of participants that mentioned advice in Category 11

Category Grouping 11: Design Optimization						
Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
1	x		x			x
2		x	x		x	
8		x		x	x	
9	x		x			x
13		x		x	x	
TOTALS	2	3	3	2	3	2

Table B-27: Characteristics of participants that mentioned advice in Category 12

Category Grouping 12: Cost-effective methodologies						
Participants	0 - 20 years	21 – 30+ years	Civil Engineering Qualification	Non-Civil Engineering Qualification	Executive and/or Leadership Position	Project and/or Construction Management Position
9	x		x			x
13		x		x	x	
14		x		x	x	
16		x		x		x
17	x			x		x
TOTALS	2	3	1	4	2	3

Appendix C: Design-bid-build phases

Design-bid-build phases

Figure C-1 shows the 11 design-bid-build phases along with a brief description of each phase.

Design-bid-build phases	Brief descriptions of the phases
1. Conceptualization	Initial phase where project ideas and objectives are defined and a preliminary project concept is developed.
2. Pre-Design Planning and Preparation	Detailed planning activities that include site analysis, feasibility studies, budgeting and establishing project requirements.
3. Design Development	The project concept is translated into detailed engineering and architectural designs, including drawings, specifications, and material selections.
4. Planning and Permitting	Obtaining necessary permits and approvals for relevant authorities, ensuring compliance with regulations and standards.
5. Tender Preparation	Preparation of bid documents and contracts to invite potential contractors to submit their proposals for the construction project.
6. Tendering	Solicitation of bids from qualified contractors, evaluation of proposals and selection of a contractor based on criteria such as cost, experience and capabilities.
7. Mobilization	The selected contractor prepares for the construction project, including setting up temporary facilities, procuring materials, hiring personnel, project scheduling, contract coordination and stakeholder engagement.
8. Construction	Actual construction activities take place according to the approved design and construction schedule, involving site preparation, foundation work, structural erection and installation of systems and services.
9. Commissioning	Testing and inspection of completed systems and components to ensure they function properly and meet the project requirements and specifications.
10. Handover	The transfer of the completed project from the contractor to the owner, including final inspections, documentation and the official acceptance of the project.
11. Post-Project	Activities that occur after the project is handed over, such as warranty management, finalizing documentation, addressing any remaining issues, transitioning to maintenance and operations and having close-out meetings.

Figure C-1: Design-bid-build phases with each of their definitions

Appendix D: Advice phrases grouped into the additionally created constructability concepts A to H

Additional constructability concept A: Mentorship and supervision by more senior engineers or individuals should be encouraged for all levels of experience, as well as continuous learning about the impact that your design has on construction.

Table D-1: Advice phrases categorized into additional Constructability Concept A

Advice Phrase	**Location in Appendix B.2**
Sending young engineers to the site before design instead of experienced engineers who know what information to look for	Table B-1
Do not design in isolation	Table B-5
Soundboard ideas with more experienced seniors/individuals	Table B-9
Do not proceed with assumptions	Table B-9
Do not allow students to do work unchecked or go to the site alone as they do not have enough experience to adequately consider construction methods	Table B-10
Learn how your design influences construction by following up during construction and soundboarding experienced individuals	Table B-10
If you are unsure about construction methods, talk to your more experienced colleagues	Table B-10
Do not proceed with assumptions	Table B-10
Learn from previous projects and similar designs	Table B-11
Visit the site often to better understand how spatial problems hinder efficient construction	Table B-11
Do not let junior engineers do documentation and site checks alone because they do not have adequate knowledge to consider the necessary aspects	Table B-11
Ask for advice from more experienced individuals	Table B-12
Get mentorship and request reviews of your work	Table B-12
Ensure a continuous learning process during the entire project	Table B-12
Instead of working in isolation, share information and request support from the project team	Table B-12

Additional constructability concept B: Effective and continuous communication, interaction and collaboration with all project participants should be prioritized.

Table D-2: Advice phrases categorized into additional Constructability Concept B

Advice Phrase	Location in Appendix B.2
Lack of communication and engagement to gain all the information that will influence the design	Table B-1
Not prioritising value engineering exercises before construction	Table B-1
Not involving the contractor early enough in the project	Table B-1
If a product or material is not available due to unforeseen circumstances, ensure that this is communicated to the whole project team regarding schedule and cost changes	Table B-2
Negotiate with the architect about spatial requirements	Table B-4
If spatial requirements cannot be considered, provide suggestions to the contractor and include the risk in the tender	Table B-4
Discuss complex methodologies with the project team and the contractor	Table B-4
Ask the contractor for advice on accessibility and spatial requirement decisions	Table B-4
Consider the importance of fast decision-making	Table B-5
Gain local advice from suppliers about the availability of resources	Table B-9
Negotiate with the client and/or architect about the choice of resources	Table B-9
Ask a contractor or subcontractor about their knowledge of available resources on the market	Table B-9
Get a trusted sales representative and obtain guarantees	Table B-9
Collaborate with the contractor and discuss the design	Table B-10
Ensure clear and constant communication to all parties about sudden changes to the design	Table B-10
Get advice, provide suggestions and collaborate with the contractor as early as possible	Table B-11
Put yourself in the contractor’s shoes	Table B-11
Negotiate with the architect about spatial requirements	Table B-11
Gain advice from contractors and collaborate on the required changes to be made	Table B-12
When providing alternatives to elements in a design, also analyse which of the alternatives is the best option and communicate that to the contractor	Table B-12
Put yourself in the contractor’s shoes	Table B-12
Clearly and constantly communicate changes to all project parties to avoid problems later on in the construction process	Table B-13
Get different perspectives from seniors and other project participants to obtain the best solutions	Table B-13

Additional constructability concept C: Continuous research, gaining of new information and enthusiastic learning about all aspects of construction should be encouraged for all levels of experience.

Table D-3: Advice phrases categorized into additional Constructability Concept C

Advice Phrase	Location in Appendix B.2
Ensure that materials/products/technology are available in the country	Table B-2
If the specified material/product/technology is difficult to procure in the country, research and consider other options	Table B-2
Reconsider using methods/materials/technologies that have not been used often in the country or require specialised skills	Table B-2
If the designer does not specify the exact material/product to use, the designer should research the options that will be available to the contractor on the market and determine whether those options suit the specifications	Table B-2
Gain an understanding of the complexity of installing multiple services on site: MEP and underground water services	Table B-3
Ensure that you have a good understanding of standard scaffolding, formwork and crane dimensions	Table B-4
Gain knowledge of the standard dimensions of scaffolding, formwork, pipes, windows, doors and bricks	Table B-6
Gain an understanding of the complex manufacturing process	Table B-6
Ensure a good understanding of the processes and requirements of prefabrication	Table B-7
Do research about the developments of prefabrication and modularization in your country	Table B-7
Gain local knowledge about availability in the country	Table B-9
Do research about the resources that are best suited for the site circumstances	Table B-9
Gain a better commercial awareness	Table B-9
Do research about the standard turning radii of commonly used heavy construction vehicles	Table B-11
Make yourself aware of standard sizing and dimensions and know how to calculate them	Table B-13
Stay informed about available products and read the supplier brochures	Table B-13
Look at what other countries are doing and evaluate the benefits from another perspective	Table B-14
Keep up with changes and developments in the industry	Table B-14
Encourage involvement in R&D, academic institutions and innovation competitions	Table B-14

Additional constructability concept D: Careful consideration of the practicality of design decisions in terms of their impact on construction activities.

Table D-4: Advice phrases categorized into additional Constructability Concept D

Advice Phrase	**Location in Appendix B.2**
Think practically about the contractor's limitations	Table B-2
Think practically about material transportation to the site	Table B-2
Ensure that maintenance of the materials/products will be available in the future	Table B-2
Ensure that the transport of materials to a site is possible and practical	Table B-3
Consider the location on site of the contractor's offices	Table B-4
Consider the turning radii of the heavy vehicles that will be required during construction	Table B-4
Ensure that service shafts are placed in practical positions and that services connect practically to the service shaft	Table B-5
While thinking of the end product, consider the specialist skills that are required to obtain the end product	Table B-10
Make a checklist for yourself containing everything that has to move on and off-site	Table B-11

Additional constructability concept E: Clarity about the scope and specifications should be ensured to enable efficient and optimal planning.

Table D-5: Advice phrases categorized into additional Constructability Concept E

Advice Phrase	**Location in Appendix B.2**
Ensure a good understanding of the client's scope and that you collaborate with your project team	Table B-5
Ensure the correct interpretation of building codes	Table B-5
To fully consider prefabrication as an option, first ensure a good understanding of the project scope and specifications	Table B-7
Provide alternative materials or products to mitigate material acquisition risk	Table B-9
Spend more time on planning, researching and defining the scope	Table B-10
Ensure that the scope is clear and gain a good understanding of the project requirements	Table B-11
Spend enough time planning, doing research and reviewing similar past projects	Table B-12
Ensure clear specification of work	Table B-13

Additional constructability concept F: Design-specific details should be carefully considered through the use of appropriate software solutions.

Table D-6: Advice phrases categorized into additional Constructability Concept F

Advice Phrase	**Location in Appendix B.2**
Not using 3D modelling software and clash detection software	Table B-1
Do not take accountability for the degree to which their design is construction-sensitive	Table B-1
Ensure that the concrete aggregate can fit in between the rebar and that the rebar is adequately encased in concrete	Table B-3
Ensure that there is enough space for cranes and that the ground or structure they stand on can support the weight of the crane	Table B-3
Ensure that structure front door heights are high enough to prevent water from flowing in and that slopes are correctly calculated for efficient water runoff	Table B-3
If services are specified to be added to the roof, ensure that this does not add significant weight to the roof and require a redesign	Table B-3
Ensure that all services and design elements' dimensions are correctly indicated in drawings	Table B-3
Ensure that emergency services (e.g., fire, health) can easily and practically reach fire taps and have adequate space to operate	Table B-3
Ensure that the inside of the structure has adequate ventilation to avoid reaching the dew point	Table B-3
Ensure that MEP (Mechanical, Electrical and Plumbing) services are well coordinated and that pipes do not clash with design elements like boundary walls and foundations	Table B-4
Ensure that concrete can fit in between the rebar and that the rebar is adequately encased in concrete	Table B-5
Ensure that load-bearing walls do not include large doors or sliding doors to avoid extra structural support requirements	Table B-5
Consider whether insulation is required to prevent the doming of floors	Table B-5
Use 3D modelling software and clash detection capabilities	Table B-11
Use BIM (Building Information Models) and 3D modelling software	Table B-12

Additional constructability concept G: The safety of construction staff should be prioritized and the identified safety hazards should be addressed during design.

Table D-7: Advice phrases categorized into additional Constructability Concept G

Advice Phrase	Location in Appendix B.2
Provide as much detail as possible to the contractor and, if possible, suggest safety measures specific to hazardous activities	Table B-8
Consider the uniqueness of the infrastructure type and identify hazards that may occur during the operational phase of the project	Table B-8
Identify hazards within your design and understand how your design influences safety	Table B-15
Take accountability for safety and research previous similarly complex projects to obtain the safest solutions	Table B-15
Have a close-down meeting to discuss the safety hazards that were identified and not addressed early enough	Table B-15
Share the hazards identified with the entire project team and determine how to mitigate the safety risk	Table B-15
Make suggestions about construction methods that may reduce safety hazards	Table B-15
Consider the uniqueness of the project and identify hazards associated with the unique aspects	Table B-15
Provide the contractor with as much detail as possible to allow him to mitigate hazards and add the required items to the bill of quantities	Table B-15
Attend webinars and conferences to stay up to date with new technologies and developments in the industry that improve construction safety	Table B-15

Additional constructability concept H: For lengthy construction projects, the changes to site conditions should be monitored as construction advances.

Table D-8: Advice phrases categorized into additional Constructability Concept H

Advice Phrase	Location in Appendix B.2
For a lengthy construction project, monitor changes in the site conditions as construction advances	Table B-3

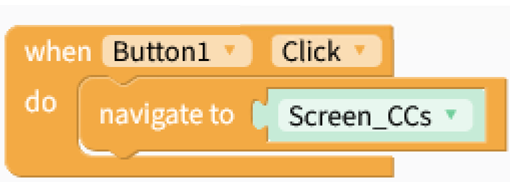
Appendix E: Visual coding description of constructability tool features

Thunkable is a user-friendly and versatile platform that enables creators to develop mobile applications using block-based programming. It provides a visual interface through which creators can design, create and customise applications. Notable features of Thunkable include the capability to implement interactive components, integrate databases and utilize device functionalities. For the development of the constructability tool application, key steps included the initiation of actions based on user inputs, integration of data sources for constructability concepts and contractor advice and the incorporation of functionalities such as search filters, alerts and the addition of user-generated input to the existing database. Unique functions were created to achieve the search feature, the alert feature and the ability of the user to add information to the database.

E.1 Feature 1: User viewing the constructability concepts with definitions

In this section, the two visual code blocks to implement feature 1 are presented and a brief description of the code is provided.

Code block 1



Code block 2

Brief description of code for Feature 1:

Code block 1: Constructability concept list button action

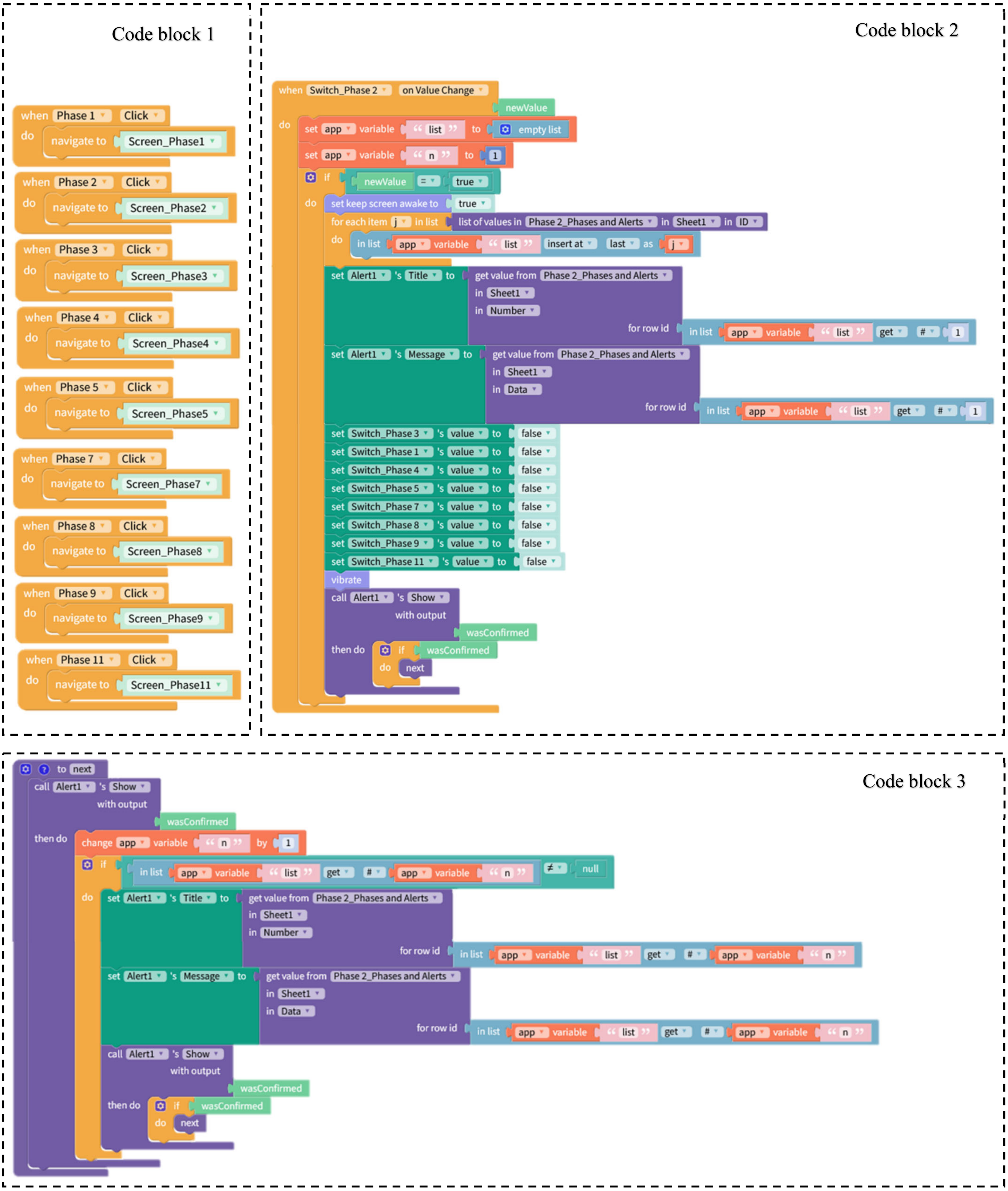
- A control block is employed to trigger an action when the constructability concept list button is clicked. The action specified is to navigate to the concept list.

Code block 2: Back button action

- Similarly, a control block is utilised to determine the action when the back button is clicked. The defined action is to navigate back to the start screen.

E.2 Feature 2: Visual coding for Feature 2: User receiving data as alerts

In this section, the three visual code blocks to implement feature 2 are presented and a brief description of the code is provided.



Brief description of code for Feature 2:

Code block 1: Phase 1 to 11 button action

In this code, control blocks are employed to handle the action when the buttons corresponding to Phase 1 to Phase 11 are clicked. Upon clicking the button associated with Phase 2, the application navigates to the screen displaying the Phase 2 contractor advice.

Code block 2: Switch activation

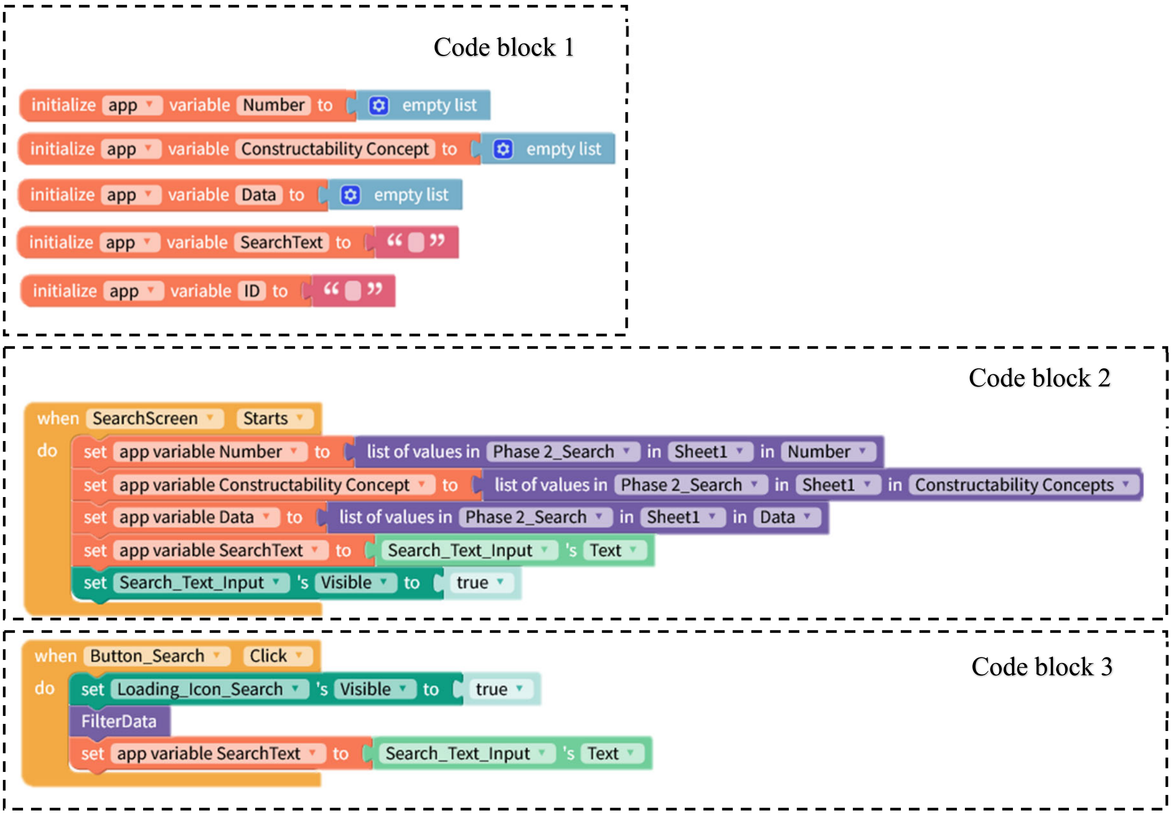
- A control block is utilized to execute the code within it when the value of the phase 2 switch changes.
- A variable block initializes an empty list.
- Another variable block initializes a counter variable with the value 1.
- A control block (If, do) is used to initiate the alert every time a new switch value is "true".
- A device variable ensures that the device screen remains on when the alert is displayed.
- A control block, a data source block and a list block are utilized to iterate through the data source for phase 2 and add each item (j) to the initialized empty list.
- Two alert blocks set the title and message of the alert, respectively, using data from the now-populated list for each item (n) in the list.
- Switch blocks are used to set all other phases switched to "false" if the phase 2 switch is activated.
- A call alert block initiates the alert function and proceeds to the next item (n) upon user confirmation.

Code block 3: Alert function

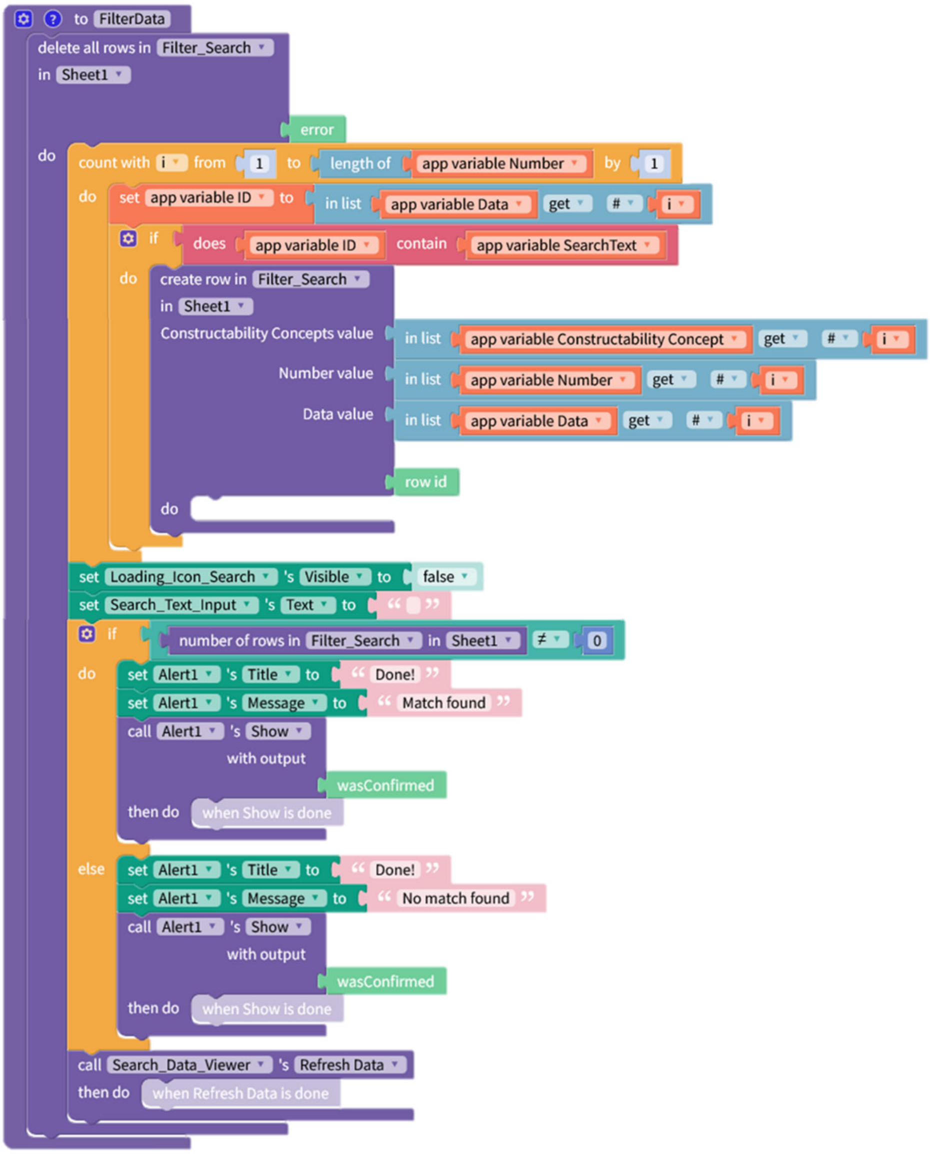
- The alert function contains an alert block within which the initialized app variable "n" is set to change in increments of 1.
- A control block (if, do) is utilized and the code within it is only carried out if the app variable "n" in the list is not equal to zero.
- Two alert blocks are used to set the title and the message of the alert to the data item number and the contractor advice data, respectively. List blocks are utilized to obtain the respective information from the now populated list, for every "n" item in the list.
- A call alert block initiates the alert function and proceeds to the next item (n) upon user confirmation.

E.3 Feature 3: Visual coding for Feature 3: Search function for user to filter the data

In this section, the four visual code blocks to implement feature 3 are presented and a brief description of the code is provided.



Code block 4


to FilterData
delete all rows in Filter_Search
in Sheet1
error
do
count with i from 1 to length of app variable Number by 1
do set app variable ID to in list app variable Data get # i
if does app variable ID contain app variable SearchText
do create row in Filter_Search
in Sheet1
Constructability Concepts value in list app variable Constructability Concept get # i
Number value in list app variable Number get # i
Data value in list app variable Data get # i
row id
do
set Loading_Icon_Search 's Visible to false
set Search_Text_Input 's Text to " "
if number of rows in Filter_Search in Sheet1 ≠ 0
do set Alert1 's Title to " Done! "
set Alert1 's Message to " Match found "
call Alert1 's Show
with output
wasConfirmed
then do when Show is done
else set Alert1 's Title to " Done! "
set Alert1 's Message to " No match found "
call Alert1 's Show
with output
wasConfirmed
then do when Show is done
call Search_Data_Viewer 's Refresh Data
then do when Refresh Data is done

Brief description of code for Feature 3:

Code block 1: Variable initialization

- App variables "number", "constructability concept" and "data" are initialized as empty lists.
- App variables "search text" and "ID" are initialized as empty variables.

Code block 2: Search screen activation

- Upon opening the start screen, variables "number", "constructability concept" and "data" are assigned to the respective columns in the phase 2 data source.
- App variable "search text" is assigned to the text added in the search bar, which is also set to "visible".

Code block 3: Search button action

- When the search button is clicked, the loading icon is set to "visible"
- The "FilterData" function is called.

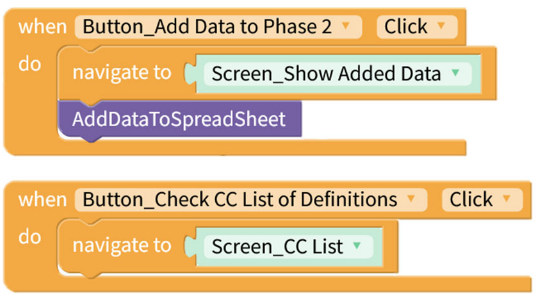
Code block 4: Filter data function

- The filter data function requires two data sheets: the phase 2 data source and an empty datasheet called the filter sheet.
- In the filter data function, the filter sheet is first cleared to ensure no data previously transferred remains.
- A count control block iterates from 1 to the length of the app variable "Number", representing the number of rows in the phase 2 data source.
- The app variable ID is set to be the i-th item in the phase 2 data source.
- A control block (If, Do) is used to add the constructability concept, the item number and the contractor advice data to the filter sheet if the app variable "ID" contains the text that was input into the search bar.
- The loading icon is set to "visible" and the search text is cleared.
- A control block (If, Do, Else) is used to trigger an alert displaying the search result if the data in the filter sheet is not empty. Otherwise, the alert will show that no result was found.
- The data view used to present the search results is refreshed to display the data transferred to the filter sheet.

E.4 Feature 4: Visual coding for Feature 4: User data added to the contractor advice database

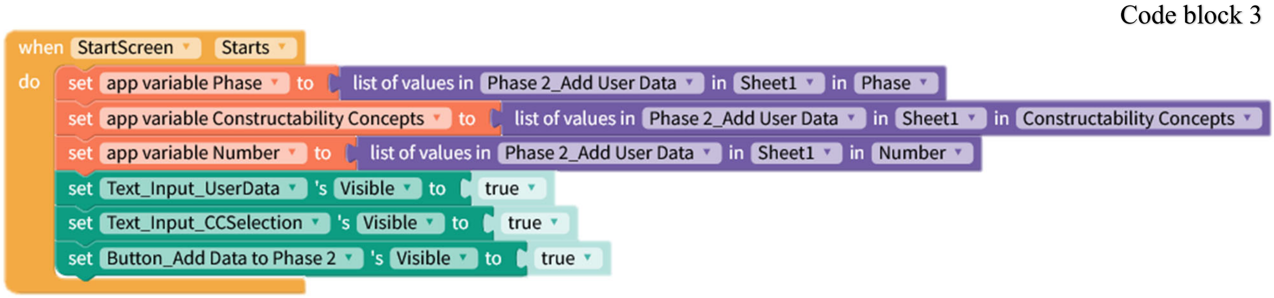
In this section, the four visual code blocks to implement feature 4 are presented and a brief description of the code is provided.

Code block 1

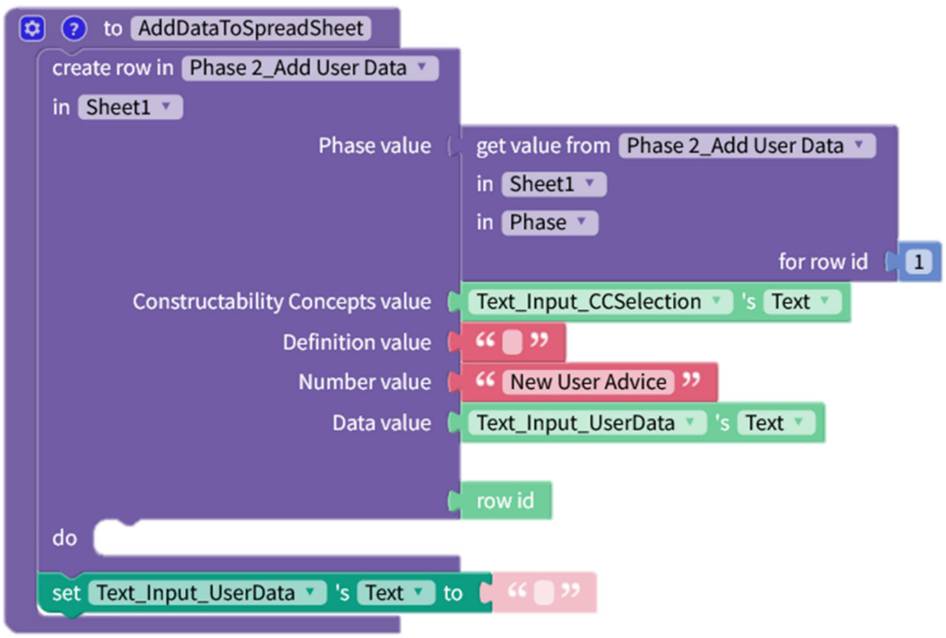


Code block 2

Code block 3



Code block 4



Brief description of code for Feature 4:

Code block 1: Add data button and constructability concept list button action

- A control block is utilized to navigate to the screen displaying the added user data and execute the "AddDataToSpreadSheet" function upon clicking the "Add data to phase 2" button.
- Another control block is used to navigate to the constructability concept list when the "Check constructability concepts" button is clicked.

Code block 2: Variable initialization

- App variables "Phase", "Constructability Concepts" and "Number" are initialized as empty lists using variable blocks.
- Additionally, a variable block is used to initialize the app variable "NewDataToAdd", setting it as an empty variable.

Code block 3: Start screen activation

- A control block defines the actions to be taken when the start screen opens.
- App variables "Phase", "Constructability Concepts" and "Number" are set to the respective columns in the Phase 2 data source.
- The text input for the first text box is set to "visible".
- The text input for the constructability allocation text box is set to "visible".
- The button to add the data to the phase 2 data source is set to "visible".

Code block 4: Add data to the spreadsheet function

- The "AddDataToSpreadSheet" function facilitates the creation of a new row in the phase 2 data source for the new user data.
- Using the "create row" function, the constructability concept column value and the data information from the user input in the respective text boxes are obtained.
- The "Number" value, which serves as the title of the data display, is set as "New User Advice".
- After execution, the text boxes are emptied, ensuring a clean interface for future data input.