Decision making between Hybrid and In-situ Concrete Construction in South Africa

by

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DECLARATION

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SUMMARY

A construction method that proves to be the best today will not necessarily be the best method for application in 20 years. Therefore, with changing circumstances, engineers have to consider all the options before selecting a specific method. Options that are weighed in this study are in-situ concrete construction and hybrid concrete construction.

Hybrid concrete construction is the combination of in-situ and precast concrete in structures, with the purpose to exploit the advantages of each to its full potential. This construction method gained popularity in the United States and in Europe due to its distinctive benefits. However, the increase of its application in some countries (including South Africa) has been slow and possible reasons for this are investigated in this study. With the intention of improving the South African construction industry, a model is developed for decision making between hybrid concrete construction and in-situ concrete construction.

The main purpose of a larger research project is to assist project teams in the decision making between precast concrete and in-situ concrete in building construction projects. This decision making is not based on decision making models with mathematical output, since the decision of a construction method is influenced by many variables that may not all be quantifiable. Consequently, instead of prescribing a decision making method, the relevant information is to be provided for the decision maker. The aim of this study is to identify the relevant parameters and to set a framework for further in depth investigation by subsequent theses.

A decision making process in any field normally involves having a list of advantages and disadvantages of the different options. Therefore this study includes the following managerial discussion topics: factors that influence hybrid concrete construction, as well as benefits, barriers and other aspects to consider, structural systems and elements, decision making methods and important factors that will be the basis of the decision making process.

Traditionally the most important factors for decision making between construction methods were construction cost and duration, but more recently sustainability is becoming increasingly important. It is the civil duty of all parties involved in a project to foresee that most of the criteria of sustainability are met. Sustainability covers all the aspects of economic, social and environmental impacts. Furthermore quality is identified as an important aspect in the decision making process for a construction method. The comparison of precast and in-situ concrete construction is therefore discussed, considering all the abovementioned criteria and investigating possible quantification methods. This information, together with information from future studies, would then allow the project team to consider each aspect involved in the decision making process.

OPSOMMING

Die beste konstruksiemetode vandag sal nie noodwendig die beste metode oor 20 jaar wees nie. Met veranderende omstandighede, moet ingenieurs altyd al die moontlike opsies oorweeg voordat ‘n spesifieke konstruksiemetode gekies word. Opsies wat in hierdie studie bestudeer word, is in-situ betonkonstruksie en hibriede betonkonstruksie.

Hibriede betonkonstruksie is die kombinasie van in-situ en voorafvervaardigde beton elmente in strukture, ten einde die voordele van elke metode ten volle te benut. As gevolg van sy voordele, het hierdie konstruksiemetode al hoe meer gewild geraak in Amerika en Europa. Nietemin is die toename in die gebruik van hierdie metode in sommige lande (insluitend Suid-Afrika) traag en moontlike redes hiervoor word in hierdie studie ondersoek. Met die voorneme om die Suid-Afrikaanse konstruksie-industrie te bevorder, is ‘n model vir besluitneming tussen hibriede betonkonstruksie en in-situ betonkonstruksie ontwikkel.

Die hoofdoel van ‘n groter navorsingsprojek is om projekspanne te help met die besluitneming tussen voorafvervaardigde en in-situ beton in konstruksieprojekte vir geboue. Hierdie besluitneming is nie gebaseer op besluitnemingsmodelle wat wiskundige resultate lewer nie, want die keuse van ‘n konstruksiemetode word deur te veel veranderlikes, wat nie altyd kwantifiseerbaar is nie, beïnvloed. Gevolglik word relevante inligting aan die besluitnemer verskaf, eerder as om ‘n gekwantifiseerde besluitnemingsmetode voor te skryf. Die doel van hierdie studie is om relevante aspekte te identifiseer en om ‘n raamwerk te skep vir verdere, in diepte studies van volgende tesisse.

‘n Besluitnemingsproses in enige veld word gewoonlik gebaseer op ‘n lys van voordele en nadele van die verskillende opsies. Daarom sluit hierdie studie die volgende bestuursaspekte in: faktore wat hibriede betonkonstruksie beïnvloed, asook voordele, beperkings en ander aspekte om te oorweeg, strukturele sisteme en –elemente, besluitnemingsmetodes en belangrike faktore wat die basis van die besluitnemingsproses sal wees.

Tradisioneel was die belangrikste faktore vir besluitneming tussen konstruksiemetodes die koste en tydsduur daaraan verbonde, maar deesdae word volhoubaarheid al hoe meer belangrik geag. Dit is die plig van alle persone betrokke by ‘n projek om te sorg dat die projek aan so veel as moontlik van die kriteria van volhoubaarheid voldoen. Volhoubaarheid sluit al die aspekte van ekonomiese-, sosiale- en omgewingsimpakte in. Verder is kwaliteit ook geïdentifiseer as ‘n belangrike aspek in die besluitnemingsproses van ‘n konstruksiemetode. Die vergelyking van voorafvervaardigde- en in-situ betonkonstruksie word dus bespreek met die oog op al die bogenoemde kriteria en, sover moonlik, word die kwantifisering van hierdie aspekte ondersoek.

Met hierdie inligting en die inligting van toekomstige studies, kan die projekspan dan elke aspek in die besluitnemingsproses oorweeg.

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- Finally, my Creator, to Whom I give the glory for all my work.

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GLOSSARY

AHP	Analytical Hierarchy Process
AUTOCOP	Automation Option Evaluation for Construction Processes
BPCF	British Precast Concrete Federation
CFRI	Construction Field Rework Index
CNCI	Cement and Concrete Institute
HCC	Hybrid Concrete Construction; the combination of in-situ and precast concrete construction
IMMPREST	Interactive Method for Measuring Pre-assembly and Standardization benefit across the construction supply-chain
MCDM	Multiple Criteria Decision Making
NPCAA	National Precast Concrete Association Australia
Precast elements	All pre-manufactured concrete elements, including prestressed hollowcore floor panels, but excluding concrete bricks
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UK	United Kingdom
U.S.	United States of America
VWSA	Volkswagen South Africa

Chapter 1

INTRODUCTION

1.1 Background

Hybrid concrete construction is considered as an art where in-situ concrete and precast concrete are combined to construct buildings in the most effective way (The Concrete Centre, 2005). It is believed that the main reason for the use of HCC is its construction speed (Soetanto *et. al*, 2004). In-situ construction and HCC is not necessarily a trade-off between construction time and cost as this study reveals.

Goodchild (2001) stated that the main role players in the decision making process between construction methods are design engineers. Design engineers in South Africa often specify in-situ concepts without investigating what prefabricated concrete elements can offer (Surridge, 2011; Queripel, 2011). This is mainly due to a lack of available information on prefabricated elements such as its benefits, cost, design guidelines etc. (Jarrat, 2011; Jurgens, 2008).

This study originated from questions that have risen in the South African construction industry regarding the implementation of hybrid concrete construction (HCC) in building structures. It has been found through surveys that in the construction of buildings in South Africa, relatively little precast elements are used compared to some other countries. The reason for this is not yet clear, but the investigation starts at the decision making between the construction methods. Therefore the aim of this study is to set a framework to ultimately assist project teams to decide between HCC and in-situ concrete construction. This requires identifying of and research on the relevant aspects involved in the abovementioned decision making process. Details for some of the identified aspects will only be completed through subsequent theses.

Many articles have been published regarding the different facets involved in HCC, including benefits and classifications of important and less important factors. However, none of these factors have been quantified. Therefore ways in which to quantify certain factors are investigated and discussed, because as Peter Drucker once said, “If you can’t measure it you can’t manage it” (Drucker, 1973).

Blismas *et. al* (2006) stated that “Until evaluation is more holistic and value-based rather than cost-based, off-site production uptake in construction will be slow”. This implies that the aspects that should be investigated do not only include cost, time and quality as some project teams might think. Other considerations that contribute to the value of a project are the elements of sustainability. Therefore environmental and social concerns also have to be incorporated in the decision making process between construction methods. After identifying the aspects that need to be considered in the decision making process between precast and in-situ cast concrete in multi-story structures, these aspects must be quantified. It was not possible within the time frame of this study to quantify all aspects comprehensively. The first objective was thus to identify the relevant parameters and to provide a framework for an in depth study of all parameters in a broader research project. Some information is however already provided in this study for quantification of certain aspects.

1.2 Aim

A lack of knowledge of benefits of precast construction leads to suboptimal delivery of structures. Therefore, initially the aim of this study was to find a model to assist project teams to decide between precast and in-situ concrete construction for any given project. In a literature study, it was found that appropriate decision making models do exist. However, these models require accurate input in the form of quantifiable factors that are weighed in the decision. These models provide output in the form of mathematical values for each option considered, which implies that the answer is automated and the project teams would not make these decisions themselves, which is not necessarily useful.

The scope of such a study to complete a decision making model is recognized to be a complex task, which commences in this thesis, but cannot be completed in a single thesis. The aim of this study is to provide a framework to ultimately assist project teams to decide between precast and in-situ concrete construction. In addition, where possible, the aim is to quantify factors involved in the decision making or to identify methods to quantify these factors. Conclusions made in this study may already serve as information to assist project teams in their decision between different construction methods. However, recommendations are made for future studies to provide guidelines and ultimately a decision making model for project teams.

1.3 Objectives

With the ultimate goal of improving the South African construction industry, HCC is investigated and compared to traditional in-situ construction, keeping in mind international trends. The main objectives of this study are therefore as follows:

- Identify relevant aspects involved in decision making in construction;
- Categorize the necessary factors that influence this decision;
- Investigate potential decision making systems;
- Identify structural systems used in South Africa in order to define the scope of this investigation;
- Evaluate these structural options by considering the essential factors identified;
- Document information from specialists in the field to facilitate decision making;
- Provide information on relevant aspects to project teams;
- Quantify aspects to the extent possible;
- Provide proposals for those areas where quantifiable information is not readily available;
- Make recommendations for further studies to assist project teams in the decision making process.

These objectives are accomplished through a literature study, personal interviews, questionnaire surveys and calculative comparisons between HCC and in-situ construction in South Africa.

1.4 Scope

A scope is required to set boundaries to a study. The boundaries of this study are as follows:

- The area of interest for precast application is structural elements in building structures. Consequently any civil precast elements are not considered, such as pipes and kerbs, bridges and also bricks for low cost housing. Tilt-up panels and facades are also excluded.
- This study is limited to structural systems and elements that are being used in South Africa, i.e. the options that are currently available and being used for project teams to decide on.
- Managerial aspects of the decision making process are investigated. Technical issues such as connections and corbels are addressed in other studies.
- It is assumed that both in-situ and precast construction is possible and that precast elements are available for the project under consideration.

Precast construction is often more comprehensively discussed than in-situ construction when a specific topic is considered. The reason for this is that in-situ construction is accepted as the "norm" against which the alternative element (precast construction) is weighed.

1.5 Methodology

The methodology of this study is as follows:

Step 1: Investigate decision making models and relevant factors

Step 2: Establish a scope by identifying the types of structural systems used in South Africa

Step 3: Quantify relevant factors influencing the different construction types or identify what needs to be quantified in future studies

These steps are carried out by means of literature studies, personal interviews and own calculations. The structure is discussed in more depth in the following paragraphs.

The relevant factors for decision making between in-situ concrete construction and HCC as well as possible decision making methods are identified in Chapter 2. Aspects such as cost, quality and environmental concerns that need to be considered in the decision making model between precast and in-situ elements are identified by means of a literature study. Furthermore, possible decision making methods are also explored in the literature study.

As mentioned earlier, two barriers are identified in the decision making methods. The first barrier is that a decision making method cannot be used without quantitative factors to populate the model. Therefore quantitative figures have to be established before such a method can be used to assist a decision maker. The second barrier is that once these quantitative factors are available, it cannot be used in a mathematical formulation to determine the best option. Decision making between construction methods will always be a process which depends on the project team. Therefore this study aims to provide the necessary information to project teams. This will enable an evaluation of the different construction methods for a specific project.

HCC can include numerous variations and structural systems vary in different countries. In order to evaluate different construction methods forming part of the decision that South African project teams face, the available options in South Africa have to be identified. The decision making has to be based on relevant elements and systems. Therefore the types of elements and systems used in South Africa and internationally were identified through a small local questionnaire survey aimed at identified professionals in the industry and an international literature study discussed in Chapter 3. Results of the local questionnaire are limited by the size of the survey, but fulfill the aim of the survey, which is to identify the structural elements and systems that are used in South Africa. Options are limited to South African applications. Other types of elements that are used internationally are discussed and a further investigation can be carried out to establish the feasibility of using these elements in South Africa.

Factors that form part of decision making, which are identified in Chapter 2, are then quantified for the different construction options identified in Chapter 3. The quantification of different factors is performed and presented in Chapters 4 to 7 through comparisons between the different available options. Calculations for comparisons are carried out in Appendices. Where possible, information was gathered in the form of interviews with specialists in order to formulate the necessary comparisons. For instance, the material cost of in-situ and precast floors are compared and the necessary information for this comparison was obtained through interviews with a quantity surveyor and verified with a precast manufacturer. Where information is insufficient to make a comparison, schemes or approaches to obtain the necessary information is proposed for further studies.

Due to the nature of the study, most of the data consists of information gathered through personal interviews with specialists in the field or through questionnaire surveys. Therefore, information may include personal views of architects, design engineers, manufacturers, contractors and quantity surveyors. However, the validity of comments is carefully considered through cross verification against each other.

Finally conclusions are made in Chapter 8 on the findings of the study. A framework is proposed and recommendations are made in Chapter 9 for necessary further investigations.

A graphical presentation of the methodology, is provided in Figure 1.

1.6 Graphical Presentation of This Study

The methodology followed in this study is presented graphically in Figure 1.

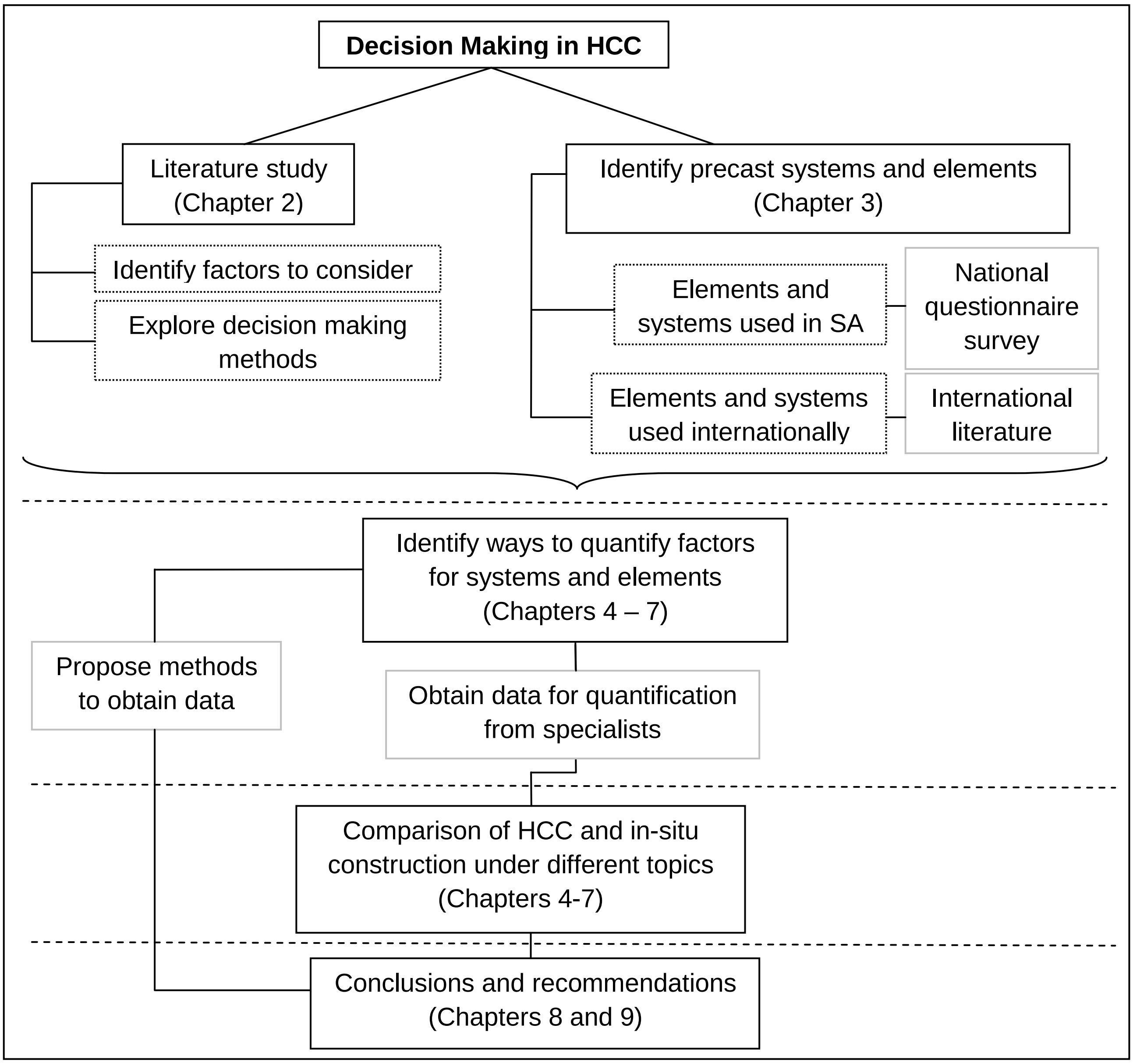

Figure 1: Graphical presentation of this study

Chapter 2

LITERATURE STUDY

The literature study includes available information on the topic of Hybrid Concrete Construction (HCC) and decision making models. This chapter is structured around the following aspects:

1.1. An introduction to HCC and its use
- A brief historical background of HCC and implementation thereof
- Background of the development of HCC in the United Kingdom
- South African precast implementation and design guide

1.2. HCC factors
- Benefits of and barriers to the use of HCC
- Quantifiable factors influencing the decision making in HCC
- Other aspects that should be kept in mind when considering HCC

1.3. Decision making methods and available toolkits
- Different decision making methods available, including AHP, AUTOCOP and a hybrid decision making model
- A useful toolkit (IMMPREST) identified, that offers assistance to inexperienced HCC users
- The use of decision making methods and toolkits

2.1 An introduction to Hybrid Concrete Construction and its use

HCC has developed over the last century. Some of its history and uses in relevant countries are discussed in this subsection. Also, as part of its application, the relevant precast concrete design standard is investigated.

2.1.1 Background of Hybrid Concrete Construction

Apart from the concrete used by the Egyptians, the application of modern concrete (with aggregate) started in 1756 (Bellis, 2011). It is traditionally one of the most common building materials, specifically in the in-situ form. Precast concrete construction was invented in 1905 by John Alexander Brodie (John Alexander Brodie, England City Engineer (1858-1934), 2011) and the technique was exploited in America and Europe.

Hybrid concrete construction is the concept of combining in-situ concrete with precast concrete in construction to make optimum use of the distinctive advantages of each construction type (The Concrete Centre, 2005). "HCC is about providing best value in structural frames" (Goodchild & Glass, 2004).

It has been found that data of precast concrete projects are generally undocumented and that decisions to use precast concrete elements are not based on well defined information (Pasquire *et al.*, 2005). Very little if any quantitative comparisons exist that project teams can apply to consider precast concrete as an option for the construction of buildings.

Despite the multiple benefits that HCC has to offer, the uptake thereof in various markets has been slow. Although different countries have different reasons for this, some common barriers exist that are discussed later in this review. The most intensive research on this topic was found to be carried out in the United Kingdom (UK) and consequently many of the referenced studies are from the UK. It is therefore necessary to provide background of the development of HCC in the UK.

2.1.2 Background of Hybrid Concrete Construction in the United Kingdom

After the first official use of precast concrete in 1905 in England, the method's architectural benefits were exploited in Eastern Europe, but strangely enough it never really became a conventional method in Britain (GPS Precast Concrete, 2011). Justification of this statement was provided by Goodchild (2011), who stated that it is due to two factors: firstly, the aesthetical appearance of precast structures is too simple for architects and secondly there were two incidents in the UK where precast structures failed in the 1960's. Consequently there was no growth in the precast industry of the UK in that time.

In 1998 Sir John Eagan presented a report on the Construction Task Force to the Department of Trade and Industry in the UK. The aim of the report was to improve the efficiency of the construction industry in the UK. This brought change in the approach of construction in the UK. In the report targets were set to reduce construction cost and time in order to improve the industry (Eagan, 1998).

Based on these requirements, Goodchild launched a study in 2001 on the feasibility and use of hybrid concrete construction. It was found that HCC is not necessarily more expensive than traditional construction methods; it can save construction time and has numerous other benefits such as innovative architectural finishes and improved sustainability (Jurgens, 2008).

After these studies identified the numerous potential benefits that HCC has to offer, new interest rose in the method. However, there was a lack of guidance to the use of HCC (Goodchild *et al.*, 2004). This lead to the publication of "Best Practice Guidance for Hybrid Concrete Construction" by Goodchild *et al.* (2004). Ever since, the industry has gained faith in hybrid concrete construction again and its use in the UK is currently increasing (Goodchild, 2011). This statement was confirmed by a report published by AMA Research (2011).

2.1.3 South African precast implementation

South Africa does not implement HCC in structures as much as many other countries. A study is performed later in this document to quantify more or less how much precast elements is actually used in South Africa as well as internationally. Also, the types of structural systems used are explored later on in this document.

No database exists on the types of precast elements used in structures in South Africa. Data on the amount of precast used in South Africa is also not available (CNCI, 2011). It is recommended that the uses of HCC technologies be documented for future reference. A database of precast applications would be useful for project teams to learn from.

In order to find the uses of HCC in South Africa, a list of the structural precast element suppliers is formulated in Appendix A. It was found that the South African precast market is relatively small and precast concrete producers mainly manufacture concrete pipes, kerbs, etc. Other products include facades, tilt-up elements and bridge beam elements.

In Appendix A, products that are produced according to the suppliers' websites are also provided. The products include only those elements that are manufactured for structural purposes in buildings. Structural precast elements that are used in South Africa at the moment are mainly floor systems. The two common systems available are hollowcore concrete panels (Figure 2) and the rib-and-block floor system (Figure 3).

Figure 2: Hollowcore concrete panel (High-strength structural lightweight concrete, 2003)

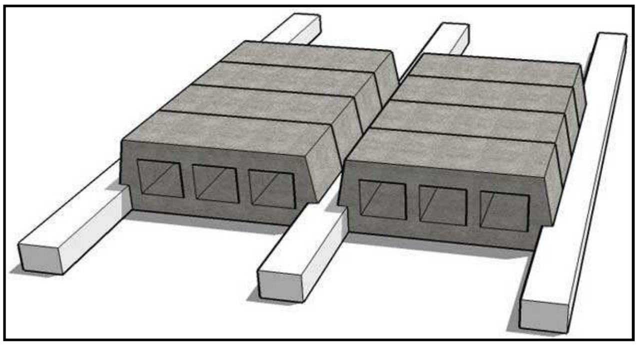

Figure 3: Rib and block floor system (Products – Bricks – Deck Block 190 Triple cavity, 2001)

A survey was also carried out by Jurgens in 2008 on the South African HCC industry. Eight contractors and twelve design engineers participated in the survey. The primary findings were the following:

- 67% of the designers and 75% of the contractors indicated that they never or seldom encounter precast concrete structures.
- 75% of the designers and 62.5% of the contractors felt that insufficient information exists for decision making between precast and in-situ systems.
- 75% of the participants see a future for precast concrete construction in South Africa.
- The design-and-build method of procurement is suggested by a few respondents.

It was concluded that currently little precast construction is applied in South Africa. Insufficient information is available to assist project teams to decide for or against precast elements. However, there is a future for HCC in South Africa.

2.1.4 Precast design standards and guides

Currently South African Standards for structural design are based on those of different countries. For instance, SANS 10162:2005 (The structural use of steel) is based on the Canadian Standard whereas SANS 10100:2000 (Code of practice for the structural use of concrete) is based on the old British Standard (Retief, 2008). However, it is likely that all the South African building standards will be modified over time to and will eventually be based on the Eurocodes. The Eurocodes have been adopted in the European Union countries (EN 1992-1:2004). Therefore the degree of details of the South African standard for structural concrete (SANS 10100:2000) is compared to that of the Eurocode (EN 1992-1:2004).

A basic comparison was drawn by Jurgens (2008) between the sub-clauses in the abovementioned standards. The main finding was that the two standards mostly cover the same design aspects, but the EN1992-1:2004 is more comprehensive than the SANS10100:1989 when it comes to precast concrete elements. For instance, EN1992-1:2004 includes aspects such as the design of hollowcore panels and also the design of diaphragm action in floors, both of which are excluded from the South African Standard. SANS10100:2000 is therefore found to be not as comprehensive as EN1992-1:2004 in terms of precast concrete design.

In terms of design guides and manuals other than standards, Blismas *et al.* (2005) identified the unavailability of guidance for off-site manufacturing as one of the barriers of HCC. Jurgens (2008) found that in many countries design guides are available and suggesteds that such a guide for South Africa might improve the use of precast concrete in the country. The alternative for South

African designers at the moment is to use international guides and standards for a comprehensive precast design.

It is concluded that South African design standards need to be updated to include all the aspects of precast concrete design and it would be beneficial to have a design guide for precast elements.

2.1.5 Conclusions of Hybrid Concrete Construction use

HCC is a method that is invented to improve the construction industry. However, data of this method is fairly undocumented. The most available data on this method was found from sources in the UK. This is possibly due to multiple investigations carried out in the UK to determine why the uptake of HCC was slow.

Although construction in South Africa is behind other countries such as the UK when the types of precast applications are explored, it does not necessarily imply that the South African industry will follow the same route as the UK industry. The South African construction industry has its own unique barriers (investigated further on). Currently few structural precast elements are implemented in the construction of South African buildings. However, according to Jurgens' findings, the majority of South African designers and contractors are positive about the future of HCC in South Africa. Due to this positive attitude and successful use of HCC in other countries (investigated further on), this method is worth exploring.

In the following paragraphs important managerial factors in HCC are identified.

2.2 Hybrid Concrete Construction factors

Relevant HCC factors are all the aspects that form part of a framework for future studies to assist project teams in their decision between hybrid and in-situ concrete construction. These aspects include benefits and barriers of HCC, factors to be quantified and concerns specifically related to HCC. All of these aspects are discussed in the following paragraphs.

2.2.1 Benefits of Hybrid Concrete Construction

When it comes to why HCC is used in construction projects, the answer lies in the numerous advantages that it offers. Benefits that precast concrete construction has to offer, depend on the conditions of each specific project (Blismas *et al*., 2006). One of the advantages that HCC may offer is reduced whole-life costs. Among the many others are speed, buildability, less on-site labour and improved safety (Goodchild *et al*., 2004; National Precast Concrete Association Australia; 2011, The Concrete Centre, 2010).

Apart from the benefits that concrete inherently offers as a material, the combination of precast concrete elements with in-situ concrete can also be beneficial for construction projects. For instance, having precast panels with increased element qualities and reduced formwork together with the flexibility of in-situ connections and toppings, this construction method is extremely versatile.

Too often direct cost determines the decision for the construction material or product. Non-cost based attributes such as safety and environmental aspects are seldom considered. This statement can be supported by benefits that were identified by Soetanto *et al.* (2004) by means of questionnaire responses from UK practitioners. Clients, engineers, architects, quantity surveyors and main contractors, identified the following most important benefits of HCC (in order of importance):

- Construction speed – projects complete on time
- Increased quality
- Cost – projects complete in budget
- Enhanced client satisfaction

Also, according to research carried out in the UK through interviews with construction clients, the main benefits listed were savings that are not directly related to the cost of the items and also value-adding items that does not relate to cost (Blismas *et al*., 2006). A list of benefits that were gathered from various reference resources are as follows:

- Reduced activities and less congestion on site (Blismas *et al*., 2006)
- Less weather depended activities (Chen *et al*., 2010; NPCAA, 2011)
- Less on-site labourers (Blismas *et al*., 2006)
- Improved safety (Blismas *et al*., 2006; Goodchild & Glass, 2004)
- Minimizing the duration of construction (Blismas *et al*., 2006; NPCAA, 2011)
- Improved and more predictable quality elements and finishes (Blismas *et al*., 2006; NPCAA, 2011)
- Reduction in overall cost (Soetanto *et al*., 2004; NPCAA, 2011)
- Reduced environmental impact (British Precast Concrete Federation, 2008; Blismas *et al*., 2006)
- Less disturbance to neighbouring communities (British Precast Concrete Federation, 2008)
- Increased sustainability of construction (British Precast Concrete Federation, 2008)

Therefore HCC may offer a better package than traditional concrete construction when all aspects are considered. The aim of this study is to find methods to quantify the abovementioned aspects with respect to precast and in-situ construction.

2.2.2 Barriers to the use of Hybrid Concrete Construction

Although precast elements for civil works, such as pipes, kerbs and roof tiles are being exploited in the South African construction industry, structural precast elements are not manufactured on the same scale. The uptake of structural precast elements in the South African industry has been slow. Possible reasons for this and barriers to the implementation of HCC are discussed in the following paragraphs.

In a questionnaire study carried out in the UK by Glass & Baiche (2001) to establish the relevant issues according to people that would typically be involved in HCC, the majority of the concerns were related to management and design practices and not to technical factors. Common barriers are:

- Insufficient guidance
- Innovation barriers
- Distance from precast yard to site
- Risks of precast applications

Furthermore, some barriers that were identified by South African design engineers in practice are as follows:

- Insufficient knowledge (Jarrat, 2011; Jurgens, 2008)
- Insufficient quality (Ronné, 2006; Smith, 2010)
- Insufficient skills (Jurgens, 2008)
- Job creation (Mitchell, 2010)

The abovementioned barriers are discussed in more detail in the following paragraphs.

2.2.2.1 Insufficient guidance

The first and foremost barrier against increased HCC as identified by Goodchild (2004) is the deficiency of guidance. As stated earlier, the precast design section of SANS10100:1989 need to be revised and a guide for the design of precast elements is required. Jurgens (2008) stated that various countries found that with the publication of design guidance for precast elements the use of these elements increased.

Furthermore it would also be of great assistance if precast construction projects are recorded for future reference. Jurgens (2008) investigated the construction of the Volkswagen South Africa (VWSA) paint shop building that was built using precast columns, beams and floor panels. In this investigation problems that had been encountered were recorded and these records can be valuable guidelines for future projects.

Establishing a data base of HCC projects, providing sufficient guidance for the design of HCC and an upgrade of the SANS10100:1989 are possible over time. Therefore the lack of guidance is a barrier that can be overcome.

2.2.2.2 Innovation barriers

"The adoption of modern methods of building construction is often constrained by conventional design thinking" (Precast Concrete Structures, 2011). Hewitt and Gambatese (2002) also mentioned that "resistance to change" is one of the barriers of construction automation.

Innovation is furthermore a barrier for fragmented industries. Fragmentation results in an increase in the number of people involved in a process. Where more people need to learn and accept an innovation, the innovation process takes longer (Hassel *et al*., 2003; Alsashwal *et al*., 2011). This is the case with the fragmentation of the construction industry which leads to the slow uptake of innovations such as HCC.

This is confirmed by Levitt (2011) who explains the fragmentation barrier of innovation as follows: the construction industry (as many other industries) evolved from a state where one company typically manufactured and installed all the components, to a fragmented industry where the separate tasks are performed by smaller, specialized companies. It can be compared to a mobile phone manufacturing process with components as shown in Figure 4.

Figure 4: Mobile phone components (Our Nokia, 2011)

Modular innovations within a specialized company (for instance the company that manufactures the batteries, or the screen of a mobile phone) are possible, but integral innovations that affect multiple manufacturers and contractors are much more difficult. Therefore the range wherein innovations can easily occur is small. Big changes take time, because more than one party must buy into the new concept. The only way to solve this situation is that contractors and subcontractors must form alliances to collaborate in multiple projects and in the long term. This will allow the development of better products and will ultimately improve innovation processes (Levitt, 2011). Collaborations can also be considered by architects and engineers.

2.2.2.3 Distance from precast yard to site

Where the distance from the precast yard to the construction site is far, it is a barrier for HCC (Blismas *et al*., 2005). This is due to high transportation cost for elements that are transported over great distances. Precast concrete suppliers in South Africa are generally situated in urban areas (refer to Appendix A). The application of precast elements fabricated off-site is generally not feasible for projects in distant locations. Therefore this is a barrier for remote construction projects.

2.2.2.4 Risks of precast applications

A potential increase in risk with the use of precast elements has to be considered. The more parties are involved in a project, the greater the risk of budget and schedule overruns of construction projects. Precast elements, that are typically subcontracted, would increase the risk of a construction project's schedule and budge overrun.

Despite the benefits that new technologies have to offer, there always exists an amount of uncertainty in new methods. The vagueness causes a risk of incorrect application and therefore many designers rather avoid new methods (Hewitt & Gambatese, 2002).

Other risks include:

- The risk of safety for inexperienced workers (Jurgens, 2008)
- Technical risks such as tolerances (Jurgens, 2008)
- Late changes to the project specifications (own identification)
- Availability of elements and transport (own identification)

Risk is currently a barrier to the use of precast elements. However, the more precast elements are implemented and the more it becomes a common application, the more experienced the users will become. The amount and magnitude of risks will reduce with increased precast applications. For instance, the more experienced workers become with the technology, the smaller the risk of safety will be. The barrier of risk can therefore be overcome.

2.2.2.5 Insufficient knowledge

HCC incorporates not only precast elements, but also in-situ elements. The application of HCC therefore requires that the project team has sufficient knowledge of both precast and in-situ elements.

Some design engineers in the South African industry indicated that precast practices are unknown and therefore it is avoided as far as possible by designers that are unfamiliar with precasting (Jarrat, 2011). This is a problem that coexists with insufficient guidance and in addition it is a result of insufficient training.

At university level the design of precast concrete does not form part of (or forms a very small part of) concrete design modules. Seven of eight universities in South Africa do not offer HCC courses in the undergraduate or postgraduate modules (in thesis of R Hanekom, December 2011: Increasing the Utilisation of Hybrid Concrete Construction in South Africa). It would be beneficial for the precast industry if universities would spend more time on precast concrete design in both undergraduate and postgraduate courses. Furthermore precast manufacturers can market products through seminars or presentations at design companies.

In this study it is assumed that the design team has sufficient knowledge to design any of the alternatives discussed. Also, it is assumed that the construction team has sufficient knowledge to successfully construct any of the alternatives discussed.

2.2.2.6 Insufficient quality

There is a common view that construction quality in South Africa may be too low for precast elements to be used effectively (Anonymous design engineer, 2010). Concrete construction quality in South Africa was investigated by Ronné (2006) and Smith (2010) and it was found that there is a considerable amount of non-compliances of dimensional tolerances of concrete elements to SANS2001-CC1:2007 in projects. This is discussed in more detail in Chapter 5.

2.2.2.7 Insufficient skills

A study was performed on the construction of the Volkswagen of South Africa paint shop building in Uitenhage. The building was built using precast columns, beams and floor elements. One of the problems that was encountered was a shortage of skills on site. Workers that are not familiar with precast construction struggled and crane operators had difficulties placing precast elements (Jurgens, 2008). However, skills can be improved and with an increase in the use of precast elements, these are barriers that can be overcome (Angelucci, 2011).

2.2.2.8 Job creation

The South African government promotes job creation (Ramutloa, 2011). Precast construction possibly requires less man hours than in-situ construction. In order to quantify the amount of man hours for each construction method, a further investigation should be carried out. However, precast manufacturing can offer a safer environment than in-situ construction. Precast manufacturing also requires labourers with a higher skill level and therefore offers a better lifestyle to labourers than in-situ construction jobs (Angelucci, 2011). Labour is discussed further in Chapter 6.

2.2.2.9 Summary

Constraints that were identified must carefully be considered and where a problem is identified, it must be discussed by the project team. Most of the barriers identified, can be overcome. The purpose of this study is to set a framework for future studies to assist project teams in decision making between precast and in-situ concrete construction and therefore quantifiable factors are explored.

2.2.3 Factors influencing decision making in Hybrid Concrete Construction

Similar to the decision between any other construction methods and materials, the choice between precast and in-situ concrete elements in structures is influenced by numerous factors. Relevant factors are categorized in this subsection. Several documents identify and classify these factors, of which over 90 items are categorized by Pasquire *et al*. (2005).

Although cost is one of the most important aspects recognized by all documents considering factors influencing hybrid concrete construction, it should not be the only consideration. Sustainability is a factor that was traditionally not one of the most significant concerns, but is becoming increasingly important (Goodchild, 2011). To many people, the expression “sustainability” refers to the environment, or the term “green”. However, the fundamental definition of sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (The SustainAbility story so far, 2010). This implies incorporating the concept of the triple bottom line.

The triple bottom line was originally formulated by Andrew Savitz to “develop and implement environmental, social and economic sustainable strategies” (Sustainable Business Strategies, 2009). These facets are arranged to establish the definition of sustainability being the circumstances where environmental, economical and social needs are met. See the graphical illustration of this principle in Figure 5.

The factors of the triple bottom line are in fact chosen to be considered in the decision making process between construction methods. This approach would ensure a decision based on a holistic approach. Apart from obvious factors such as cost, time and quality, the decision is also influenced by other aspects such as social considerations. For instance, in South Africa labour and job creation should definitely form part of the decision making process. Labour is discussed in more detail in Chapter 6. This study is therefore structured around a sustainability point of view.

Figure 5: The triple bottom line (Elkington, 1997)

Pasquire et al. (2005) identified the following decision making criteria for construction methods:

- Construction and manufacturing cost
- Project cost
- Project life cycle costs
- Time
- Quality
- Health and safety
- Sustainability
- Site issues

Later Chen *et al.* (2010) identified similar criteria for decision making between construction methods and he also ranked the criteria according to an industry survey in the U.S. Thirty-three economical, social and environmental criteria are summarized under the seven subdivisions listed below (Chen *et al*. 2010):

- Initial cost
- Long-term cost
- Constructability
- Quality
- Impact on health and community
- Architectural impact
- Environmental impact

These criteria cover the three sustainability aspects as given in Figure 5. Therefore these main topics are addressed in the following chapters:

Chapter 3 – Precast elements, structural systems and structures (types of systems for evaluation in the subsequent chapters are identified)

Chapter 4 – Cost and time (this includes initial cost and long-term cost)

Chapter 5 – Quality (this includes constructability)

Chapter 6 – Social aspects (this includes the impact on health and the community as well as the architectural impact)

Chapter 7 – Environmental impact

2.2.4 Other aspects concerning Hybrid Concrete Construction

Project teams that want to apply HCC have to keep certain aspects in mind that are not typical to traditional in-situ construction. When the use of precast elements is not managed properly in construction, it may lead to severe delays, budget overruns and buildability problems (Chen *et. al*, 2010). Aspects to keep in mind as well as ways to improve precast construction are discussed below. These aspects are not quantifiable. However, it should be considered when HCC is planned by project teams.

2.2.4.1 Procurement methods

Traditional procurement methods are mostly used in South Africa, rather than the design-and-build procurement method. Mitchell *et al*. (2007) found that the design-and-build procurement method is only used in 9% of construction projects in South Africa. By nature traditional methods exclude the contractor at preliminary stages of a construction project and it is argued that this is a drawback to the use of precast elements (Goodchild *et al*., 2004).

However, in other countries, precasting is implemented effectively in projects that use the traditional procurement method (Bärgstadt, 2011; Bailey, 2011). Therefore, this is a continued topic for debate as Glass & Baiche (2001) found in their study. They found disagreement in the responses to their questionnaire on the topic of applicable procurement methods. Having contradicting opinions in the abovementioned literature, further investigation is required to determine the feasible procurement methods for the South African precast market.

2.2.4.2 Early contractor involvement and communication

Early contractor involvement is an aspect that has been under discussion for all types of construction. It is preferred that input from contractors be acquired from an early stage of a project in order to minimize expensive changes later on in the project. Early contractor involvement would offer expert knowledge when the primary design is being carried out (Goodchild *et al.*, 2004).

With precast elements, early contractor involvement is even more important due to the added complexity of pre-manufacturing of elements (Glass & Baiche, 2001). For instance, the type of crane(s) that the contractor has available plays a role in the selection of the building elements.

The structural layout and integration system is particularly important in HCC (Soetanto *et al.*, 2004). In order to produce a design that is not only the most economical, but also structurally sound and buildable, co-operation and decent communication channels between all the project members from the client to the contractor are required.

Also, regular review meetings should be held by project teams wherein team members must rethink and discuss ideas regarding the structural system and selection of materials. This would ensure that important priorities are reached throughout the project.

A support group exists in the UK where contractors from different companies meet to discuss safety issues that they have encountered (Elhag, 2011). This provides an environment where contractors can learn from each other's mistakes.

It is concluded that extensive discussion and thinking sessions between team members (including the contractor) are preferred in the planning phase of a project (Pasquire *et al.*, 2005; Surridge, 2011). Attention should also be paid to effective communication between project team members (Jurgens, 2008). In addition, a support group can be established for precast users to address issues in the industry.

2.2.4.4 Standardization

Maximizing standardized precast elements for a building would facilitate the most economical design option. Such standardization results from a team effort with early contractor involvement and effective communication.

Standardization must be kept in mind when considering precast construction for a building project (Hewitt & Gambatese, 2002), because the structure must be adapted to suit this construction method right from the start. For instance, weather steps on balconies need to be incorporated in the conceptual design. Also, non-uniform slab layouts should be discouraged to optimize standardization.

2.2.4.5 Prioritize project objectives

In order to successfully reach the goal of any specific project, the objectives must be prioritized. No construction method can fulfill all the possible objectives (such as low cost, high quality, etc.) and therefore the project team must decide on the most important objectives (Hewitt & Gambatese, 2002). This was supported by Gibb (2011) in a personal interview. This corresponds to and once again highlights the importance of early contractor involvement and effective communication.

2.2.4.6 Summary

The application of HCC involves combining in-situ and precast elements. A project's procurement method should not restrain the construction to in-situ elements only. Precast elements together with in-situ elements can successfully be used in projects that are based on traditional procurement methods. Involvement of all the project team members is crucial for this construction method. For the successful use of precast elements, effective communication between the team members is required in order to maximize standardization and also to identify the most important objectives of the project to ensure a successful product.

2.2.5 Summary of Hybrid Concrete Construction factors

Benefits of HCC found in the literature are promising. Advantages identified in the chapter are construction speed, lower cost, increased quality, improved safety, less disturbance to neighbouring communities, less on-site labourers, reduced environmental impact and more.

The validity of these benefits must be considered for the South African industry. For instance, it must be determined whether HCC in South Africa does indeed cost less than in-situ construction (this is investigated further on). Also, less on-site labourers might be beneficial for first world countries with high labour cost, but it might not be beneficial in South Africa, where job creation is promoted (this is discussed further on).

Apart from projects where the distance between the precast yard and the site is far, and where job creation is an issue, HCC barriers are mostly obstacles that can be overcome with an increase in the use of precast elements.

It should be noted that quality is an aspect that is listed as a benefit in international literature; however, it was identified as a barrier in South Africa. Therefore this aspect must be carefully examined.

In order to compare precast and in-situ concrete construction, the following quantifiable factors are identified in the light of sustainability:

- Cost and time
- Quality
- Social aspects
- Environmental impact

Potential decision making methods and a toolkit are explored in the following paragraphs.

2.3 Decision making methods and toolkit

Numerous decision making methods are available that can be implemented in the decision making process between construction elements. Most of the available methods apply matrix vector algebra to find the best solution according to certain values. Some of these methods that may be suitable for decision making between in-situ and precast concrete construction, as well as a relevant toolkit are discussed below.

2.3.1 AHP and AUTOCOP

Many decision making challenges worldwide have been solved using the Analytical Hierarchy Process (AHP). The AHP utilize data as well as the experience based knowledge of the user to find the best solution between two options. A hierarchy of the criteria and sub-criteria is set up with each factor’s relative importance. Each option’s relative suitability is determined by multiplying a matrix containing the quantities of different factors, with a vector containing the relative importance of the factors. Finally a priority vector is obtained by adding the column entries of the matrix. The outcome is two number values for the two options which indicate the preferred alternative (Hastak, 1998).

Based on the AHP, Hastak (1998) suggests a technique called Automation Option Evaluation for Construction Processes (AUTOCOP) that is basically a structured method which analyzes two options with the AHP by using the views of a group of team members. AUTOCOP first establish the relative importance of each factor in the decision making process is, based on each team member's opinion. Input can be obtained from different team members and the outcome will depend on the weights of the different team members' opinions. This method can be useful for decision making between two options.

The drawback of AHP and AUTOCOP, however, is that the output is numerical values that are assigned to two possible solutions. Unlike other decision making methods that ranks numerous options, it can only assess two options at a time.

For the application of decision making between precast and in-situ concrete construction, it is likely that the options available are more than two. The available options would typically comprise of an in-situ construction method (or methods) and different precast technologies in combination with in-situ concrete and furthermore alternative combinations of precast and in-situ concrete elements in a structure. Therefore the AHP and AUTOCOP method is not suitable for decision making between more than two construction methods.

2.3.2 MCDM

A "Multiple Criteria Decision Making" (MCDM) system based on the "Elimination and choice expressing the reality" (ELECTRE III) method was developed by Ulubeyli & Kazaz (2009) to choose between types of construction equipment.

With several alternatives having several corresponding characteristics, the system ranks the alternatives in an order of priority. Quantitative and qualitative factors are listed with their importance factors as an input. The different options are then basically compared to one another until a final ranking is achieved.

The drawback of this method is the fact that the criteria are formulated in a list, instead of in a hierarchical arrangement. In decision making between different construction methods, the factors that influence the decision are not listed, but are hierarchical. For instance, cost is a main consideration and this category includes design cost, cost of elements, first cost of the project, maintenance cost, etc. Instead of placing these factors in a hierarchy under cost, it is directly compared to sub factors of other aspects, such as health and safety of labourers, job creation and neighbouring communities. Therefore, because ELECTRE III does not have the option of ranking the factors, it is not the appropriate choice of decision making method for the decision between in-situ and precast concrete construction.

2.3.3 Hybrid decision making method

Razmi & Sangari (2008) combines two decision making methods, namely TOPSIS and PROMETHEE, to form a hybrid method for decision making between several alternatives. It is implemented to assist in decision making of business options that have both quantifiable and unquantifiable criteria.

According to Razmi & Sangari (2008) the "Technique for Order Preference by Similarity to Ideal Solution" (TOPSIS) is based on having positive ideal and negative ideal reference values to which the available options would relate. A decision matrix is created by the different criteria factors of the different options. This matrix is normalized and weighted normalized values are assigned to each factor. Positive and negative ideal values are obtained by ranking each criterion's values from best to worst. A 'distance' to the positive and negative ideal is determined by means of a formula. 'Closeness to the ideal solution' is determined by means of a formula (refer to Razmi & Sangari, 2008) for each criteria. The best alternative would be the option that relates the best to the positive ideal and the worst to the negative ideal.

"Preference Ranking Organisation Method for Enrichment Evaulations" (PROMETHEE) was formulated by Brans and Vincke in 1985. It was developed to rank options based on their scores for certain criteria. The PROMETHEE method uses a preference index of one method over another. It is based on a formula (refer to Razmi & Sangari, 2008), which also incorporates the criteria to be maximized as well as the weights associated with the criteria. The order of preference of different options is iteratively determined.

The hybrid decision making method implements TOPSIS in the first stage to assess all the possible options and PROMETHEE is applied in the second stage to rank the alternatives (Razmi & Sangari, 2008). Results of the 'closeness to the ideal solution' from the TOPSIS application are integrated in PROMETHEE. This method is the most promising of all the methods for decision making between in-situ and precast concrete elements, since it does not only allow for more than two options, but also incorporates a hierarchical order in the first step, when applying TOPSIS.

2.3.4 IMMPREST Toolkit

IMMPREST is an "Interactive Method for Measuring Pre-assembly and Standardization benefit across the construction supply-chain" toolkit developed by a research team at Loughborough University. This toolkit is currently only used for academical purposes (Gibb, 2011).

The main function of IMMPREST is to determine how appropriate precast construction is for a particular project (Pasquire *et al.*, 2005). It does not compare in-situ and precast construction.

Advice is provided on the suitability of off-site manufacturing. Recommendations include the following factors: cost, time, quality, design or aesthetics, sustainability, health and safety, process, procurement and site constraints. For instance, if the user selects in the input of the toolkit that overall project time is very important, the recommendation would be that off-site production is a good option.

It was discovered that the IMMPREST toolkit offers a thinking space for project teams to establish what the most important aspects of their project are. Pasquire *et al*. (2005) hope that with this extensive thinking the way that project teams consider construction projects will change in such a way that they will think differently about the need of recording meaningful information.

This toolkit is appropriate for inexperienced users of precast construction and can be used to establish where issues might arise when applying HCC. However, it does not offer quantifiable factors to consider for decision making of any project. Therefore it is not implemented for decision making between the construction methods in this study.

2.3.5 The use of decision making methods and toolkits

Of the decision making methods identified, the hybrid decision making method is the most promising. The IMMPREST toolkit that is available would offer assistance in the decision making process.

Although the methods investigated can all be applied to decision making between different construction methods (whether for two or more options), there are two major concerns regarding these methods. Firstly, the sensitivity of the models is a problem and secondly automating decision making is inappropriate.

The decision making methods are not sensitive enough to major aspects of consideration, especially when the model has a large set of criteria. For instance, if a certain aspect is very important and even though it may have a very heavy weight in the model, it does not necessarily have a great effect on the outcome. It will be a problem when, for example the petrol price is high and the distance to site should play a key role in the decision. Also, if the effect of a construction project on a neigbouring community is for some reason a major concern, these mathematical decision making methods would not necessarily be easily influenced by this concern and therefore it is not suitable for the decision making process.

Another problem that eliminates a decision making model is the fact that many decisions cannot be automated. Although a decision making model would assist the user in the decision making process, the user would rather want to know what the benefits and barriers are for the different options. Complex decisions have to be made physically by knowledgeable team members.

The application of HCC involves complex decisions, because it is an art to effectively combine in-situ and precast concrete elements to construct a building. Essentially there are so many different options for precast and in-situ combinations in HCC and therefore the decision should be made by the project team themselves.

Having reviewed the advantages and disadvantages of mathematical decision making methods, the focus of this study has been identified. Instead of attempting to find a model where the user punches in the required input and obtain a numerical output, it was decided to rather focus this study on all the aspects that need to be considered in the decision making process. Quantification of these aspects or possible ways to quantify these aspects is explored. The decision maker(s) can then study the influencing factors and its roles on the different methods and make the necessary conclusions to decide on the best alternative.

2.4 Concluding summary

2.4.1 Background of Hybrid Concrete Construction and its use

Hybrid concrete construction is about providing the best solution. Currently little precast construction is applied in South Africa. Insufficient information is available to assist project teams to decide for or against precast elements. However, the majority of the respondents have the view that there is a future for HCC in South Africa.

2.4.2 Benefits, barriers and aspects to consider of Hybrid Concrete Construction

Benefits, barriers and factors of HCC to consider in the decision making process, are summarized in Table 1.

Table 1: Benefits, barriers and factors to consider in HCC

Benefits	**Barriers**	**Factors to consider**
• Construction speed	• Insufficient guidance	• Procurement methods
• Increased quality	• Innovation barriers	• Early contractor involvement
• Less congestion on site	• Distance from yard to site	• Communication
• Less weather dependent	• Risks of precast applications	• Prioritizing design objectives
• Reduced environmental impact	• Insufficient knowledge	• Standardization
• Less disturbance to neighbouring sites	• Insufficient quality	•
• Increased sustainability	• Insufficient skills	
• Timely identification of problems	• Job creation	

Barriers of HCC can mostly be overcome. For instance, skills and guidance can be addressed. Furthermore, risk and quality will reduce with an increase in the use of precast applications.

An evaluation of in-situ and precast construction methods are performed in this thesis, based on economical, social and environmental considerations. In addition, quality is also identified as a decision making factor and therefore it is investigated in a independent chapter. The chapter divisions are as follows:

Chapter 4 – Cost and time (this includes initial cost and long-term cost)

Chapter 5 – Quality (this includes constructability)

Chapter 6 – Social aspects (this includes the impact on health and the community as well as the architectural impact)

Chapter 7 – Environmental impact

2.4.3 Decision making methods and available toolkits

Various decision making methods are available. None of the methods considered are considered suitable for HCC decision making. Rather than the proposal of a mathematical decision making method, the approach used in this study is to supply project teams with the information gathered and investigated. The decision maker(s) can then study the characteristics of the different methods and make the necessary conclusions to decide on the best alternative.

The IMMPREST toolkit identified is useful to provide guidance to inexperienced users. However, the toolkit does not supply comparisons of precast elements to in-situ elements and therefore it is not used in this thesis.

2.4.4 Recommendation

It would be beneficial for the South African precast industry to have recorded data of precast applications. It is suggested that a data base be developed. Such a database should contain the following information of HCC projects:

- Descriptions of HCC projects
- Building types
- Precast elements used
- Problems encountered during construction and in the use phase

The most appropriate organization to drive this database, would be the Cement and Concrete Institute.

Chapter 3

PRECAST ELEMENTS, STRUCTURAL SYSTEMS AND STRUCTURES

The general term "precast construction" is frequently used in this document. Precast construction can refer to numerous applications in different fields and countries and therefore it is necessary to define the applicable precast elements, structural systems and structures for this investigation.

In-situ and precast construction in concrete frame buildings is examined in this study. This excludes all non-structural precast elements such as those elements used in civil works and façade panels. It excludes tilt-up panels and hollowcore precast bricks. Furthermore precast bridge elements are also excluded from this study.

In addition this investigation is limited by the availability of structural building precast elements in South Africa. Not all types of precast elements are available in South Africa yet. For comparison purposes of this study, the aim is to first provide a framework for information to be offered to project teams based on the elements that are available. As a future study a further investigation can be carried out on the feasibility for the South African market of structural systems and elements that are not available yet. Should it be feasible, the South African industry must ultimately strive to implement those precast elements that are successfully used internationally.

Due to different conditions in South Africa than for instance in Europe, the preferred elements and structural systems are somewhat different. With lower labour cost and a high unemployment rate (refer to Chapter 6 for information regarding labour), more labour intensive projects and less automated activities are applied in South Africa. In Europe, more severe weather conditions lead to increased off-site manufacturing of construction elements.

As discussed in Chapter 2, little information is available on HCC projects in South Africa. This makes it difficult to identify the elements, systems and structures that are implemented in HCC. It is recommended that a database be developed for HCC projects. This will serve as guidance for future projects.

In this chapter precast elements investigated are based on what is available and being used in South Africa. Precast elements refer to building elements that are precast, such as precast beams, columns, walls or floor elements. The application of products used internationally is also mentioned for future reference. Subsequently, structural systems that are applied in the South African construction industry are discussed. Structural systems refer to the combination of building elements, for example precast floor elements on load bearing brick walls.

3.1 Precast elements

Although there is a growth in the use of precast concrete elements in South Africa (Surridge, 2006), it is still not nearly as often used in construction projects as in other countries such as Sweden, Finland, the Netherlands and some other first world countries. Before identifying the type of precast elements that are used, it is established to what extend precast concrete elements are implemented internationally.

3.1.1 The use of precast elements internationally and locally

In a small survey done in this study, data was gathered in the form of personal opinions on the usage of precast elements in different countries. The aim of the study is not to find exact values of precast usage internationally and locally, but rather to determine the relative implementation of precast usage in the different countries. This was estimated as a percentage of the total usage of concrete in buildings.

The aim was to determine whether there exists a clear correlation between a country's productivity and its use of precast construction. Although information obtained is at most considered to be qualitative, it nevertheless shows that there is not a clear correlation. Results obtained are provided in Appendix B. It is the view of the participants in the survey that 5-25% of concrete in building construction in South Africa consists of precast elements. This is lower than the precast usage in Denmark (75-95%), Switzerland (45-55%) and the Netherlands (35-45%).

Note that these results are not accurate. The survey was not scientific and limitations of this information must be recognized.

3.1.2 Types of precast elements

The types of precast elements used in South Africa are fairly simple. As indicated in Chapter 2, prestressed hollowcore panels (Figure 6) and rib-and-block systems (Figure 7) are basically what the South African market has readily available. Refer to Table A.1 in the Appendix A for structural precast manufacturers in South Africa.

Figure 6: Hollowcore floor (Hollowcore, 2010)

Figure 7: Rib-and-block floor (Royal Concrete Slabs, 2011)

Another type of floor system is semi-precast flooring. This is a technology that is used in other countries (NPCAA, 2011; Bensalem, 2011), but is not yet available in South Africa. Figure 8 shows a semi-precast floor element. This concept is also used for double T-shaped floor structure units as shown in Figure 9. According to Bargstädt (2011) semi-precast floor systems offer the best of both worlds: it has the flexibility of in-situ construction, yet it does not require shuttering. Therefore this construction method is being exploited internationally and in some places it is the preferred method of construction for suspended floors (NCPAA, 1998).

Figure 8: Semi-precast Floor Panel (Lattice Girder Floors, 2011)

Figure 9: Semi-precast double T-shaped floor units (Bargstädt, 2011)

According to manufacturers' websites (Appendix A) these semi-precast floors are not yet used in South Africa. A South African manufacturer's comment on this system was that they try to keep the systems as simple as possible at present. The reason being to get broader acceptance of the precasting systems first (Queripel, 2011).

Other elements such as precast beams and columns can be manufactured in South Africa on request, but this is not often produced. Jurgens (2008) found that for the Volkswagen paint shop in Uitenhage which was completed in 2006, precast column and beam elements were used. This is however not commonly implemented. Structural precast walls are very rarely specified in South Africa.

In South Africa there are also other applications for precasting. Civil elements such as precast poles, kerbs, pipes, bricks and roof tiles are commonly manufactured. Hollow blocks are commonly applied for low cost housing projects. Façade elements and tilt-up precast elements are also used as well as precast bridge elements. However, the focus of this study is to investigate structural building options. Therefore, the precast elements that will be investigated in this study are the readily available floor systems, namely prestressed hollowcore panels and rib-and-block systems.

3.2 Structural systems

The structural systems that will be considered in this study are combinations of frame and floor structures. Sub-structures are not considered in this study. In order to establish the state of the structural floor industry (both in-situ and precast), a small non-scientific questionnaire survey was carried out to identify structural systems used in South Africa.

The aim of the survey was to obtain an idea of the extent of the use of relevant structural systems in South Africa. Therefore, a limited amount of contractors and consultants were targeted to share their views on the South African building industry. Feedback received is sufficient to identify structural systems that should be included in the options of decision making process of project teams in South Africa. Results of the survey are given in Appendix C. Considering the small sample, a statistical analysis of the information was not contemplated for this study. The purpose was rather to identify what types of structural systems are commonly constructed in South Africa.

Assumptions that can be made from the survey are as follows:

- Floors constructed on load bearing brickwork are mostly in-situ concrete floors (up to 80%, which is the highest score in the survey) and the remainder is hollowcore and rib-and-block floors (see Figure 10).

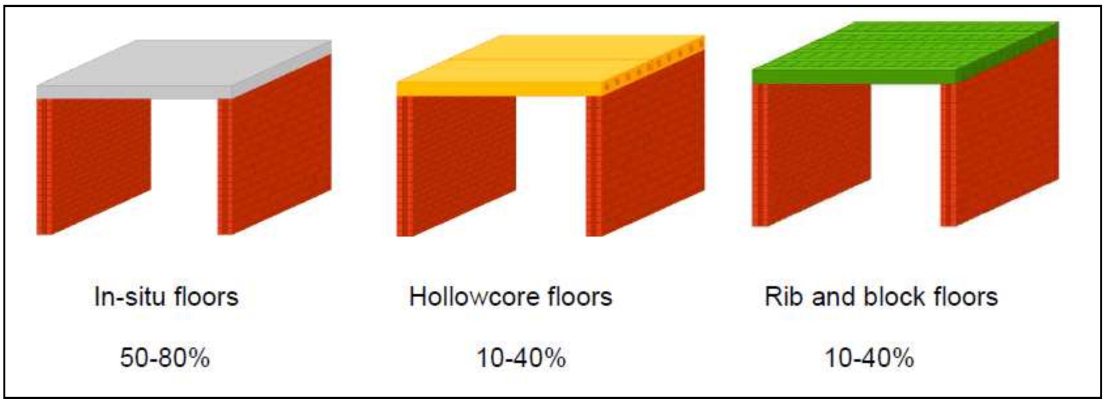

Figure 10: Floor systems on load bearing brickwork structures

- About half of the concrete frames have normally reinforced flat slabs (see Figure 11).

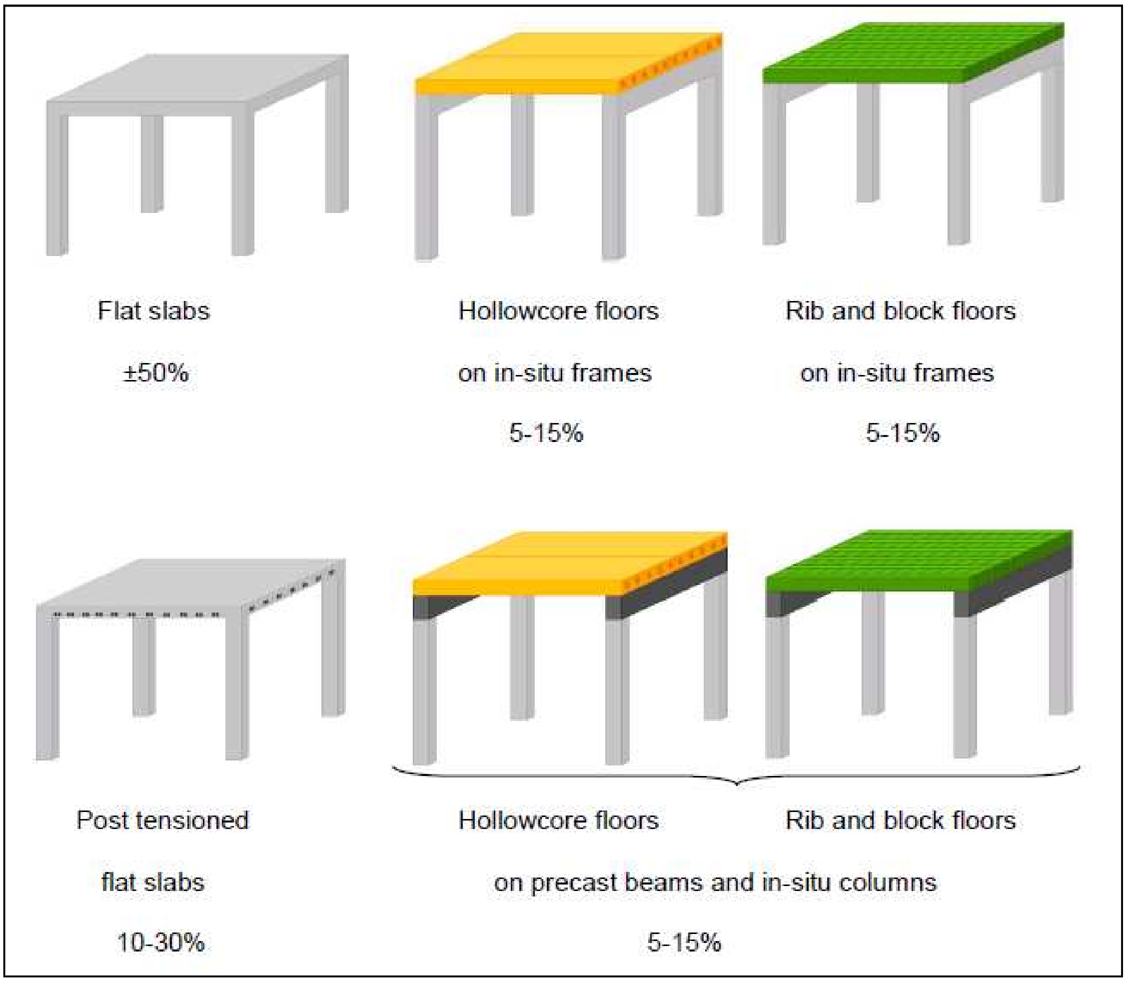

Figure 11: Floor systems on concrete frames (percentages represent estimated percentages of concrete frames with these floor systems)

- Precast columns and beams are very seldom, if ever, used (see Figure 12).

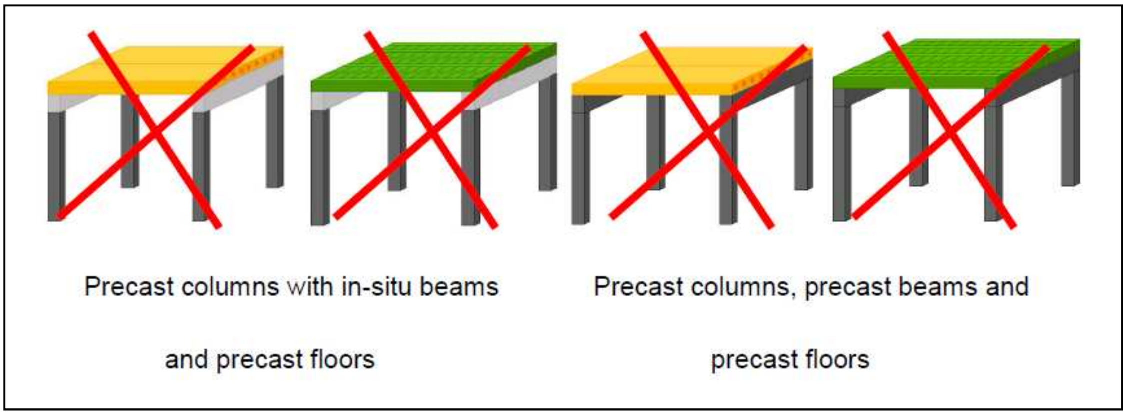

Figure 12: Precast frames

- Floors constructed on steel frames consist mainly of hollowcore panels. In addition rib-and-block systems are applied on steel frames (see Figure 13).

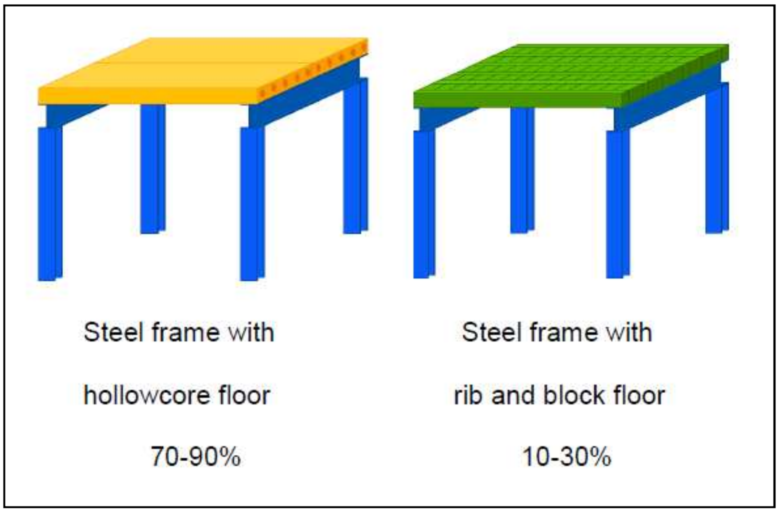

Figure 13: Floor systems on steel frames (percentages represent estimated percentages of steel frames with these floor systems)

Figures 10 to 13 indicate that, as previously mentioned, although the small sample may only provide some information, it nevertheless it is sufficient to identify the structural systems used in South Africa. For instance, Figure 12 clearly indicates that precast frames are not commonly constructed in South Africa. Although respondents of this survey have the view that precast frames are not used in South Africa, there are exceptions, such as the Volkswagen South Africa paint shop in Uitenhage (Jurgens, 2008).

For comparison purposes in this study, in-situ floors will be compared to precast floors. In-situ floors include normally reinforced and post-tensioned in-situ slabs. In South Africa, precast floors include hollowcore panels and rib-and-block systems. Support structures are currently very seldom, if ever, constructed of precast concrete elements and therefore it is assumed that the support structures are either load bearing brickwork, in-situ concrete frames or steel frames.

Comparisons made in this study are limited to one-way span floors. Therefore a normally reinforced in-situ slab, a post tensioned in-situ slab, a hollowcore floor and a rib-and-block floor are compared by assuming a one-way span floor structure. However, in-situ floors constructed in South Africa are generally flat slabs (Figure 11). In order to have a more realistic comparison, a flat slab must for instance be compared to hollowcore panels on a beam support structure. More accurate structural combinations like these can be investigated in a further study.

3.3 Structures

The types of buildings that are constructed using precast elements also vary in different areas and countries. In South Africa, precasting is seldom specified for small projects. In the UK, precast systems are commonly specified for residential houses or schools with three or more rooms and larger projects. It is less effort for the design engineer to specify precast floors for these types of buildings, because it is less time consuming to find the required size of the hollowcore panels than to provide reinforcement details for floors (Bailey, 2011).

Unfortunately no assumptions regarding the types of buildings constructed using precast elements can be made from the response to the questionnaire of the South African precast industry (Appendix C). Therefore the types of buildings investigated are not specified for this study. Only the types of structural systems and elements are defined as above.

3.4 Concluding summary

Different types of precast systems are used in different countries. The types of elements and systems investigated in this study are determined by the products available in South Africa.

3.4.1 Precast elements

In terms of structural precasting in building structures, flooring systems that consist of hollowcore panels and rib-and-block elements are mainly used in the South African industry.

3.4.2 Structural systems

Support systems for the floors are load bearing brickwork, in-situ concrete frames or steel frames. Precast support systems are currently very seldom, if ever, constructed in South Africa. However, there are exceptions such as the VWSA paint shop. Although precast support systems can be advantageous in certain cases, it is not investigated in this study.

3.4.3 Structures

No clear indication is given on the types of buildings constructed using precast elements in South Africa. Therefore all types of building structures are included in this study with the exception of low-cost houses.

3.4.4 Conclusion

Comparisons in terms of cost and other aspects can be made for the following construction methods:

- In-situ slabs
- Post tensioned slabs
- Hollowcore floors
- Rib-and-block floors

The support system for these floors may vary. However, it is decided to assume a structural concept that incorporates one-way span floors. Refer to the next chapters for more information on the comparison of the following aspects of the systems:

- Cost and time
- Quality
- Social aspects
- Environmental impact

These aspects are evaluated separately in the subsequent chapters.

3.4.5 Recommendation

As a future study other combinations of in-situ and precast systems such as an in-situ flat slab and a hollowcore floor on a beam structure may be investigated. Similarly, comparisons can be made of other types of concrete construction options not used in South Africa, such as lattice floors on in-situ concrete frames.

Chapter 4

COST AND TIME

Cost is normally the first consideration that comes to mind when different options of construction methods are available. In this chapter the costs associated with different construction methods are investigated. Comparing the cost of different construction methods entails more than comparing the material cost alone. Initial construction cost as well as time related cost must be included in cost estimations for a project.

Although designers in South Africa have a certain perception that precast elements are more expensive than in-situ elements (Mitchell, 2010; Du Toit, 2010), it is not necessarily the case. South African contractors recognize that the implementation of precast elements in a structure has potential financial benefits (Burger, 2010).

Before the costs of the different methods are compared, the relevance of the cost difference should be considered. The structure of a building typically represents only 10% of the construction cost of a project (Goodchild & Glass, 2004). In building structures, the floor elements are of importance in this study (refer to Chapter 3). According to the National Precast Concrete Association of Australia (2011), floor elements make up 6-8% of the structural cost of a building. It follows that floor elements cost roughly 0.6 - 0.8% of the total construction cost of a building project. Therefore the cost of the floor elements is not that significant when the overall value of a project is considered.

Goodchild & Glass (2004) furthermore stated that initial cost of a structure is not what the value measurement of a project is about. It should also include “softer” aspects such as sustainability. However, in this chapter an investigation is nevertheless carried out on a scheme to determine the costs of the different construction methods.

When comparing the cost of precast floors to that of in-situ floors, the different components of the cost of a project that need to be considered are:

- The cost of elements (i.e. only the cost of the floor system);
- The overall cost of a project (this includes other costing items such as cladding, staircases etc. as well as the possible savings due to different construction durations); and
- The lifetime cost of a project (based on long term cost).

These differences in costs are investigated in this chapter and its importance in the decision making process is considered.

Other aspects to keep in mind when estimating cost are:

- The methods of costing;
- The effect of changes on cost; and

Factors that have an additional effect on the cost of the different construction methods are:

- Market conditions
- Geographical location
- Size of the project

These aspects are discussed in this chapter.

4.1 Costing aspects

4.1.1 Costing methods

Quantifying and costing of in-situ construction building projects are normally carried out by a quantity surveyor in building projects in South Africa. Rates that quantity surveyors use when costing elements, are based on national indices. Indices in South Africa are updated by the Joint Building Contracts Committee on a daily basis. The cost of every component of an in-situ structure is determined accordingly. For instance, rates per m^2 are specified for formwork and temporary support for slabs. These predetermined rates are dependent on the finish and the thickness of the slab (Du Toit, 2010). Therefore the method of costing in-situ elements is fixed.

On the contrary, no specific index or method exists to price precast elements. Typically a quantity surveyor sends the necessary drawings to a precast manufacturer, who provides a quotation (Du Toit, 2010; Nauta, 2011;). Calculating a quote for precast elements is considered as an art rather than a science. Depending on the circumstances, the manufacturer decides what the prices of the elements are, unlike the pricing of in-situ elements. For instance, a change in the economic climate would influence the fluctuation in price of precast elements much more than that of in-situ elements. Therefore a universal cost comparison is complicated and perhaps somewhat objective since it is time specific, manufacturer specific and location specific (Anonymous manufacturer, 2010; Queripel, 2011). Since the prices of precast elements depend on a limited number of manufacturers, rather than national specified indices, price fluctuations of precast elements are higher than that of in-situ elements.

4.1.2 The effect of changes on cost

Changes to a project's specification leads to an increase in construction cost and time. If a change is made at an early stage in a project, it has a small effect on the cost and schedule of the project. However, changes made at a late stage in a project have a significant influence on the cost and schedule of the project. This trend is illustrated in Figure 14. Note that values are not of importance in Figure 14. Discussions regarding the effect of changes on a project's cost, are based on the trend.

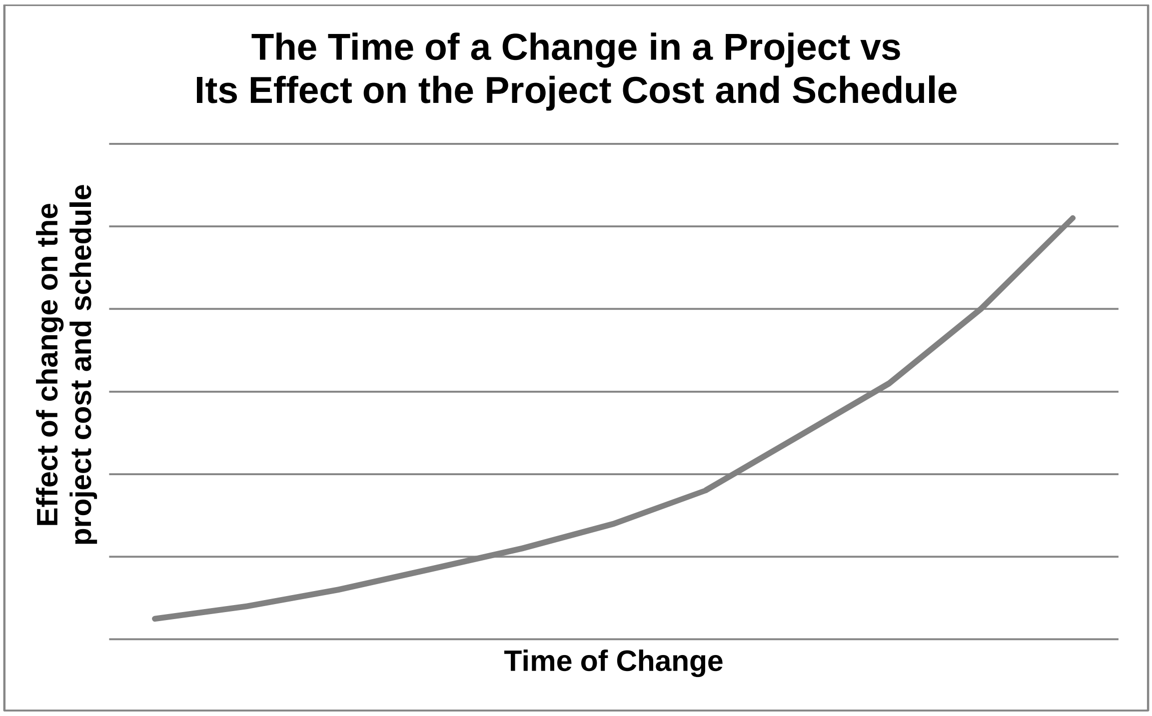

Figure 14: The time of a change in a project vs its effect on the project cost and schedule (Malan, 2010)

In precast construction, the project team is forced to make decisions at an earlier stage in the project than in in-situ construction. The difference in the time at which changes takes place in in-situ and precast construction has certain advantages and disadvantages that are discussed below.

In-situ construction projects have more flexibility to incorporate changes at a later stage in the project than precast construction projects, because elements are not pre-manufactured. The disadvantage of this flexibility is that project teams are not forced to make decisions at early stages and it becomes a habit to postpone decisions to the last minute (Gibb, 2011). As Figure 13 illustrates, these late decisions generally have a significant effect on the construction cost and schedule.

However, with the use of precast elements, the design team is obliged to make decisions at an early stage in the project. As Gibb (2011) says, "it challenges the need of last minute changes". If accurate decisions are made at an early stage in the project, it leads to fewer changes at a later stage. Therefore the use of precast elements contains the potential benefit of minimizing schedule and budget overruns.

4.1.3 Factors influencing cost

Factors that contribute to price fluctuations are market conditions, the geographical location of the project and the size of the project. These factors are discussed below.

4.1.3.1 Market conditions

Fluctuating market conditions cause a variation in element prices over time. This variation is reflected in the indices that quantity surveyors use to price in-situ components of a structure.

The method to price precast elements, however, is not fixed, as discussed earlier. As an example, during a time of good market conditions the price of precast elements might be up to three times more than in a time of poor market conditions (Anonymous manufacturer). Such a variation cannot be predicted and consequently tendencies of price fluctuations due to market conditions cannot be estimated. Therefore a cost comparison between in-situ and precast elements is dependent on the economical climate.

4.1.3.2 Geographical location

In South Africa, the prices of precast products vary within the country. There is a general tendency that the cost of precast floors is 5-10% lower in Johannesburg than in the other cities such as Durban and Cape Town (Queripel, 2011; Surridge, 2011).

However, the cost of in-situ components does not vary within the country. Prices of in-situ components are predetermined by the national indices, as mentioned earlier. Therefore a cost comparison between in-situ and precast elements in South Africa is dependent on the precast manufacturer and on the geographical location of the project.

4.1.3.3 Size of the project

Rates of in-situ elements are independent of the size of the project. However, the management cost of an in-situ construction project (preliminaries and general cost) is a variable that depends on the size of the project. This cost is typically between 7% and 10% of the project cost, depending on the project (Du Toit, 2010).

The price of precast elements depends on the size of the project. For large projects, a manufacturer can produce precast elements at a lower cost per floor area. This sliding scale effect can however not be predicted, because it depends on the manufacturer and the economical climate. Therefore a cost comparison between in-situ and precast elements is also dependent on the size of the project.

4.2 Cost comparison

4.2.1 The cost of elements

In Chapter 3 floor systems are identified for investigation in this study. The floor systems considered include a normally reinforced in-situ floor, a post tensioned in-situ floor, a hollowcore floor and a rib-and-block floor.

The cost of elements in precast and in-situ floors are said to be more or less equal (Goodchild & Glass, 2004). However, a simple study is performed here to estimate and compare the cost of the different types of elements in the South African industry.

This comparison is made to provide information to a project team, which may be used in order to do a critical evaluation of construction options for a specific project. In this study a 500m^2 suspended floor is designed for the different construction methods. The support system is of such a nature that the floor span in one direction. In-situ floors have continuous spans, whereas the hollowcore floor has single spans and the rib-and-block floor is semi-continuous.

Five different design layouts, each having a size of approximately 500m^2, are used to accommodate varying span lengths between 4m to 8m. The construction site is assumed to be within 35km from the precast yard. The most economical slab is designed for each option, i.e. no extra conservatism was built in.

Designs of the in-situ options are performed in accordance with SANS 10100-1:2000 (The structural use of concrete). Hollowcore floor panels as well as rib-and-block floor elements are selected from informative guides provided by manufacturers. Based on the designs, the necessary quantities are calculated.

Quantity items for in-situ options include:

- Concrete
- High tensile strength reinforcement
- Mild tensile strength reinforcement
- Post tensioning tendons
- Anchors for tendons
- Horizontal formwork
- Vertical formwork

Hollowcore floors are quantified in terms of floor area. Quantities of the following pricing components are required for a cost estimation of a rib-and-block floor:

- Lintels (ribs)
- Blocks
- Y12 bars
- Reinforcing mesh
- Concrete for structural topping
- Formwork for structural topping
- Transportation
- Installation

The following actions are performed in this design example.

1. Design of different floor options with a constant load, but varying span lengths.
2. Calculation of quantities.
3. Calculation of cost for all the different options. Rates are obtained from quantity surveyors and precast manufacturers. Installation fees are included in the cost of the floor elements.

Rates of in-situ floor components were obtained from quantity surveyors and estimated rates for precast floor components were obtained from manufacturers. Rates from the quantity surveyors were obtained in October 2010 and again in August 2011. In this time, in-situ construction rates stayed fairly constant, with the exception of a 6% increase in the price of reinforcement. The latest rates are used in the cost comparison. Rates from manufacturers were obtained in March 2011. Price ranges were confirmed by alternative manufacturers.

Using rates as described above, the installed cost per m^2 of the different options is determined. Refer to Appendix D for design calculations, quantities and rates. A comparison of the cost of the different options over varying span lengths is given in Table 2. A graphical presentation of these costs is given in Figure 15. The rib-and-block floor system used in this example has a maximum span of 7.5m. Post tensioned floors generally do not have small span lengths, therefore a post tensioned floor is not designed for the 4m span option.

Table 2: Summary of the cost per square meter of different floor construction options

Floor system	4m	5m	6m	7m	8m
Normally reinforced in-situ slab	R322/m^2	R358/m^2	R400/m^2	R450/m^2	R506/m^2
Post tensioned in-situ slab	n/a	R368/m^2	R404/m^2	R438/m^2	R486/m^2
Hollowcore	R425/m^2	R450/m^2	R490/m^2	R550/m^2	R600/m^2
Rib-and-block	R418/m^2	R443/m^2	R475/m^2	R475/m^2	n/a
Cost differences:					
• Hollowcore vs in-situ option with lowest cost	32.1%	25.7%	22.5%	25.7%	23.3%
• Rib-and-block vs in-situ option with lowest cost	29.9%	23.7%	18.7%	8.6%	n/a

As discussed earlier, the prices are subject to change over time. In addition the rates of the hollowcore as well as the rib-and-block floor are dependent on the manufacturers, their geographical location and the size of the project. Furthermore, if the distance between the precast yard and the site is further than 35km, the precast options would be more expensive than in this example. The price of transport was calculated as R1166 per ton for a 35km radius distance.

Table 2 and Figure 15 show that for this example, at shorter spans (up to 6m), the normally reinforced floor has the lowest cost. At longer spans (7m and 8m), the post tensioned floor has the lowest cost, being up to 4% lower than the normally reinforced in-situ floor. In all of the abovementioned cases, the rib-and-block floor as well as the hollowcore floor are more expensive than the in-situ floors. For different span lengths, rib-and-block floors are between 8% and 30% more expensive than the in-situ floor option with the lowest cost. Hollowcore floors are the most expensive option, being between 22% and 32% more expensive than the in-situ floor option with the lowest cost. The difference in cost of the in-situ options and the precast options decreases as the span lengths increase.

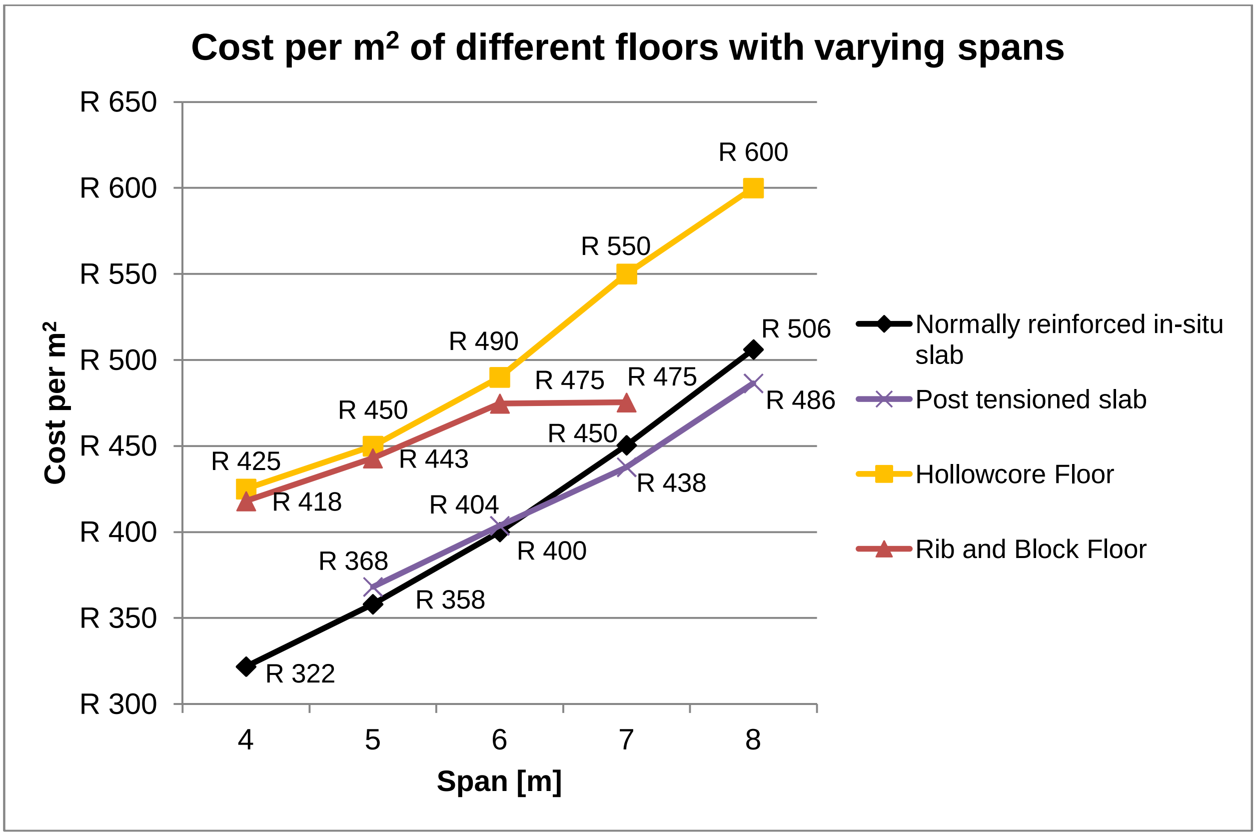

Figure 15: Material cost comparison

Rib-and-block floors have three block sizes (small, medium and large). For the 6m and 7m span options, large blocks are required, which leads to equal material quantities for the rib-and-block floor options of 6m and 7m span lengths.

From this example study, a difference in the cost of the different elements is recognized.

4.2.2 The overall cost of a project

The overall cost of a project includes not only the cost of the structural floor material, but also other items such as cladding and the rise of staircases. Quantities of these items are influenced by the floor-to-floor heights and are therefore dependent on the type of flooring element implemented. Furthermore the cost of a project is influenced by the construction time of the project. Savings in construction time can lead to significant savings in the cost of a project due to reduced project running cost (Burger, 2010).

A project cost comparison was performed in the UK to establish what the effect is of different floor systems on the overall cost of a project. The relevant principles and findings of this comparison are provided below. Thereafter the possibility of a similar comparison for South African projects is investigated. Furthermore the importance of such a comparison is discussed.

4.2.2.1 United Kingdom cost comparison

A cost comparison of projects with different floor structures has been performed by The Concrete Centre (2007) in conjunction with four consultants in the UK. The projects that were investigated are three-storey and six-storey commercial buildings. Systems in the UK cost comparison that are relevant for South African construction are the following:

- In-situ flat slab on in-situ columns
- In-situ frame with hollowcore floor panels
- Steel frame with hollowcore floor panels

The main costing components in the comparison are (The Concrete Centre, 2007):

- Substructures
- Frames and upper floors
- Cladding
- Internal planning
- Roof finishes and internal finishes
- Mechanical and electrical finishes
- Preliminaries
- Contingency and overheads and profit

According to the figures and results obtained by The Concrete Centre (2007), the flat slab proved to have the lowest cost in all of the abovementioned components. Therefore the flat slab option has the lowest overall project cost. However, the overall project cost of the in-situ frame with a hollowcore floor is only 1.01% more than the in-situ flat slab option. The steel frame with a hollowcore floor costs only 1.02% more than the in-situ flat slab option. This cost difference is sufficiently small to be considered of little importance.

4.2.2.2 South African cost comparison

A similar study to that of The Concrete Centre can be performed for South Africa. In order to do this, a scheme is provided (refer to Appendix E). This scheme is based on the UK study. The disciplines of specialists, required input, systems to be investigated and responsibilities for the implementation of this cost comparison are specified in the model scheme. With the assistance of the necessary specialists, this scheme can be used to determine the overall project cost of buildings with different floor systems in South Africa.

Apart from material cost variations between the UK and South Africa, the construction duration is also calculated differently. Construction activities might have longer durations in South Africa than in the UK. However, unlike in the UK (The Concrete Centre, 2007), projects in South Africa are often of a fast track nature. Construction on site usually takes place in parallel with design in the office – for instance the site establishment is performed while the foundations are still being designed. The same applies to precast elements which would be manufactured in parallel with other construction activities. Therefore the manufacturing time of the precast elements is not added to the total project duration.

Furthermore, precast elements are typically produced much faster in the smaller South African market than in the UK. As a comparison, a manufacturer in the UK indicated that they manufacture and install hollowcore floor elements within 3-8 weeks from the date of the order, depending on their workload (Bensalem, 2011). A South African manufacturer indicated that they manufacture and install hollowcore elements within 2 weeks from the date of the order (Surridge, 2011). However, due to the fact that the manufacturing time is normally not on the critical time path in South Africa, this does not make a difference to the overall project cost of South African projects.

By considering the above reasoning, time related cost components in South Africa will therefore be different to that of the UK. As part of a further study, the overall project cost of the different floor construction options can be compared by implementing the scheme provided in Appendix E.

4.2.2.3 The importance of the comparison of the overall project cost of different floors

As previously stated, the overall project cost difference due to different floor systems can be compared. However, the objectives of such a comparison must be considered. According to the cost comparison carried out in the UK, the overall cost of projects with different floor structures is similar. If the outcome of the scheme is therefore expected to indicate that the costs of structures with different floor systems in South Africa are similar, is it necessary to implement the scheme? It may or may not be a worthwhile investigation, depending on the desired outcome. Therefore the importance of the comparison of the overall project cost of different floor structures must be considered before the scheme is implemented.

4.2.3 The lifetime cost of a project

The lifetime cost of a project is determined by calculating the value of the project at a specific time. For instance, the present value of a project can be estimated. Each activity in the lifetime of the project contributes to the value of the project (Blank & Tarquin, 2008).

4.2.3.1 Calculating the lifetime cost of a project

A schematic presentation of the value contribution of each activity in the lifetime of the project as well as the present value of the project is given in Figure 16. In this case, the present value is determined at the start of the planning phase of the project.

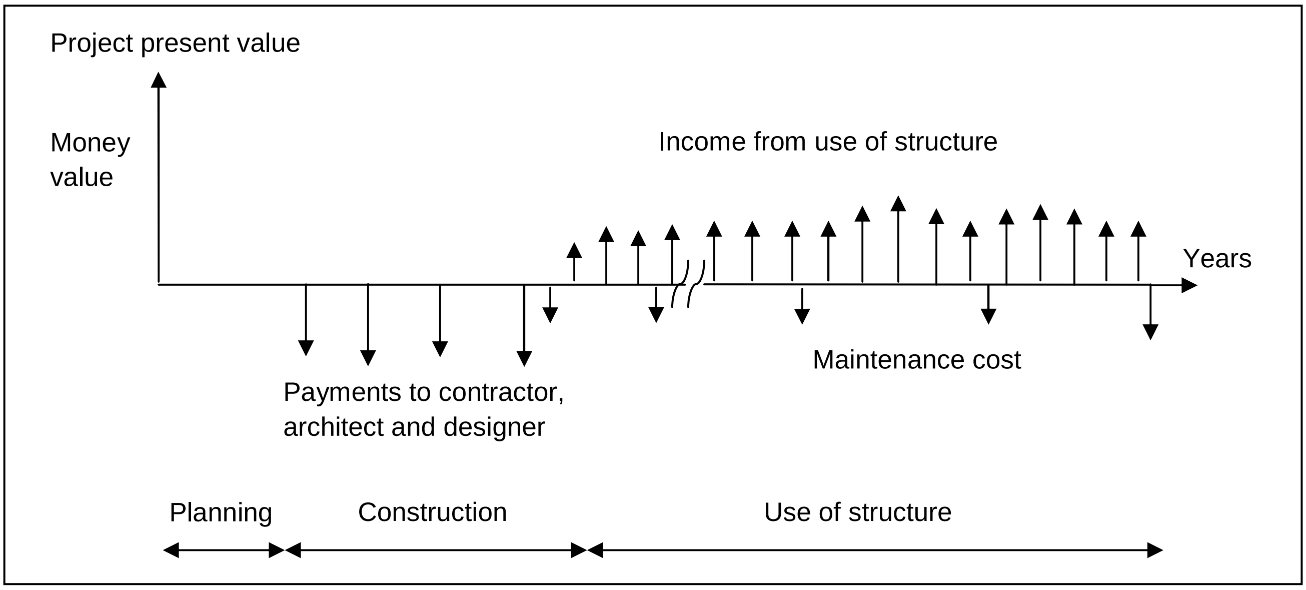

Figure 16: Schematic presentation of the present value of a project and contributing activities

The present value (P) as described above is determined according to the following equation (Blank & Tarquin, 2008):

$$P = F\left[\frac{1}{(1+i)^n}\right] \qquad \text{(Equation 1)}$$

Where:

- P is the present value for a stated future amount F
- i is the interest rate corresponding to the time; and
- n is the amount of weeks, months or years between the present time and the time of F.

Variables in Equation 1 are the time of the activities, the interest rate and the value of each activity such as the cost of maintenance. These variables are different for different construction methods.

An example comparison of lifetime costs of different constructional methods is carried out in the following subsection.

4.2.3.2 Example comparison of lifetime project cost for different construction methods

As an example, the lifetime cost of an in-situ project is compared to that of a HCC project by using fictional values. The essence of such a comparison is to investigate the time effect of money and to include the use phase of the structure in a cost calculation of the structure's value. In this section the effect of a shorter construction period on the project lifetime cost is investigated.

Instead of providing the present value of different projects, a tangible figure is provided for a client. The required monthly income is used as a basis for this comparison as this provides a potential client with tangible evidence of the impact of the construction time.

It is assumed that the initial cost and maintenance cost of the two buildings are equal. This assumption is based on the initial project cost comparison above and the purpose of the evaluation is to determine the effect of the construction period on the lifetime cost of a project. Furthermore it is assumed that the design cost and duration for the two projects are equal and therefore the present value is determined at the start of the construction phase. The construction duration is the only difference between the two projects in this example. The in-situ project has a construction duration of 24 months, whereas the HCC project has a construction duration of 22 months. Refer to Appendix F for parameter values (such as interest rate, maintenance cost, etc.) and the calculations for this example. The construction cost for this project is R80,000,000 and the monthly running cost is R1,000,000 (the running cost adds up to roughly 25% of the total construction cost, which may be unrealistically high).

It was found that for the in-situ project, a yearly income of R14,440,571 is required at the start of the use phase of the building, in order for the present value to breakeven. For the HCC project this required yearly income is R14,018,046. Therefore, at the start of the use phase, R422,525 less yearly income is required for the HCC project in order to have the same present value than the in-situ project. This is 3% of the total yearly income of the HCC project. It is therefore clear that a two month saving in the construction time leads to a decrease in the required income or an increase in the value of the project.

The sensitivity of the comparison is tested by using a lower (more realistic) project running cost of R350,000 per month. This adds up to more or less 10% of the construction project cost. Other values are the same as for the previous calculation.

Results are as follows: for the in-situ project, a yearly income of R12,278,165 is required at the start of the use phase in order to breakeven. This income required for the HCC project is only R12,056,208. For the HCC project, yearly income of R221,957 less than the in-situ project is required for breakeven of the present project value. This is a difference of 2% in the yearly income at the start of the use phase.

Therefore, if the project running cost in this example is 10% of the total project cost, instead of 25% of the total construction cost, the required yearly income of the HCC project is 2% (instead of 3%) lower than that of the in-situ project for break even.

By adjusting different parameters of this comparison in a further study, the sensitivity of the comparison to each parameter can be determined.

4.2.3.3 Factors influencing the lifetime cost of projects implementing in-situ or Hybrid Concrete Construction

Apart from the interest rate, the duration and value of activities in the lifetime of the project also influences the lifetime cost of the project. It is for instance less time consuming for a designer to specify precast elements than to detail an in-situ slab. On the other hand, co-ordination between the architect, designer and manufacturer for precast layouts and special services would require extra planning time. Therefore precasting might have a longer planning period than in-situ elements, whereas the in-situ construction duration is generally longer. Also, the initial cost and long term cost for the different construction methods varies. Therefore a difference in the construction method of a project leads to a difference in the lifetime value of the project.

The likeliness of a project team taking the lifetime cost of a project into account, depends on the economical situation. In depreciating economical times, the importance of the lifetime cost of a project is often ignored and clients are inclined to make decisions based on initial cost (Gibb, 2011). It is however in the interest of the client to compare the project lifetime values when implementing different construction methods.

4.3 Concluding summary

4.3.1 Background of costing methods and cost of a floor

Costing methods of in-situ and precast elements are different. Estimating cost of an in-situ project is carried out according to a fixed method and rates are determined nationally. Estimating the cost of precast elements can be considered as an art. The price of precast elements is dependent on the manufacturer and the geographical location of the project. Therefore a cost comparison between precast and in-situ elements is dependent on the time and place of the investigation.

Precast and in-situ floor systems are considered in this study and theoretically the cost of floors comprise of around 0.6 – 0.8% of the construction cost of a building. Therefore the value of a project does not lie in the initial cost of the floor system. Comparisons are nonetheless carried out.

4.3.2 Element cost

The cost of different floor elements is determined for a 500m^2 one-way span floor within 35km from the precast yard. A live load of 2.5kPa is assumed.

It is found that precast floor options are more expensive than in-situ floors. At short span lengths (up to 6m), the normally reinforced in-situ floor has the lowest cost and at longer span lengths (7m and 8m), the post tensioned floor has the lowest cost. Depending on the span length, the rib-and-block floors in this example are between 8% and 30% more expensive than the in-situ option with the lowest cost. Hollowcore floors are the most expensive, being between 22% and 32% more expensive than the in-situ floor with the lowest cost. Note that prices are subject to change. Prices obtained are time, manufacturer and location specific.

4.3.3 Overall project cost

According to a study carried out in the UK, the difference in the overall cost of a project that consists of a structure with an in-situ flat slab was only 1.01% less than the in-situ concrete frame structure with a hollowcore floor. The steel frame with hollowcore floor panels was only 1.02% more expensive than the in-situ concrete structure with a flat slab. A similar study can be carried out with the assistance of specialists in South Africa to determine the difference in the total project cost with different construction options. Such a scheme is provided in Appendix E. However, in the light of the UK findings, the importance and aim of such a comparison should be considered.

4.3.4 The lifetime cost of a project

The lifetime cost of a structure includes the design phase, the construction phase and the operating phase. The value of a project can be determined by considering the present value of all the activities in the lifetime of the project. Values of projects incorporating different construction methods can be determined accordingly.

An example comparison is carried out to determine the required yearly income of an in-situ project and a HCC project for breakeven of the present project value. Fictional values are used for the cost, interest rate and project durations. The only difference between the two options is the construction duration. The HCC project’s construction duration is 2 months shorter than that of the 24 month in-situ construction project. Maintenance costs in the use phase of the structure are the same for the two projects in this example. The construction cost for this project is R80,000,000 and the monthly running cost is R1,000,000 (the running cost adds up to roughly 25% of the total construction cost, which may be unrealistically high).

For the in-situ project, the yearly income at the start of the use phase required for breakeven, is R14,440,571 and for the HCC project, it is R14,018,046. In order for the two projects to have the same present value, R422,525 less yearly income is required for the HCC project than for the in-situ project. This is 3% of the yearly income required by the in-situ project. Therefore the difference in the construction duration has an effect on the lifetime value of the project.

When adjusting the monthly running cost of the construction project to R350,000 (which adds up to roughly 10% of the total project cost), the yearly income required by the HCC project, is only 2% less than that of the in-situ project for breakeven of the present value

4.3.5 Conclusion

Based on findings from specific comparisons in this chapter, the costs of the different construction methods compare as follows:

- Rib-and-block elements and hollowcore elements are more expensive than equivalent in-situ floor elements;
- Overall project costs of in-situ and HCC projects are more or less equal;
- The lifetime costs of HCC projects are less than that of in-situ projects.

These conclusions are based on specific layouts, design parameters and quotations. Project teams should critically compute costs of different construction options before these conclusions are accepted to be true.

4.3.6 The relative importance of cost

Even though cost is generally the first consideration that comes to mind when assessing different options for a project, it should not be the only criteria. Quality should also play a role in the decision making process and in addition sustainability must be achieved. Therefore social and environmental aspects must also be considered in the decision making model. This is addressed in the subsequent chapters.

Chapter 5

QUALITY

Where precast elements are considered for a project, it is important that the aspect of quality be addressed. The reason for this is that the potential cost and time savings can diminish if too little attention is paid to the quality aspect of the products. Quality is thus a very important matter.

Cornick (1991) defines quality as the "conformance to or meeting requirements". Gransberg and Molenaar (2004) took the definition a little further by identifying two different facets that contribute to a product's quality, when value or cost is ignored. They are:

- "User-based: fitness for intended use; and
- manufacturing-based: conformance to specifications"

These two aspects represent short and long term quality. Whilst manufacturing is a short term aspect, the usage phase of a structure represents the long term aspect of a structure.

Quality cannot be seen in the absence of durability. Durability and its relation to quality is described by Rwelamila & Wiseman (1995). If a structure is durable, it performs its intended function over its design life. Therefore, long term quality of a structure includes durability.

When considering element quality, precast elements are said to have a higher quality than in-situ cast elements, because it is manufactured in a more controlled environment (BPCF, 2003; Goodchild & Glass, 2004; NPCAA, 2011). Although BPCF and NPCAA are precast associations that are possibly promoting their products, Soetanto *et al.* (2004) investigated criteria to assess HCC and found that precast elements have higher quality than in-situ elements. This sounds reasonable, because better quality control can be applied in controlled environments such as precast factories, than on sites. If managed correctly, cover dimensions and concrete mixes are controlled better on precast yards than on site. However, in HCC not only the precast products, but also the in-situ construction contributes to the overall buildability of a structure. Therefore it is important that all the elements meet the requirements throughout a project.

Measuring quality can be difficult. For instance, aesthetical quality depends on personal opinions that are quite hard to measure objectively. Other aspects such as product and structural quality are typically not evaluated in practice, but rather systems are implemented by different countries to achieve and maintain a certain level of quality. For instance, national standards set certain quality requirements. However, instead of measuring the conformances of the elements, the non-conformances are measured.

Before quality measurement is examined, background is given on the quality in South Africa, the standards used and the compliance to the standards is investigated. Although this background does not relate to quantification of quality for decision making, valuable conclusions are acquired from this exploration, which may be useful when considering HCC. Furthermore, overall structural quality, when using precast floor elements, is also discussed in this chapter. Aesthetical quality is however considered as a social aspect and therefore it is discussed in Chapter 6. Lastly a method to measure quality in terms of time and money is identified.

5.1 Quality of construction in South Africa

In South Africa, some engineers have the opinion that the level of quality of construction is the reason why precasting is not the preferred method of construction (Anonymous Consultants, 2010). An investigation is reported on later in this chapter to establish the level of quality of South African construction. An investigation into the South African construction quality in this chapter provides a better understanding of the abovementioned statement.

The purpose of precast construction is to enhance buildability (precast floor panels are designed to make construction easier and faster). However, when the quality of construction elements is not up to standard, it causes unnecessary rework in HCC.

The lack of quality of construction is not necessarily that of the precast elements, but also that of the in-situ cast elements. For instance, precast seating that are perfectly manufactured to fit onto in-situ cambered beams, will not fit if the surface finish of the in-situ cambered beams are not within allowable limits and consequently rework would be required. See the illustration in Figure 17.

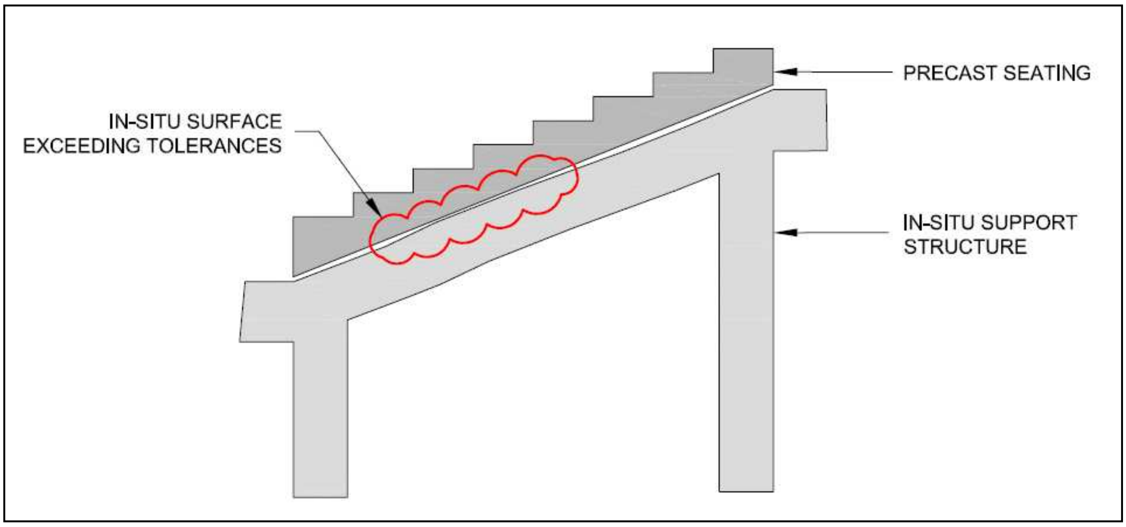

Figure 17: Precast seating fitting on in-situ support structure

Therefore the scenario exists of overall quality not meeting the required standard (specifications are discussed in the next sub-section) and the application of precast elements are considered problematic in terms of quality, even though the precast elements are not necessarily of a low quality.

Consequently, precast elements are often not specified by engineers, because the construction quality in South Africa is not suitable to make it practically feasible and on the other hand the quality does not improve, because the precast market is not big enough. The only way to break this trend is to improve the quality of in-situ construction and to produce structural products (both precast and in-situ) that comply with the standards and can be trusted by clients (Bensalem, 2011).

Possible roots of the construction quality issue in South Africa are as follows:

- Inadequate specification of element quality in the South African Standard
- Negligence of designers to specify details regarding quality on construction drawings
- Inadequate quality control or quality management of construction work

These possibilities are investigated in the following subsections.

5.2 Standards

The South African Standard SANS 2001-CC1:2007 provides the necessary specifications for structural concrete in the South African construction industry. Different aspects such as the quality of the concrete, aggregate grading and reinforcement requirements are specified in this Standard.

The specifications of the South African Standard and how it compares to the Eurocode, are investigated. Possible areas of quality issues of elements are the following:

- Material of the element
- Element tolerances

5.2.1 Specification of the South African Standard

As shown in Figure 17 one of the more problematic areas that is currently identified, is the "lack of fit" and surface finish of the elements, therefore the regulations regarding formwork and tolerances are considered in this section. The material of the elements manufactured is not generally a problem in precast construction. In SANS 2001-CC1:2007 three different degrees of accuracy are identified for tolerances as shown in Table 3.

Table 3: Degrees of accuracy for concrete construction (SANS 2001-CC1:2007)

Degree	Description
I	Where special materials or systems are used, for example prefabricated elements
II	Normally applies where accuracy grade is not specified
III	Where high accuracy is not important, for example mass foundations

SANS 2001-CC1:2007 states that for HCC the applicable tolerances shall be compatible for the precast elements to fit onto or in-between the in-situ concrete elements. In other words when precast elements are applied, in-situ and precast components must comply with the degree of accuracy I specified in the South African Standard. Allowable tolerances are supplied in Appendix G. These allowable limits are compared to that of the Eurocode in the following subsection.

5.2.2 Comparing the South African Standard to the Eurocode

The level of tolerance specifications of SANS 2001-CC1:2007 is measured to that of the European Standard; more specifically ENV 13670-1:2000. The European Standard identifies two tolerance classes that are given in Table 4 (ENV 13670-1:2000).

Table 4: Tolerance classes for concrete (ENV 13670-1:2000)

Class	Description
I	Normally applies unless stated otherwise
II	For national standards*

*In the Eurocode some values are not stipulated, but are left to the different countries to specify. It would typically be the values that are influenced by safety, which is a national concern and differs from country to country (EN 1992-1:2004).

The normal tolerance class of concrete construction in Europe is Class I, whereas degree of accuracy II normally applies in South African concrete construction.

It has been found in Appendix G that the level of the South African Standard for degree of accuracy II is comparable or even more conservative than tolerance class I of the European Standard. Therefore there is no problem with the level of the South African Standard. There might rather be a problem with the compliance to the given standard, which is investigated next.

5.3 Compliance to the South African Standard

Compliance to the South African Standard is the responsibility of both the designer and the contractor. According to international literature the most important source of quality failures in construction is design related (Love & Li, 1999). This is verified by Fayek et al. (2003) that found in a case study that 62% of rework had to be performed due to engineering and review errors.

The designer is responsible to specify a degree of accuracy for a specific project. In cases where precast elements are used in a construction project, attention should be drawn to the fact that precast construction requires a tolerance degree of accuracy I (SANS 2001-CC1:2007). Designers are responsible to specify this on construction drawings.

It is furthermore the responsibility of the contractor to ensure that the structure is built according to the required level of accuracy. The compliance (or non-compliance) with the Standard, i.e. SANS 2001-CC1:2007 of both of the abovementioned parties are investigated in the following subsections.

5.3.1 Specifications on drawings

In traditional in-situ construction, dimensional tolerance is not such a big problem to ensure buildability. Tolerance errors at in-situ element connections are handled relatively easy on site by adjusting the formwork. However, with the use of precast elements it is crucial to specify that degree of accuracy I is applicable in order to assure that precast elements fit onto or in-between in-situ elements.

In a small questionnaire survey carried out in South Africa (refer to Appendix C) it was established that, according to opinions of the respondents, the standard of quality is mostly indicated on engineering drawings. Therefore specifications on drawings are not considered problematic. How the construction industry complies with these specifications is discussed below.

5.3.2 Field studies of compliance to the South African Standard

A field study was performed by Smith (2010) to determine variations in concrete strength, geometry and cover to reinforcement in slabs and beams constructed in South Africa. This investigation was on construction sites of in-situ buildings in and around the Stellenbosch area. Different contractors were involved, therefore it is assumed for the purpose of this study that results obtained are representative of construction in South Africa.

In all of these projects, degree of accuracy class II as described by SANS 2001-CC1:2007 was applicable (refer to Appendix G for specifications). I.e. the cross-sectional dimensions (thickness of slab, width of beams and height of beams) may have values of between -5mm and +15mm of the dimensions given on the design drawings.

Dimensions were taken of five different slabs and five different beams. Although all the mean values are larger than the designed dimensions (i.e. on the safe side), there are still a considerable amount of non-compliances. 44% of the slab measurements and 23% of the beam measurements do not comply with SANS 2011-CC1:2007. This gives an indication of the compliance to the standards in the South African construction industry.

Another study was performed by Ronné (2006) to investigate the variation in cover to reinforcement of concrete structures in South Africa. It was found that 30% of the South African cover data does not meet the criterion.

Having 44% of slab measurements and 23% of beam measurements (according to Smith's data) and 30% of cover data not complying with South African Standards (according to Ronné), it is clear that non-compliance is a problem in the South African construction industry. This becomes a relevant issue when HCC is applied.

5.4 Structural quality

Structural integrity is a concern that has to be investigated for any new structural element or system (Rodriguez *et al*., 2007). Precast elements are not new in the industry anymore, but concerns have been raised regarding the structural integrity of precast concrete as a result of some failures during testing, specifically in the field of seismic design (New Zealand Department of Building and Housing, 2011).

Structural quality depends firstly on the quality of the elements and secondly on the quality of the connections of the elements. Since the quality of precast elements are generally good (BPCF, 2003; NPCAA, 2011), the area of concern in HCC is the connections of the elements.

In the short term (construction phase) the following connection problems might be encountered:

- Lack of fit due to incorrect overall dimensions of precast or in-situ elements.
- Lack of fit due to surface finish of in-situ elements that does not comply to standard.

In the long term (use phase) the following are potential connection problems (NPCAA, 2011):

- Failure of parts of the structure. This can be due to insufficient bearing capacity.
- Insufficient bonding between elements which prevents structural continuity.

When using precast elements in a structure the designer must be aware of its possible failure mechanisms and design the elements accordingly in order to ensure structural quality.

5.5 Measuring quality

Quality has to be quantified in order to be incorporated in the process of decision making. According to Cornick's definition of quality previously described, measurement of the quality of concrete products would imply measuring its compliance with requirements. Reversing this statement, quality of concrete products in this case can be measured by its non-compliance with requirements. While long term non-conformance of concrete results in maintenance or total structural failure, short term non-conformance results in rework.

In this section, the aim is to provide a framework for the development of a model to measure quality of in-situ- and precast concrete structures in the future. Firstly, for the short term quality measurement, rework has to be defined. A case study of rework that was performed for a project by Fayek *et al*. (2003) is summarized and thereafter a possible rework factor for South Africa is investigated. Finally a method for short-term quality measurement is proposed. Since the principle issue identified regarding quality is the buildability or short-term quality, the measurement of maintenance is not considered. However, long term quality should also be measured in the future. This may entail measuring the amount of maintenance required (for instance due to cracks) as well as recording the amount of total structural failures.

5.5.1 Definition of rework

A study was carried out at the University of Alberta to measure and classify construction rework wherein rework was defined as: "activities that have to be carried out more than once or activities which remove work previously installed, where no change order has been issued and no change of scope has been identified by the owner" (Fayek *et.al*, 2003). Rework in this sense is used purely to measure the quality of the elements on site.

In order to measure the rework as defined, Fayek *et al.* (2003) proposed a Construction Field Rework Index (CFRI). The CFRI is basically an indication of the cost of rework, relative to the total cost of a project or a field thereof. An equation is used to describe the index:

$$\text{" CFRI} = \frac{\text{Total cost of rework performed in the field}}{\text{Total field construction phase cost}}\text{ "} \qquad \text{(Equation 2)}$$

5.5.2 Case study

In the case study by Fayek *et al*. (2003), a mining expansion in Alberta (Canada) was investigated and the rework was monitored. It was found that the total rework index over an eight month period was 0.87%. Primary causes of the rework were also tracked and the result was that 62% of rework had to be carried out due to engineering and review errors. Although this rework index of 0.87% is not cumbersome, it is clear that engineering designs should receive more attention. Note that this study was performed on a mining expansion that has different characteristics than normal buildings studied in this thesis.

5.5.3 Rework in South Africa

The factor of South African rework was estimated by participants of a limited and targeted questionnaire survey. A questionnaire was sent to eighteen professional consultants and contractors. Six consultants and four contractors responded to the questionnaire. Results of the survey are given in Appendix C.

Participants were asked to give approximations of the amount of time and money (as a percentage of the total time and money) that is spent on rework due to quality issues (i.e. not due to changes) in any typical project. This includes rework in in-situ construction and HCC projects. Conclusions from the survey in Appendix C are the following:

- 15 – 20% of time is spent on rework
- 5 – 20% of money is spent on rework

It should be kept in mind that these figures are estimations and for accurate answers and causes of this rework, projects will have to be monitored. However, these figures are much higher than the relatively low index of 0.87% obtained from the case study by Fayek *et al*. (2003). Although Fayek measured the CFRI of a mining expansion, whilst respondents to the questionnaire was asked what the rework percentage is in general, the difference in results are larger than expected.

The high percentages of rework that was estimated by respondents to the survey may very well be explained by the results obtained from the case studies carried out by Smith (2010) and Ronné (2006). As mentioned earlier, it was found in both these case studies that a significant amount of elements constructed in South Africa do not comply quality requirements in the relevant standard. Therefore there is a potential general lack of quality in the South African construction industry.

5.5.4 Proposed method of short-term quality measurement for more accurate indices

Short-term quality can be quantified by measuring rework. The construction field rework index proposed by Fayek *et al*. (2003) as defined in Equation 2 can be used in HCC and precast construction projects. A CFRI can also be obtained for in-situ construction projects through monitoring.

On HCC projects, it would be difficult to divide the rework carried out on an HCC project into the rework required due to insufficient quality of in-situ and precast products respectively, therefore an overall factor for HCC projects can be obtained. The assessment of these two factors would reflect the comparison of the quality of the two different construction methods.

This would not only be important for the comparison of in-situ and precast concrete quality, but it would also be valuable for the construction industry in general to identify major reasons for rework so that these issues can be improved.

5.6 Concluding summary

5.6.1 Background of quality

Quality is the conformance to requirements. Quality can be measured by non-conformances. Short-term quality can be measured through the amount of rework that is necessary. Long-term quality (or user-based quality) can be measured through the amount of maintenance necessary over the life of a structure, as well as the amount of structural failures.

The quality of HCC projects depends on the quality of the precast as well as the in-situ elements and their connections. It has been found that the short term quality issues regarding HCC might be due to a lack of quality of in-situ construction in South Africa. The measurement of long term quality issues have to be addressed in future studies.

5.6.2 Construction quality in South Africa

The dimensional tolerances of concrete elements SANS 2011-CC1:2007 compares to that of the ENV 13670-1:2000. Compliance to the standard, however, is cumbersome.

Approximately 30% of a typical project in South Africa does not comply to SANS 2001-CC1:2007. Rework in South African construction projects is estimated by a small survey to cost between 5% and 20% of the total project cost.

5.6.3 Recommendation

In this chapter, it is proposed that more accurate indicators for South African construction quality should be obtained by monitoring rework in projects. HCC and in-situ construction projects can be monitored respectively and indicators can be compared to find the best method in terms of quality.

By identifying the reasons for rework and addressing those issues the short-term quality of construction projects in general may be improved. Furthermore, maintenance and structural failures should also be measured in order to quantify long term quality of both in-situ and HCC South Africa.

5.6.4 Next chapter

Social aspects are independent from quality and are therefore treated separately in the following chapter.

Chapter 6

SOCIAL ASPECTS

Construction activities generally have an influence on three different groups of a society. It influences the following groups of people (Wells, 2003):

- The labourers that are taking part in the activity
- The local public around the activity
- A broader global society

Wells (2003) indicates that construction activities have a relatively small impact on the global society and the greatest impact is that on the workforce of the activity itself. Therefore labour is the greatest social concern in construction activities.

Background on local issues regarding labour is given below. The impact of the different construction methods (in-situ and precast construction) on the labourers and on the neighbouring communities are also discussed in this chapter.

6.1 Labour

Labour is the greatest social concern in construction activities (Wells, 2003). Furthermore, it is a special concern in South Africa, having a high unemployment rate and low skilled labour. The status of South African labour, labour in the different construction methods, the impact of the construction methods on the labourers and measurement of the number of labourers in the different construction methods are discussed in the following paragraphs.

6.1.1 South African labour

One of the social considerations that may in some instances be a key driver of the decision making process between the different construction methods available, is labour. Unlike most other countries that successfully implement precast construction, the cost of South African labour is relatively low.

Also, apart from having relatively affordable labour available, job creation is an issue in third world environments such as South Africa. These circumstances need to be taken into account in whatever construction method is used. Whilst first world countries are moving towards automation in most production processes, third world countries have to be innovative in job creation.

The very first strategic objective of the Department of Labour according to the Minister of Labour of South Africa is to "contribute to employment creation" (Ramutloa, 2011). Therefore South African industries frequently strive to implement production methods that are labour intensive, especially in public projects. This is mainly due to the fact that although the unemployment rate of South Africa has decreased from 31.2% to 23.8% in 6 years, this rate is still well above the world's average unemployment rate of around 6% (World Bank, 2011).

Furthermore, South African labour has a relatively low productivity rate. The labour productivity rate is measured as "the rate of output per worker per unit of time as compared with an established standard or expected rate of output" (Business Dictionary, 2011). It is computed as the "gross domestic product" per employed person. The World Bank (2011) provides the yearly labour productivity rates of different countries on their website.

According to The World Bank statistics (2011), South Africa had a productivity rate of 12,000 in 2008 (this is the latest figure available). This is low compared to productivity rates of countries implementing precast construction frequently, such as Sweden with a productivity rate of 50,000, Switzerland with 43,000, Denmark with 46,000 and the Netherlands with 47,000 (see Appendix H for productivity rates of different countries).

Having this low productivity rate, relatively low labour cost and a high unemployment rate, the use of precast construction in South Africa can be questioned. Productivity rates of different countries are plotted against their percentages of precast usage in Figure 18. Different confidence levels are indicated by different indicators (such as ■, ♦ and ●).

Note that the percentages of precast usage were obtained from a small survey provided in Appendix B and therefore the values may not be accurate, but it nonetheless gives an indication of the applicable range. As indicated in Appendix B, ranges of precast usage and the confidence levels of the respondents are obtained through the survey. For instance the respondent from Sweden indicated with an 80-100% surety that 45-55% of concrete in structures are constructed using precast elements. Therefore the average percentage of precast usage is assumed to be 50% for Sweden and the average percentage of confidence level of the respondent from Sweden is 90%.

Through the graph in Figure 18, it is attempted to find a relation between productivity rates and precast usages of different countries, seeing that information was gathered of the latter.

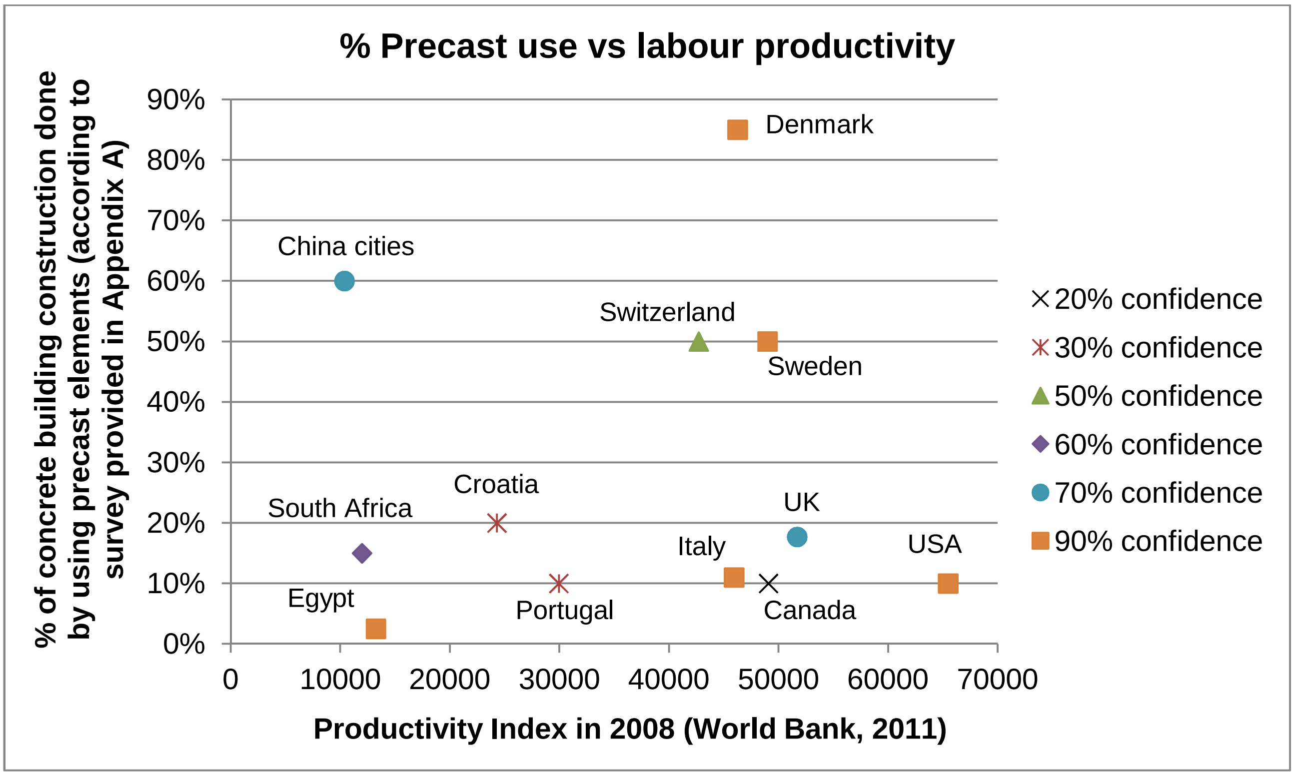

Figure 18: Percentage of precast use vs. labour productivity indices of different countries

Since some values in this graph are based on personal opinions, no accurate conclusions or correlations can be drawn. The qualitative, rather than quantitative information however provides some information regarding the trends.

It is clear from Figure 18 that South Africa has a much lower productivity rate than countries that have higher precast construction activity. Apart from cities in China, the countries with higher percentages of precast usage also have higher labour productivity indices. However, some countries with high labour productivity rates do not have high percentages of precast usage. Therefore, should the labour productivity rate of South Africa improve, it would not necessarily imply that the percentage of precast usage would increase.

For a more accurate study, scientific information must be obtained. This can be achieved by contacting national precast concrete institutes. Also, other labour-related factors should be measured (such as the average cost of labour, or expertise levels of labourers) against precast usage. This information was not available at the time of this thesis.

6.1.2 Labour in precast construction

The matter of maximizing labour needs comprehensive evaluation. Precast manufacturing can be an automated process that utilizes machinery and is not very labour intensive. This is typically the case in European countries that have relatively expensive labour. However, it can also be a process that makes use of machinery, but still requires a reasonable amount of man hours, depending on the needs of the industry. Manufacturers in South Africa modify the processes to suit the needs of the industry (Angelucci, 2011; Surridge, 2011).

Influences of different construction methods on labourers, are discussed in the subsequent sections.

6.1.3 Influences on labourers

"A socially responsible construction industry is one that enhances the positive aspects of employment while protecting the workforce from negative ones" (Wells, 2003). Influences on labourers in the construction industry are:

- Safety
- People development and career path
- Job security

The influences of the different construction methods on these labour related aspects are discussed. A proposed method to measure labour activities for the different construction methods is also given.

6.1.3.1 Safety

Construction sites are a hazardous working environment (Wells, 2003). Differences in safety for in-situ and precast construction processes are investigated.

Generally, controlled environments such as precast manufacturing facilities are safer, given that it is correctly managed. This would imply that having labourers on a precast yard rather than on site, improves the level of safety of the construction process (Bargstädt, 2011; Blismas *et al.*, 2006; Goodchild & Glass, 2004).

On-site operations of precast construction are argued to be safer than that of in-situ construction. It is human to have great respect for bulk precast elements on site. Therefore more attention is paid to the dangers of big precast elements being placed than pieces of wire lying around on the ground (Bargstädt, 2011). Refer to Figures 19 and 20.

Figure 19: Placement of precast beam at VWSA paint shop in Uitenhage (Jurgens, 2008)

Figure 20: Rebar off-cuts on in-situ construction site (Crawford, 2003)

Also, reducing the amount of labourers that has to work at heights, would improve safety. Manufacturing precast elements on the ground is safer than constructing in-situ elements at heights. This is provided that the labourers are properly trained and has the skill to handle precast elements.

Preceding statements are observations that are not quantified nor conclusive. However, aspects that have to be taken into account when considering safety, are identified. A more in depth study is required to establish the level of safety for each construction method. Levels of safety for in-situ and precast construction processes can be quantified by monitoring the frequency and severity of accidents in both construction methods.

6.1.3.2 People development and career path

The precast manufacturing industry offers people development. Rather than working on construction sites, labourers in precast manufacturing processes work in factories. This provides a safer, more constant environment for the workers and it improves social upliftment. More complex skills are required for precast manufacturing than in-situ construction and therefore labourers in the precast industry receives better training (Angelucci, 2011).

6.1.3.3 Job security

Having job security is important for any person. The construction industry and in particular the structural construction industry varies with the economy. Therefore it is an industry where labourers, especially low skilled labourers do not have much job security.

However, working in plants and manufacturing environments offers better job security and therefore job security is assumed to be improved when precast construction methods are used (subject to further justification). This is possible provided that the precast manufacturing plant is still in production and producing reasonable amounts of precast products.

In times of low construction activity the precast manufacturers are also likely to manufacture less elements. Labourers in precast manufacturing plants can then also be dismissed, but it needs to be investigated whether they will not perhaps have a better chance of getting another job since they are higher skilled than in-situ construction labourers of the same level.

Furthermore precast manufacturing requires less mobility of labourers. Chances are greater that they will be working in the same location for a longer time than when they are involved in in-situ construction.

It would be a difficult to measure job security of in-situ and precast construction labourers. However, it is assumed, based on the above reasoning, that precast construction offers better job security.

6.1.4 Measuring labour activity

In the decision making process for a choice between in-situ and precast concrete construction, influences on labour can be compared for the different construction methods. Job security are not quite measureable, but aspects such as safety can be compared by monitoring accidents for the different construction methods. For precast elements, the manufacturing, transport and erection stages must be included in the activities to be monitored. The following labour activities can be measured:

- Number of labourers in or man hours required for each construction process.
- The level of safety of each construction process, by means of the frequency and severity of incidents.
- The level of people development, by means of training levels.

6.2 Neighbouring communities

Buildings are built for people. Therefore it should fulfill the needs of the people. For a community, the best building would be the one that is built in the most effective way (with the least disturbances) and which provides the most benefits in the long run. This implies having an aesthetical appealing building that forms part of its environment and offers a pleasant place for the community.

Each construction project and building has an influence on the community. Influences of construction activities on neigbouring communities are noise pollution, dust and disturbance. These are classified as short-term influences. A long term influence of a structure on the neighbouring community is its aesthetical quality. Both the short term and long term influences are discussed below.

6.2.1 Short-term influences

Precast construction causes less noise pollution and produces less dust than in-situ construction (British Precast Concrete Federation Ltd, 2003). Therefore, disturbance to neighbouring communities is less when precast elements are used.

In order to quantify and compare disturbances to the neighbouring communities of projects, noise levels and dust levels will have to be measured on neighbouring sites of in-situ and HCC projects.

6.2.2 Long-term influence: aesthetics

The appearance of a building is the first and most prevailing impression that one has of a structure. It even represents the company, business or people that work or stay in the building. Concrete is not only a functional material in terms of structural applications. It is nowadays also recognized for its aesthetical properties. With numerous shapes, surface finishes and colours, concrete offers architects more freedom to shape aesthetically appealing architectural structures (Freedman, 2001).

With buildings having more than structural functionality, designs are increasingly based on the building's aesthetical appearance. The seven elements of aesthetical design are as follows (Architecture Student Cronicles, 2011):

- Texture
- Colour
- Tone
- Direction
- Proportion
- Solid and void
- Form and shape

These elements are easily obtainable through concrete as a building material. Precast concrete elements can offer incredible architecture. The first architectural precast concrete was used in 1923 by Auguste Perret (PCI, 1989). The great aesthetical advantage of precast concrete construction above in-situ construction is that it can be molded, shaped, customized and cut to very precise elements (BPCF, 2003). Therefore, in terms of aesthetics, precast concrete elements have the potential of more enhanced aesthetical appearances than in-situ concrete elements.

It should however be kept in mind that specially shaped elements are expensive and it may be more cost-effective to construct these than to use in-situ elements. The real advantage of precast elements comes into fruition when repetition is needed extensively.

6.3 Concluding summary

6.3.1 The social influence of construction

The social aspect of an activity is one of the three main facets of sustainability. Socially, construction activities influence the workforce, neighbouring communities and the broader global society.

The greatest social influence of a construction project is that on the workers themselves. Therefore labour is an important matter to consider in the decision making process of a construction method.

6.3.2 Labour in South Africa

South Africa has relatively low labour cost and all the activities in the country, especially governmental projects, are under pressure to improve the employment rate, i.e. to reduce the unemployment rate.

The South African productivity rate is relatively low and the usage of precast in buildings is also low. However, it is found that there are instances where countries have relatively high productivity rates, but their precast usage is also relatively low. Therefore an increase in productivity would not necessarily lead to increased precast usage.

6.3.3 The influence of construction activities on labourers

Manufacturing processes can be modified to suit local needs. Precast construction in Europe is not labour intensive. However, in South Africa the manufacturing process is labour intensive as far as possible. It does not suggest that precast construction uses the same amount of labourers as in-situ construction. In future studies, the amount of man hours can be measured and compared to quantify the use of labourers for the different construction methods.

Furthermore, the process of precast construction offers better job security, people development and higher levels of safety than the in-situ construction process.

6.3.4 The influence of construction activities on neighbouring communities

Neighbouring communities are more disturbed by in-situ construction activities than precast construction activities. In future studies, noise levels and dust levels can be measured and compared to quantify the disturbances of the different construction methods on neighbouring sites.

A building's quality is not only evaluated by its structural soundness, but also by its aesthetical appearance. According to literature, precast concrete offers more flexibility for the architect and therefore it has the potential to offer greater aesthetical appearance than in-situ concrete elements.

6.3.5 Recommendations

As a further investigation, the following measurements can be taken for each construction process in order to quantify the abovementioned aspects:

- For the influence of construction on labourers:
  - The amount of workers required by measuring the man hours
  - The level of safety by monitoring the frequency and severity of incidents
  - The level of people development by measuring training levels
- For the influence of construction on the neighbouring community:
  - Noise levels
  - Dust levels

In the future the abovementioned measurements will be able to assist project teams in the decision making between the different construction methods.

Furthermore, for a better understanding of the possible correlation between labor factors and precast usage, other international labour factors must be obtained (such as labour cost or level of expertise). These factors may then be plotted against precast usage in order to establish whether a correlation exists.

6.3.6 Next chapter

Considering the close relationship between social aspects and the environmental impact, the environmental impact is discussed in the following chapter.

Chapter 7

ENVIRONMENTAL IMPACT

With increasing international awareness of the environmental impact of all human activities, the significance of the construction industry's impact on the environment is of great importance. It is our human responsibility to conserve our natural resources and habitat for the present and future generations.

Having one of the largest environmental impacts, there is great focus on the construction industry to improve its construction methods. In order to minimize the environmental impact of activities, several tools or so-called "environmental indicators" have been developed to measure environmental impacts.

One of the most used indicators in the past is the measurement of the carbon footprint of activities, which have been implemented by many companies. These days, however, many different indicators or tools exist for the determination of environmental impacts of buildings (Brewis, 2011).

The Green Building Council of South Africa (2011) is the main role-player in the development of environmental indicators for South Africa. In addition there are multiple companies that develop their own environmental impact measurement tools (Brewis, 2011).

Precast concrete elements are said to improve environmental friendliness when it is compared to in-situ concrete (BPCF, 2008; NPCAA, 2011). However, as for many other aspects there is little or no quantitative information available on how the environmental impacts of in-situ and precast concrete construction actually compares. Therefore possible quantification methods are explored in this chapter in order to determine how the environmental friendliness of precast elements compares to that of in-situ elements.

This study will only include the carbon footprint measurement that is to date the most widely used environmental impact measurement tool. Apart from the carbon emissions, a study is carried out on the comparison of the raw material input required for each of the construction methods and furthermore waste generation is discussed.

7.1 Carbon emissions comparison

Greenhouse gases contribute to global warming. The most common types of greenhouse gases from human activities are carbon dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O) and halocarobons. Of these, CO_2 has produced the most radiation between 1750 and 2005 (IPCC, 2007). Therefore, the comparison of carbon emissions of in-situ and precast concrete construction is justified.

Brewis (2009) proposed a model to optimize the design layout of a building to have the smallest possible carbon footprint. In Brewis' a case study an 84x84m first floor area of a typical office block, that is constructed 25km from a precast yard, was investigated. Carbon emissions were calculated of the construction phase of a normally reinforced slab and hollowcore precast panels. Both of these floors were assumed to be supported by an in-situ beam system. It was found that where the spans exceed 4m (typically the case in buildings), the construction of precast hollowcore floors generates roughly between 10% and 22% less carbon dioxide, depending on the span lengths.

Of all the components considered in Brewis' model (2009), the following elements have the greatest contribution to carbon emissions of concrete construction: cement, reinforcement, transport and the concrete plant. Of all the components of concrete construction, cement is by far the largest contributor of CO_2. For in-situ construction, reinforcement is the second largest contributor, whereas for precast construction, transportation is the second largest contributor. Transportation of in-situ construction includes that of wet cement and reinforcement. Transportation plays a larger role in precast construction whereas normal in-situ construction uses more reinforcement.

On the one hand having the manufacturing of cement as the largest contributor of CO_2, precast concrete elements would be in favour because less cement is used. This is proved in the following subsection. On the other hand, the main variable factor of all the contributors to the CO_2 emissions, is the transportation. Distance to site therefore has a great effect on a carbon emission comparison between in-situ and precast construction and long distances between the precast yard and site can cause in-situ concrete to produce less CO_2 than precast concrete.

7.2 Material input comparison

The more materials are used, the greater is the environmental impact. As found by Brewis (2009), the largest contributors to carbon emissions in terms of materials used in in-situ and precast concrete construction are cement and reinforcement.

A simple comparison of the primary raw material inputs of the different construction methods is given here. The construction methods in this comparison include a one-way span in-situ slab, post tensioned slab and a hollowcore floor with similar support structures. In-situ floors in this example have continuous spans, whereas the hollowcore floor has single spans.

The material input of rib-and-block floors is not determined. The reason for this is that different rib-and-block floor systems are available on the market. For instance some rib-and-block systems implement lattice reinforcement systems for the ribs. Also, the shapes of the ribs for different systems vary tremendously. Therefore the material input for one type of rib-and-block system is not a good representation of rib-and-block floor systems in general.

Design calculations for a cost comparison performed in Appendix D are used for this material input comparison. Additional calculations for the material input are supplied in Appendix I. For the purpose of the calculation, the following is assumed:

- One-way span slabs
- Live Load = 2.5kPa
- Different span lengths are investigated

For the hollowcore panels, the concrete quantity is at first calculated with a 50mm screed topping. It is common practice in South Africa to apply a 50mm screed on hollowcore panels (Queripel, 2011; Surridge, 2011).

However, Walraven (2007) found that a screed topping on hollowcore panels is not required. Walraven's calculations indicate that by filling the v-joints between the hollowcore panels with in-situ concrete, enough shear bonding in the plane of the panels is achieved (see the illustration in Figure 21).

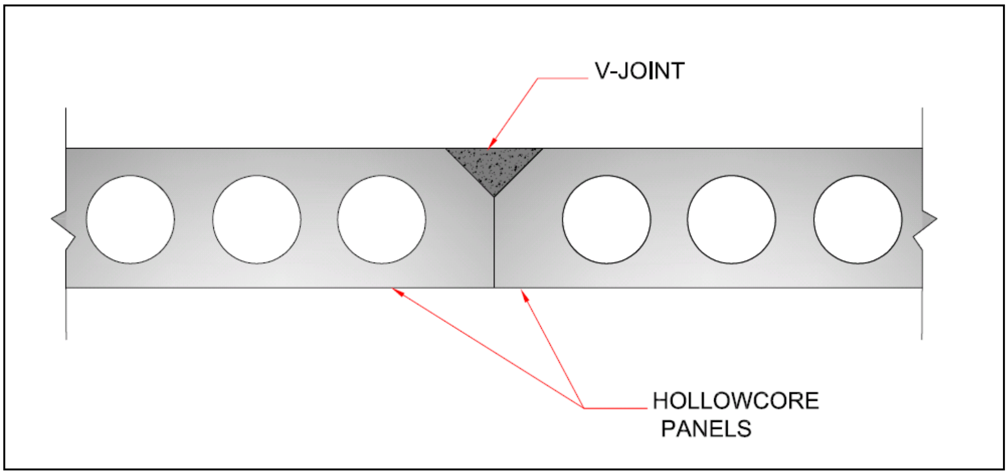

Figure 21: V-joint between hollowcore floor panels (Walraven, 2007)

Therefore a second comparison of concrete input for the different construction methods is made for the case where no screed topping is required.

7.2.1 Concrete

When the volume of a 50mm screed is taken into account, the hollowcore floor option does not necessarily use the least volume of concrete. A calculation is performed in Appendix I to determine how much concrete is required by the different floor construction methods. Results obtained are graphically presented in Figure 22. As explained in Chapter 4, a post tensioned slab is not designed for the 4m span floor option.

Without the screed topping, as suggested by Walraven (2007), the required concrete material input for hollowcore floors is even less. Calculations are given in Appendix I. Figure 22 also illustrates how the decreased concrete input of the hollowcore panels compares to the concrete input of in-situ slabs for the design parameters chosen.

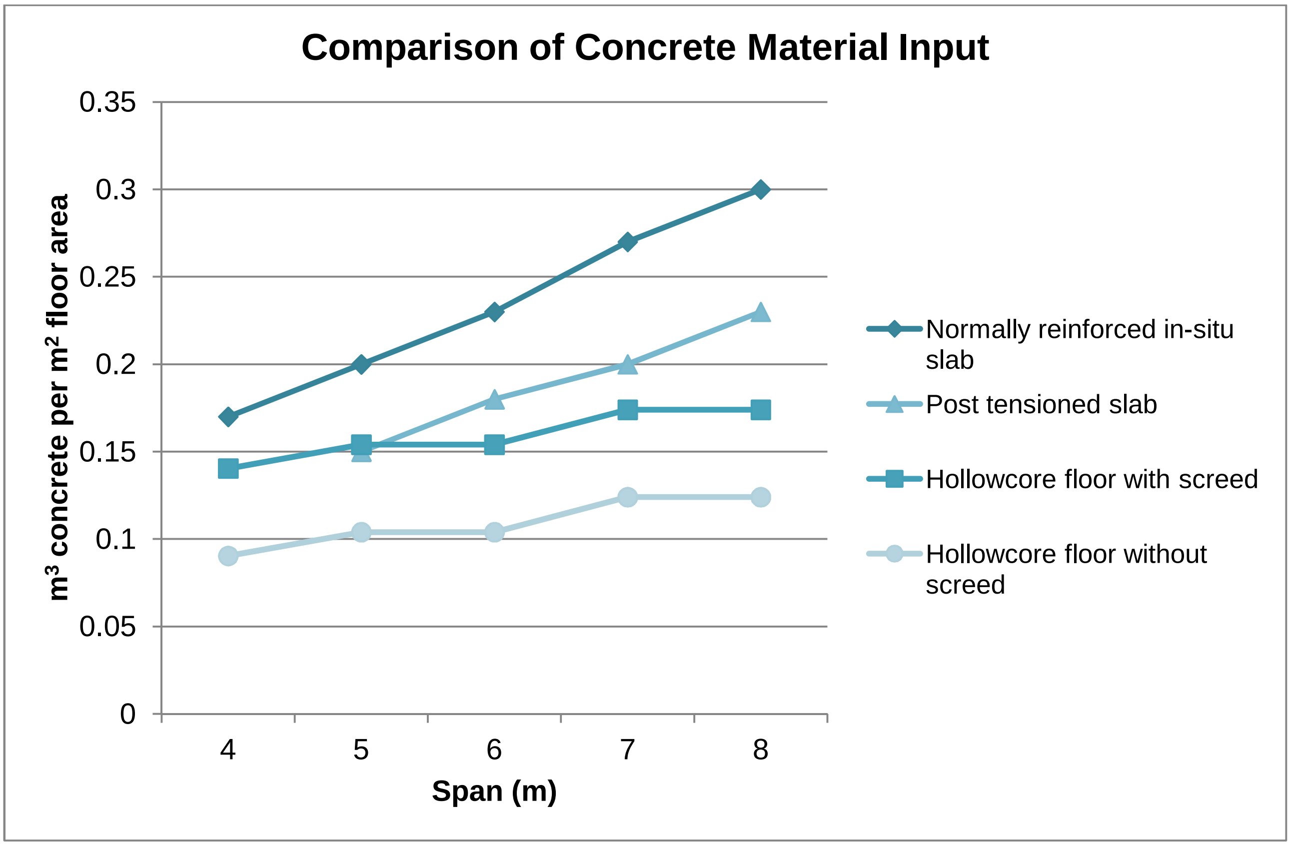

Figure 22: Comparison of concrete material input

<u>With screed</u>

For the 5m span floor in the example, the post tensioned slab requires the least concrete of all the floor options investigated. For other span lengths, the hollowcore floor requires less concrete than in-situ floors. The relative differences of the concrete required for different floor options increase as the span lengths increase. In this example, the post tensioned floor requires up to 32% more concrete than the hollowcore floor and the normally reinforced floor requires up to 72% more concrete than the hollowcore floor.

Without screed

Where no screed is required for hollowcore panels, the concrete input for the construction of a hollowcore floor is less than that of in-situ floors in all the cases investigated. For the design parameters chosen, the concrete required for hollowcore floors is between 1.9 and 2.4 times less than for normally reinforced in-situ floors, depending on the span length. The hollowcore floors without screed also require between 44% and 85% less concrete than the post tensioned floors, depending on the span length.

The abovementioned figures are high, when considering that hollowcore floors are 22-32% more expensive than in-situ floors. This may be explained by the additional transportation cost for hollowcore elements.

It is concluded that without screed, hollowcore floors require much less concrete than in-situ floors.

7.2.2 Cement

Apart from the concrete mix, the cement content in slabs also needs to be considered. The following aspects play a role in the comparison of the cement input:

- When compared to in-situ cement quantities, less cement may be used in a precast mix due to a better optimised concrete mix design for elements that are manufactured in a more controlled environment. In South Africa it is found that this principle is not applied yet (Anonymous Manufacturer, 2011), but it should be implemented when more and more precast elements are manufactured.
- Also, less cement can be used for elements that are pre-manufactured, because a lower workability type of concrete is required than on site.
- However, more cement is required in precast mixes than in in-situ mixes since precast elements typically have higher strength specification - hollowcore panels are designed to have 28 day strength of 50MPa, whereas in-situ floors normally have design strengths of 25MPa or 30MPa (Queripel, 2011).

There are therefore several factors that need to be considered when a comparison is made between the cement inputs for the concrete mixes of the different construction methods. A further investigation is required to quantify this.

7.2.3 Reinforcement

Prestressed wires have much higher yield strengths than normal reinforcement and therefore less steel is required to reach equivalent strengths. The same example is used as for concrete material input to determine what the difference is in the steel input for precast and in-situ slabs. Calculations are performed in Appendix I and the results are given in Figure 23.

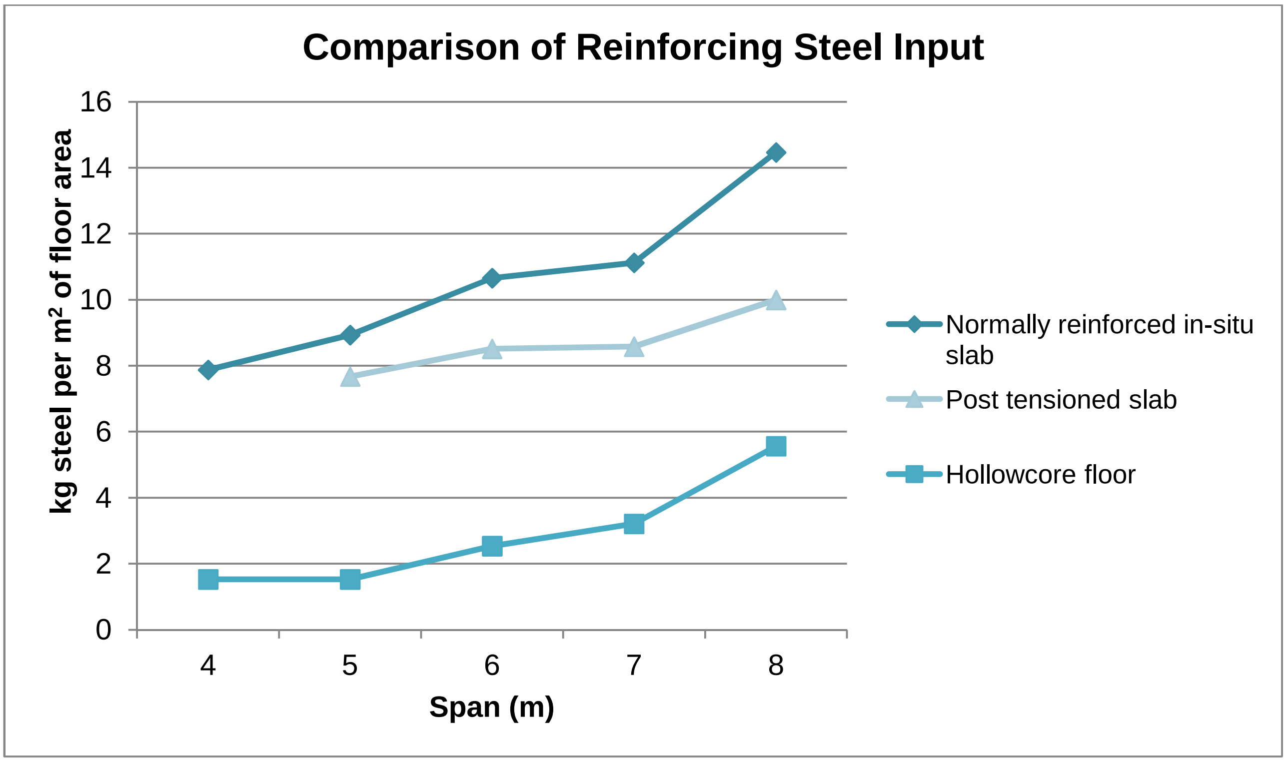

Figure 23: Comparison of reinforced steel material input

Note that the amount of steel for the different options may vary. For the hollowcore panels, different options of thickness and wiring combinations can be chosen. The amount of reinforcement required depends on the thickness of the hollowcore panels chosen. Furthermore, for the in-situ floor options, the amount of reinforcement required depends on the thickness of the floor slab.

Figure 23 indicates that the hollowcore floor requires less reinforcing steel than the normally reinforced in-situ slab. It is also clear that the hollowcore floor in the example requires less reinforcing steel than the post tensioned slab. With the parameters chosen, the normally reinforced in-situ slabs require between 2.6 and 5.8 times more steel reinforcement than hollowcore floors, depending on the span length. The post tensioned slabs require 1.8 to 5.0 times more reinforcement than the hollowcore floors.

Hollowcore floors definitely use less reinforcement than normally reinforced and post tensioned in-situ floors with the same design parameters. This is a result of reduced own weight and the high tensile steel used (when compared to normal reinforced in-situ floors).

Apart from material savings that the hollowcore floor option offer for the floor structure itself, it is recognised that support structures of this lighter floor option, also require less reinforcement and/or concrete. This offers an even greater environmental benefit to the use of hollowcore floors.

7.3 Waste

Precast concrete construction is said to generate less waste than in-situ concrete construction (BPCF, 2008; NPCAA, 2011). This statement can be justified when the following is considered:

- In a controlled manufacturing environment (i.e. precast manufacturing), less water is wasted.
- Concrete is used more effectively in a controlled environment.
- Off-cuts are much easier re-used in a controlled manufacturing environment (i.e. precast manufacturing). The example of an off-cut piece of rebar can be considered: on site it would normally be discarded, whereas at a precast yard it would more easily be used.
- Precast manufacturers are moving towards recycling i.e. crushing and re-using of off-cut concrete parts.

Measurable quantities of waste are not provided in this study. It is suggested that a comparison of waste quantities of precast and in-situ concrete construction may be performed as a further study. For instance the amount of concrete wasted for each construction method can be determined by estimating the volume of concrete that is produced in order to construct a specific size of slab.

7.4 Concluding summary

The environmental impact of an activity is a primary aspect of sustainability, which should be a major consideration in the decision making process for a construction method.

7.4.1 Carbon footprint comparison

The construction of precast hollowcore floors generates roughly between 10% and 22% less carbon dioxide than the construction of in-situ concrete floors, depending on the span length. Also, precast concrete construction generates less waste than in-situ concrete construction. These findings can be explained by the material input comparison.

7.4.2 Material input comparison

In terms of material input, a comparison is performed in order to compare the material input for the different construction methods. Options include a normally reinforced in-situ floor, a post tensioned in-situ floor and a hollowcore floor. As an example, one-way span floors were designed and quantified. Design parameters included a 2.5kPa live load. The material comparison of the hollowcore floors to the in-situ floors is given in Table 6.

Table 5: Comparison of material input of hollowcore floors to in-situ floors at different span lengths

Material	Construction method	Normally reinforced in-situ floors	Post tensioned in-situ floors
Concrete	Hollowcore floors with screed	21%-72% less	0%-32% less
	Hollowcore floors without screed	1.9 to 2.4 times less	44% to 85% times less
Steel	Hollowcore floors	2.6 to 5.8 times less	1.8 to 5.0 times less

In addition, support structures of hollowcore floors carries a lighter load than that of in-situ floors, due to the fact that hollowcore floors requires less material, as discovered in this chapter. Support structures of hollowcore floors would therefore also require less material than that of in-situ floors.

7.4.3 Conclusion

Finally it is concluded that hollowcore floors are more environmentally friendly than in-situ floors. Therefore project teams that are considering a more environmentally friendly construction method for floors should choose hollowcore panels.

Chapter 8

CONCLUSIONS

Decision making in hybrid concrete construction is investigated in this study. Factors influencing this decision have previously been documented by various researchers such as Chen et. al (2010). However, the purpose of this study is to identify a framework for possible ways in which to quantify these factors and to identify aspects that need further targeted research to quantify some of these factors. Quantifications can then be used to assist project teams in the decision making process between different construction methods available.

Decision making between construction methods cannot be automated. However, the decision maker can use information provided as well as comparisons of the different factors in order to assist with the decision making process.

Preliminary framework for project teams considering HCC

HCC is a method that is developed with the purpose of improving the construction industry in terms of cost, duration of construction, quality and social and environmental impacts. Structural precast concrete is currently implemented for 5-25% of South African building elements.

Benefits are:

- Increased construction speed which leads to less project lifetime cost
- Less on-site activities, which leads to less congestion on site, less weather dependence and less disturbance to neighbouring sites
- Reduced environmental impact
- Timely identification of problems

Potential barriers are:

- Insufficient knowledge and skills which implies greater risk in the use of precast elements
- Distance from precast yard to site
- Job creation
- Insufficient quality of construction elements

Quantifiable measurements

Quantifiable measurements determined in this study are currently based on specific case studies.

- Cost and time:
  - Precast element cost might be up to 30% more expensive for long span lengths. This is location and time specific and should be re-measured for any project.
  - However, savings in project lifetime cost due to increased construction speed may be more significant.
- Quality:
  - Quality of precast elements is higher than in-situ elements. The extent of this difference is to be investigated in further studies.
  - 30% of South African in-situ construction quality does not comply with requirements. This must also be measured for precast construction in a further study.
- Social aspects:
  - The amount of man hours that are spent on in-situ and precast construction activities for a project, can be measured in a future study.
  - Labourers are working in a safer environment. The comparison of the intensity and frequency of accidents in precast construction can be compared to that of in-situ construction in a further study.
  - Due to less on-site activities, neighbouring sites experience fewer disturbances. This can also be measured in a future study.
- Environmental impact:
  - Hollowcore floors have a carbon footprint of up to 22% smaller than that of in-situ floors.
  - Hollowcore floors use up to 2.4 times less concrete and 5.8 times less steel than in-situ floors.

Refer to the diagram at the end of this section (Figure 24) for a more comprehensive framework for considering the above mentioned factors. This framework is currently based on available information of structural systems used in South Africa. It is the foundation of a decision making model and can be extended in further studies.

Other aspects to keep in mind when considering HCC

- A certain procurement method should not restrain the project to implement precast elements. However, early communication to the manufacturer and contractor as well as a positive attitude of team members towards precasting is very important for a successful HCC project.

- As much standardized elements as possible must be designed to optimise the cost of the precast elements. This implies proper communication at an early stage between the architect, the design engineer, the manufacturer and the contractor.
- The objectives of the project must be prioritized at an early stage in the project – for example, high quality vs low cost must be prioritized.
- Structural integrity of a building containing structural precast elements must be carefully designed. Ongoing studies are investigating precast floor for seismic activities.

Project teams must critically judge this information when a specific project is considered.

Note that quantities in this model are based on figures obtained from an **example design**.

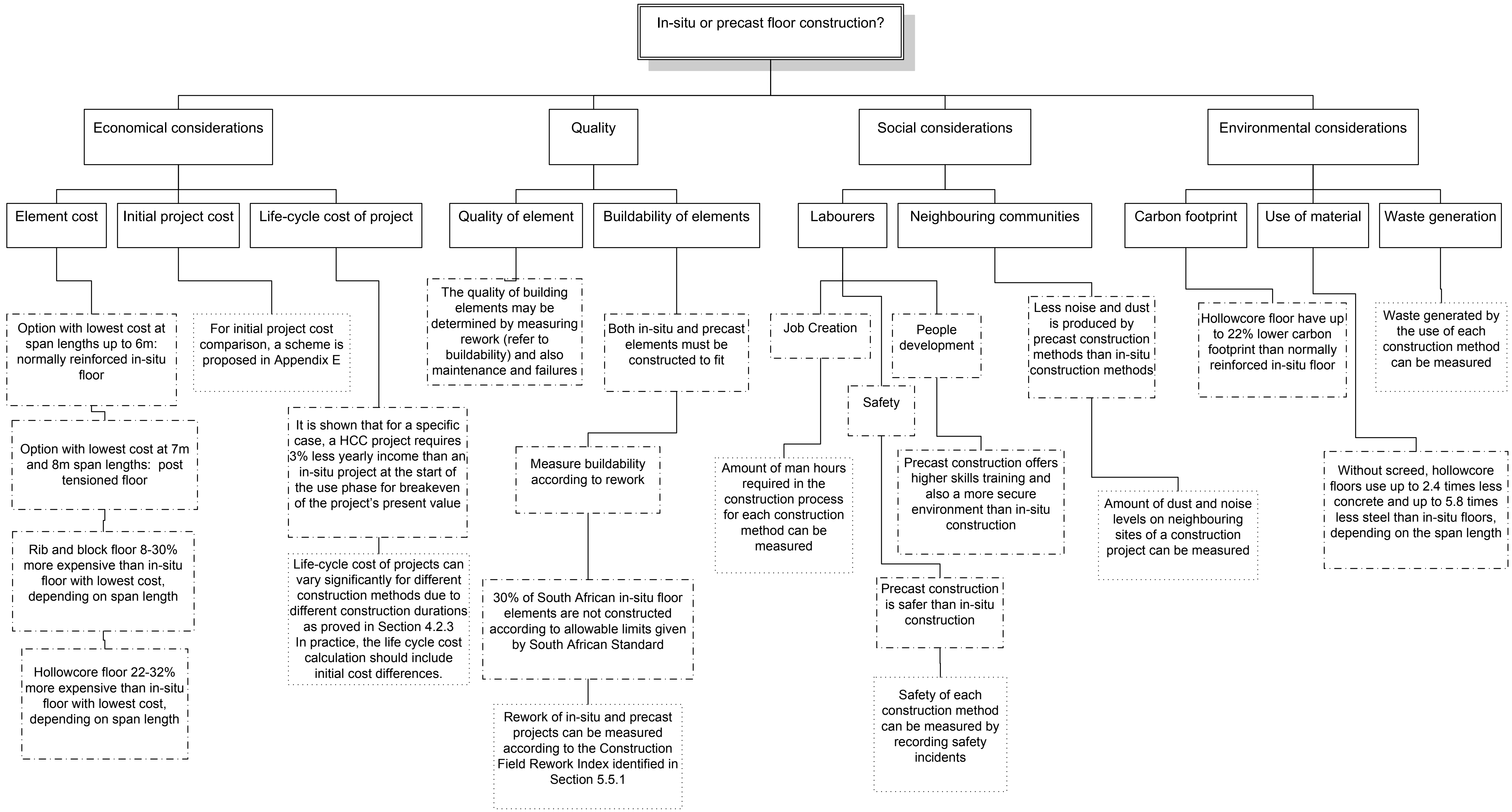

Figure 24: Framework for decision making

Chapter 9

RECOMMENDATIONS

Recommendations are provided here for the improvement of HCC and decision making in concrete construction, as well as the improvement of the South African construction industry in general.

9.1 Guidance

- SANS 10100:2000 need to be updated to include all the design aspects of precast concrete such as hollowcore floors and diaphragm action of floor systems. Furthermore it would be beneficial to have a South African design guide for precast elements.
- Precast concrete design should be a (or part of a) module in the education and training of any structural design engineer.
- Courses or presentations on the application of precast elements would be beneficial for both designers and contractors.
- Case studies of precast projects should be recorded for future reference. A data base of HCC applications would assist project teams in the planning phases of HCC projects in the future. The most appropriate organisation to facilitate such a data base is the CNCI. The following data would be useful:
    - Descriptions of HCC projects
    - Building types
    - Precast elements used
    - Problems encountered during construction and in the use phase

9.2 Quality

- Rework in projects should be monitored in order to compare the short-term quality of HCC and in-situ construction. Whilst rework is monitored, the primary causes thereof should also be recorded. This would assist contractors to identify the primary causes of rework so that these issues can be addressed.
- Maintenance and overall failures should be monitored in order to compare long term quality of HCC and in-situ construction.
- South African construction quality has to improve. In-situ concrete elements need to be constructed according to SANS 2001-CC1:2007. This would improve the buildability of the hybrid concrete construction elements.

9.3 Economical considerations

- A project cost comparison of the different construction methods can be made by using the scheme in Appendix E. These methods can include precast and in-situ floor systems, but also a wider range of elements, for instance precast and in-situ concrete frames. This would require planning, design, quantifying and costing input from specialists in the field.
- The decision for or against a construction method should not only be based on cost. Aspects such as social, environmental and many other considerations should be taken into account in the decision making process of a construction method.

9.4 Social considerations

- The influence of different construction methods on the labourers involved, can be measured by monitoring the following:
  - The amount of workers required by measuring man hours
  - The level of safety by monitoring the frequency and severity of incidents
  - People development by means of skill levels
- Influences of different construction methods on the neighbouring community can be measured by monitoring the following:
  - Noise levels at neighbouring sites
  - Dust levels at neighbouring sites
- Furthermore, for a better understanding of the possible correlation between labor factors and precast usage, other international labour factors must be obtained (such as labour cost or level of expertise). These factors may then be plotted against precast usage in order to establish whether a correlation exists.

9.5 Environmental considerations

- Many different environmental impact measurement tools are developed and used freely in South Africa. However, no standard currently exists for environmental impact measurement. Such a standard for the measurement of environmental impacts in South African projects should be set.
- It is suggested that a comparison of waste quantities of precast and in-situ concrete construction be performed as a further study. For instance the amount of concrete wasted for each construction method can be determined by estimating the excess volume of concrete that is produced in order to construct a specific slab or even a structural frame. Furthermore the

waste of other materials such as steel, aggregate and water can also be measured for each construction method by determining the amount of material used and comparing it to the amount of material required.

9.6 The choice of construction method

- Where possible, precast floors should be considered in order to improve sustainability in the construction of buildings.
- The comparison of types of construction methods can be expanded from floor systems used in South Africa only, to floor systems successfully used internationally. Furthermore, other structural elements, such as precast frames that are not used in South Africa yet, can also be incorporated in the framework provided the Chapter 8.

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Appendix A

MANUFACTURERS OF PRECAST BUILDING ELEMENTS IN SOUTH AFRICA

Table A.1: Structural building precast concrete suppliers in South Africa (Also in thesis of R. Hanekom, December 2011: Increasing the Utilisation of Hybrid Concrete Construction in South Africa)

Name of company	Information available	Location	Hollowcore panels	Rib-and-block	Beams	Columns	Staircases
Bobcrete	www.bobcrete.co.za	Cape Town	X	X			X
Cobute	www.cobute.co.za	Cape Town		X			X
Concrete Units	www.concreteunits.co.za	Cape Town		X			
Corestruc	www.corestruc.co.za	Polokwane	X		X	X	X
Echo	www.echo.co.za	Johannesburg, Durban	X				
Elematic SA	www.elematic.co.za	Johannesburg	X				
Infraset	www.infraset.co.za	Johannesburg, Durban		X			
Ital Concrete Design	www.italconcrete.co.za	Johannesburg		X			
Neat Contech	www.neatcontech.co.za	Humansdorp		X			X
Shukuma	www.shukumaflooring.co.za	Port Elizabeth	X				
Stabilian	051 434 2218	Bloemfontein	X				
Topfloor	www.topfloor.co.za	Cape Town	X				

Appendix B

INTERNATIONAL AND LOCAL PRECAST USAGE

Estimations of the usage of precast elements (% precast usage, as a percentage of concrete building construction, e.g. floor systems, beams and columns) in different countries and in South Africa are given below. Certainties of respondents' answers are also indicated. Where the certainty is not 80-100%, the data is based on personal estimates and therefore it is not accurate.

B.1 International precast usage

International and local precast usages were obtained through non-scientific surveys. For international precast usages, an e-mail was sent to nineteen contacts in different countries, requesting that he/she estimate his/her country's precast usage as well as the certainty of his/her answer. Fourteen of the contacts responded to the e-mail and their responses are summarised in Table B.1.

Table B.1: International precast usage estimations

Person	**E-mail address**	**Country**	**% precast usage**	**Certainty**
Vic Anderson	v.anderson@delcan.com	Canada	5-15%	20%
Per-Erik Josephson	Per-Erik.Josephson@chalmers.se	Sweden	45-55%	80-100%
Mikael Wimpffen Bræstrup	MWB@ramboll.com	Denmark	75-85%	80-100%
Ib Enevoltsen	IBE@ramboll.com	Denmark	85-95%	80-100%
Daia Zwicky	Daia.Zwicky@hefr.ch	Switzerland	45-55%	40-60%
Niels Peter	niels.hoj@bluewin.ch	Switzerland	25-35%	20%
Ana Mandic	mandicka@grad.hr	Croatia	15-25%	40-60%
Fernando Branco	fbranco@civil.ist.utl.pt	Portugal	5-15%	20-40%
Chris Goodier	C.I.Goodier@lboro.ac.uk	UK	10-25%	75%
Bert Snijder	H.H.Snijder@tue.nl	Netherlands	35-45%	80-100%
Nasser Darwish	nassdarwish@yahoo.com	Egypt	0-5%	80-100%
Yaojun Ge	yaojunge@tongji.edu.cn	China, big cities	55-65%	60-80%
Maria Gracia Bruschi	mgbruschi@cs.com	USA	5-15%	80-100%
Riccardo Zandonini	Riccardo.Zandonini@ing.unitn.it	Italy	10-12%	80-100%

B.2 Local precast usage

Figures for the precast usage in South Africa are not available and therefore estimations of this usage were obtained from consultants and contractors in the industry. A questionnaire was sent to eighteen contacts, of which ten responded (see Appendix C for the local questionnaire). See Table B.2.

Table B.2: Estimated usage of precast in South Africa

Person	E-mail address	% precast usage	Certainty
Neo Tladinyane	neo@bagale.co.za	15-25%	20%
Morné Gemishuys	Address not provided	5-15%	40-60%
Ruloph Theunissen	ruloph.theunissen@stefstocks.com	15-25%	60-80%
Mark Lehmann	markhwlehmann@yahoo.com	5-15%	40-60%
Chris Prinsloo	cprinsloo@basilread.co.za	5-15%	40-60%
Christiaan de Villiers	Christiaan.DeVilliers@bigenafrica.com	5-15%	60-80%
Bennie Zietsman	bzietsmann@eceng.co.za	5-15%	20-40%
Henry Fagan	henry@fagan.co.za	25-35%	20-40%
John Robberts	John.robberts@nucse.com	15-25%	60-80%
Ulrich Huber	ulrichh@BKS.co.za	5-15%	40-60%

It is assumed that 5-25% of concrete building construction in South Africa is performed by using precast elements.

Appendix C

Questionnaire Results

C.1 Database

A limited and targeted survey was carried out to determine certain aspects of the South African structural precast concrete industry. The questionnaire was sent to eighteen experienced contractors and consultants. A summary of the details of the ten respondents that completed the survey are provided in Table C.1.

Table C.1: Details of questionnaire respondents

Respondent	Reference	E-mail address	Profession	Company
Neo Tladinyane	NT	neo@bagale.co.za	Consultant	Bagale Consulting
Morné Germishuys	MG	Not provided	Contractor	Group 5
Ruloph Theunissen	RT	ruloph.theunissen@stefstocks.com	Contractor	Stefanutti Stocks
Mark Lehmann	ML	markhwlehmann@yahoo.com	Consultant; ex-contractor	Aurecon
Chris Prinsloo	CP	cprinsloo@basiread.co.za	Contractor	Basil Read
Bennie Zietsmann	BZ	bzietsmann@eceng.co.za	Consultant	Element Consulting
Christiaan de Villiers	CD	Christiaan.DeVilliers@bigenafrica.com	Consultant	Bigen Africa
Henry Fagan	HF	henry@fagan.co.za	Consultant	Henry Fagan
John Roberts	JR	John.robberts@nucse.com	Consultant	Nuclear Structural Engineering
Ulrich Huber	UH	ulrichh@BKS.co.za	Consultant	BKS

Note that the questionnaire was not completed by all the respondents at the same time. Therefore, some questions that were poorly answered or had definite results were not sent to candidates later on in the survey.

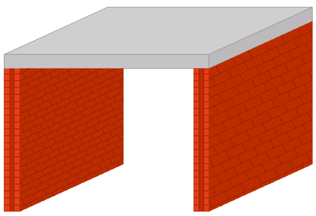
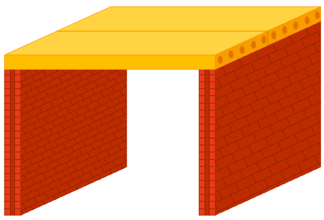
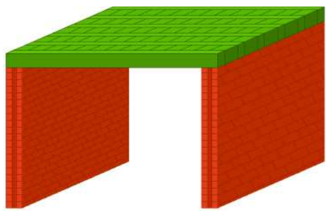
C.2 The questionnaire

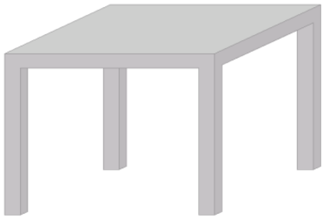
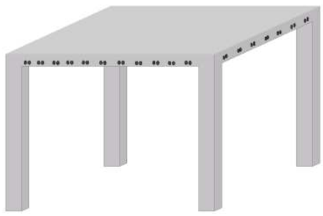
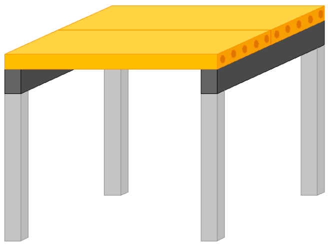
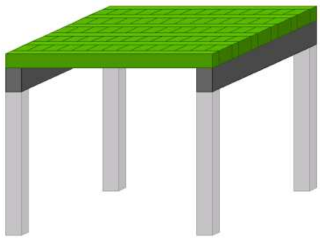
PRECAST CONSTRUCTION IN BUILDINGS

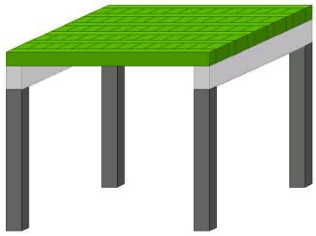
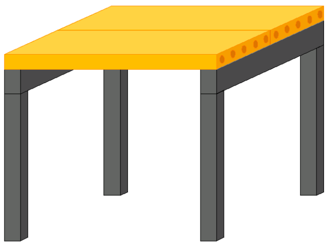
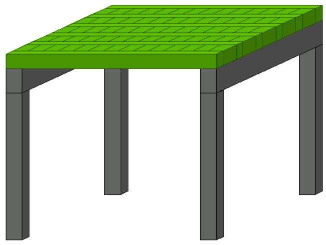
Consider the following:

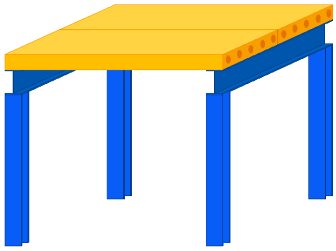
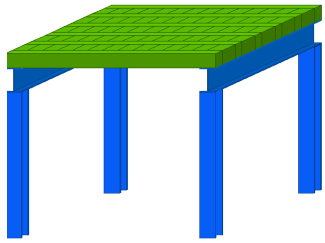
- "***Precast concrete elements***" refers to all pre-manufactured structural concrete elements, including tilt-up, hollowcore, beam-and-block and other precast concrete elements (NOT pipes, kerbs, hollow blocks etc.)

C.2.1 Structural systems and elements

<table>
<tr><td colspan="7">Indicate what percentage of buildings is constructed using the following systems:
(Total usage of every support system must add up to 100%)</td></tr>
<tr><td>Support system</td><td colspan="2">In-situ floor</td><td colspan="2">Hollowcore floor panels</td><td colspan="2">Beam-and-block floor</td></tr>
<tr><td rowspan="2">Load-bearing brickwork</td><td colspan="2">
Load bearing brickwork with in-situ floor</td><td colspan="2">
Load bearing brickwork with hollowcore floor</td><td colspan="2">
Load bearing brickwork with beam-and-block floor</td></tr>
<tr><td>Usage</td><td>NT: 70%
MG: 80%
RT: 80%
ML: 70%
CP: 30%
BZ: 50%
CD: 20%
HF: 40%
JR: 70%
UH: 0%</td><td>Usage</td><td>NT: 20%
MG: 10%
RT: 10%
ML: 60%
CP: 30%
BZ: 10%
CD: 40%
HF: 30%
JR: 15%
UH: 0%</td><td>Usage</td><td>NT: 10%
MG: 10%
RT: 10%
ML: 30%
CP: 40%
BZ: 40%
CD: 40%
HF: 30%
JR: 15%
UH: 0%</td></tr>
</table>

Concrete frames	 In-situ concrete columns with flat slab	 In-situ concrete frame with hollowcore floor	 In-situ concrete frame with beam-and-block floor
	Usage MG: 70% RT: 50% ML: 50% CP: 50% BZ: 50% CD: 40% HF: 45% JR: 88% UH: 10%	Usage MG: 15% RT: 15% ML: 10% CP: 15% BZ: 1% CD: 5% HF: 5% JR: 1% UH: 10%	Usage MG: 5% RT: 15% ML: 10% CP: 4% BZ: 15% CD: 5% HF: 5% JR: 1% UH: 10%
	 In-situ concrete columns with post-tensioned flat slab	 In-situ columns with precast beams and hollowcore floor	 In-situ columns with precast beams and beam-and-block floor
	Usage NT: 85% MG: 5% RT: 20% ML: 10% CP: 15% BZ: 32% CD: 40% HF: 25% JR: 10% UH: 70%	Usage NT: 10% MG: 3% RT: 0% ML: 20% CP: 8% BZ: 1% CD: 5% HF: 10% JR: 0% UH: 0%	Usage NT: 5% MG: 2% RT: 0% ML: 10% CP: 8% BZ: 1% CD: 5% HF: 10% JR: 0% UH: 0%

Precast concrete frames		 Precast columns with in-situ beams and hollowcore floor		 Precast columns with in-situ beams and beam-and-block floor	
		Usage	NT: 0% MG: 0% RT: 0% ML: 0%	Usage	NT: 0% MG: 0% RT: 0% ML: 0%
		 Precast columns, precast beams and hollowcore floor		 Precast columns, precast beams and beam-and-block floor	
		Usage	NT: 0% MG: 0% RT: 0% ML: 0%	Usage	NT: 0% MG: 0% RT: 0% ML: 0%
Other		JR: Composite floors where steel decks serve as permanent shuttering.		JR: Steel beams supporting steel or fibreglass grating.	
		Usage	JR: 75%	Usage	JR: 25%

<table>
<tr><td rowspan="2">Steel frames</td><td rowspan="2"></td><td colspan="2">
Steel frame with hollowcore floor</td><td colspan="2">
Steel frame with beam-and-block floor</td></tr>
<tr><td>Usage</td><td>NT: 0%
MG: 100%
RT: 0%
ML: 50%
CP: 100%
BZ: 0%
CD: 80%
HF: 75%
JR: 0%
UH: 0%</td><td>Usage</td><td>NT: 0%
MG: 0%
RT: 0%
ML: 50%
CP: 0%
BZ: 0%
CD: 20%
HF: 25%
JR: 0%
UH: 0%</td></tr>
</table>

Indicate what types of buildings are constructed using precast elements by giving percentages as fractions of precast construction: *(Total precast construction must add up to 100%)*

Respondent	NT	MG	RT	ML	CP
Residential houses	2%	2%	30%	10%	10%
Low cost housing	10%	2%		10%	5%
Apartment blocks	2%	2%	70%	20%	15%
Office blocks	10%	2%		20%	15%
Parking lots	10%	2%		10%	20%
Other Commercial	10%	2%		15%	10%
Industrial buildings	50%	8%		15%	15%
Other: MG: Pump station / E&I bld		80%			
Other: Schools					10%
	100%	**100%**	**100%**	**100%**	**100%**

In your view, how much of the concrete consumed in the building industry is constructed using precast elements? *(Indicate with X)*

0 - 5%	5 - 15%	15 - 25%	25 - 35%	35 - 45%	45 - 55%	55 - 75%	75 - 95%
	MG ML CP BZ CD UH	NT RT JR	HF				

What is the certainty of your answer? *(Indicate with X)*

20%	20 – 40%	40 - 60%	60 - 80%	80 - 100%
NT	BZ HF	MG ML CP UH	RT CD JR	

What percentages of concrete floors are constructed using the following methods:
(Usage must add up to 100%)

Floor system	NT	MG	RT	ML	CP	BZ	CD	JR	UH
Flat slabs	50%	10%	15%	5%	20%	40%	30%	50 %	10%
Post tensioned flat slab	20%	10%	15%	10%	15%	25%	40%	10 %	55%
In-situ beams and slab	5%	80%	70%	50%	30%	15%	10%	10 %	10%
Composite slabs	5%	0%		5%	20%	1%	5%	10 %	5%
Hollowcore panels	10%	0%		10%	10%	4%	7.5%	10 %	10%
Rib-and-block systems	10%	0%		20%	5%	15%	7.5%	10 %	10%
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Where precast elements have been used in construction, who made the decision or what was the process?
NT: Consultant & Contractor RT: The Contractor ML: Project Manager PC: Normally Engineer BZ: Client CD: Big projects: Engineer or Contractor Small projects: Client HF: Sometimes the Consulting Engineer, sometimes the Contractor and often the Client JR: For flooring systems it is mostly used in the domestic housing market. If the engineer is familiar with a precast system, he will recommend it. A much larger percentage of precast elements are used for bridges. UH: On projects I have worked on pre-cast elements are usually used if they are readily available from catalogues for certain standard products (e.g. manhole rings, lintels etc). Often pre-cast elements are used as covers for trenches as they need to be removable for access. Pre-cast hollow core slabs are usually used on tight construction schedules only. Large scale projects such as stadiums make it feasible to establish pre-cast yards on site to mass produce pre-cast elements mainly seating planks but also architectural feature cladding, very large façade columns and non-structural feature beams etc. The decision to pre-cast is usually jointly made by engineer and contractor. It is strongly influenced by program as pre-casting can increase construction speed provided the necessary facilities/manufacturers are in place with enough capacity. Pre-casting has the added benefit of improved control over quality. Very tight construction tolerances and superior surface finishes can be achieved. On the stadium this was one of the influencing factors in deciding to pre-cast as a very high quality concrete surface finish was desired. If the engineer details in-situ structures, where standard available pre-cast products are readily available on the market (e.g. manhole rings), the contractor will usually ask the engineer if he can change to the pre-cast option.

C.2.2 Cost

<table>
<tr><td>As an average percentage of total cost of a project, how much do the changes cost? (This includes changes made by the client, architect and design engineer)</td><td colspan="2">NT: 0%
RT: 20%
ML: 10-25%
CP: 20%
BZ: 10%
CD: 15%
HF: 20%
JR: 25%</td></tr>
<tr><td>Would the above answer be the same for buildings that are constructed using precast concrete elements? (Mark with X)</td><td>Yes
NT
RT
CP
BZ
HF
JR</td><td>No
ML
CD</td></tr>
<tr><td colspan="3">If not, please provide details:
ML: Precast elements are constructed ahead of time, if they have not been designed interchangeable modular there will be serious cost implications.
CD: It should be more complicated to accommodate changes during construction when using precast solutions.
UH: Not sure what is meant by changes? Change from in-situ to pre-cast? On the projects I worked pre-cast options were usually of the same cost as in-situ. Generally the omission of staging and formwork on site makes savings, but is replaced by crane costs for placing the pre-cast. However pre-cast can save time on a project which has a saving. On the projects I have used pre-cast extensively unfortunately the pre-cast options didn’t achieve an improvement in construction speed due to consecutive delays resulting from the complexity of the structure. However the superior quality of pre-cast was a success.</td></tr>
</table>

C.2.3 Labour

What is the amount of man hours required to construct a 500m^2 normally reinforced suspended flat slab? ML: excluding curing and stripping / resource dependant
MG: 250 mh RT: ±1200 mh ML: Falsework and formwork: 14days Reinforcing: 5days Electr & Plumbing etc: 3days Inspections: 1day Concrete: 1day TOTAL: 24days CP: 360

What is the hourly rate of a labourer (excluding managers and foremen) on site?	
NT: R130*	ML: Dependant on the country one works in
MG: R23	CP: R35
RT: Carpenter ± R40; Labourer: ± R15	

*It is possible that this respondent may have considered the daily instead of hourly rate.

C.2.4 Quality

Quantify the time that is spent on rework due to quality issues (as a percentage of the total project duration)	NT: 20% of time MG: 0,25% of time RT: 15% of time ML: 15% of time CP: 15% of time BZ: 15% of time CD: 15% of time HF: 15% of time JR: 20% of time

Quantify the money that is spent on rework due to quality issues (as a percentage of the total project cost)	NT: 20% of money MG: 0,25% of money RT: 20% of money ML: 10% of money CP: 5% of money BZ: 5% of money CD: 10% of money HF: 5% of money JR: 20% of money

How often is SABS 1200G or SANS 2001 specified on drawings *(Mark with X)*				
Never	Seldom	Regularly NT CP JR	Mostly ML HF	Always MG RT BZ CD

How often is degree of accuracy 1 specified for projects using precast elements? *(Mark with X)*				
Never RT	Seldom JR	Regularly BZ CD UH	Mostly NT MG ML CP HF	Always

Appendix D

ELEMENT COST COMPARISON CALCULATIONS

In this Appendix an example design is used to perform a cost comparison between different floor construction methods. As described in Chapter 3, the floor construction methods considered are:

- Normally reinforced floor
- In-situ post tensioned floor
- Hollowcore floor
- Rib-and-block floor

The example is limited to one-way span floors. Furthermore in-situ floors are continuous and precast floors (hollowcore and rib-and-block) have single spans.

The following actions are performed in this design example.

4. Design of different floor options (as above) with a constant load, but varying span lengths.
5. Calculation of quantities.
6. Calculation of cost for all the different options. Rates are obtained from quantity surveyors and precast manufacturers. Installation fees are included in the cost of the floor elements.

D.1 Example details

A floor slab with an approximate area of 500m^2 is used as an example to compare material costs for different construction methods. Details of the floor structure are as follows:

- One-way span floor
- Span lengths: 4m, 5m, 6m, 7m and 8m
- Live load: 2.5kPa

The floors have the following layouts:

- 4m span lengths: 20x25m; 500m^2
- 5m span lengths: 20x25m; 500m^2
- 6m span lengths: 21x24m; 504m^2
- 7m span lengths: 21x24m; 504m^2
- 8m span lengths: 21x24m; 504m^2

For every option, the design or the 5m span floor is provided and a summary is given of the quantities for the remainder of the span lengths. A layout of the floor with 5m span lengths is given in Figure D.1

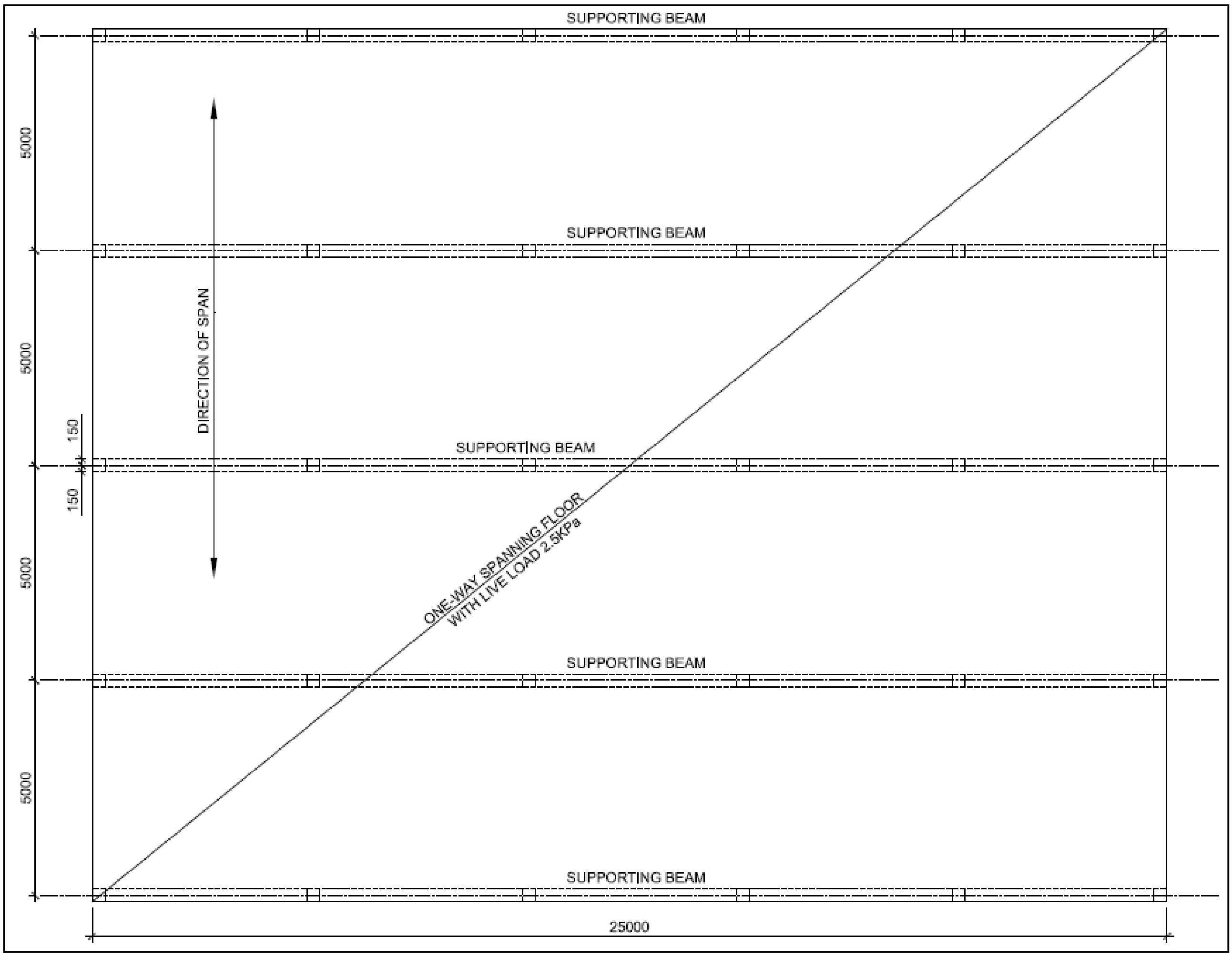


Figure D.1: 500m² one-way span suspended floor with span lengths of 5m

D.2 Normally reinforced in-situ floor

A 1m strip of the slab with continuous spans is designed. Final quantities for the different span lengths of the normally reinforced in-situ floor are given in Table D.2.

D.2.1 In-situ slab details

The in-situ floor slab has the following parameters:

- Concrete grade: 25/19
- Slab thickness: 170mm for the 5m span slab
- Cover to reinforcement: 25mm

The concrete grade and cover to reinforcement is the same for all the span lengths.

D.2.2 Loading

The minimum and maximum load on the 1m strip includes the following:

- Maximum distributed load (w) determined according to SANS 10160:2010;
- Maximum bending moment (M_{max}) determined according to the Southern African Institute of Steel Construction (2008);
- Minimum bending moment (M_{min}) determined according to the Southern African Institute of Steel Construction (2008); and
- Maximum shear (V_{max}) determined according to the Southern African Institute of Steel Construction (2008).

<u>Maximum distributed load</u>

The maximum distributed load is calculated by considering the maximum combination factors of the own weight of the slab with the live load.

w = 1.2 (Self Weight) + 1.6 (Live Load) = 1.2 (24 x 0.20) + 1.6 (2.5) = **9.76 kN/m**

<u>Maximum bending moment</u>

The maximum bending moment of the 1m strip is in the first span and is calculated below.

$M_{max} = 0.098\ w\ l^2 = 0.098\ (\ 9.76\ )\ (\ 5\ )^2 =$ **23.91 kNm**

<u>Minimum bending moment</u>

The minimum bending moment of the continuously span floor is at the first internal support. This minimum bending moment is calculated as follows:

$M_{min} = -\ 0.121\ w\ l^2 = -\ 0.121\ (\ 9.76\ )\ (\ 5\ )^2 =$ **- 29.52 kNm**

<u>Maximum shear</u>

The maximum shear of the continuously span floor is at the face of the first internal support. This maximum shear is calculated below.

$V_{max} = 1.223\ w\ l\ /\ 2 = = 1.223\ (\ 9.76\ )\ (\ 5\ )\ /\ 2 =$ **29.84 kN**

With these minimum and maximum loadings, the required reinforcement for the slab is determined.

D.2.3 Reinforcement design

Bending reinforcement

The required area of steel over the support is calculated using the minimum applied bending moment.

$$K = \frac{M}{bd^2 f_{cu}} = \frac{29.52 \times 10^6}{(1000)(200\text{-}25\text{-}6)^2(25)} = 0.0413 < 0.156$$

Only tension reinforcement is required.

The lever arm of the resisting moment in the slab (z) is provided by:

$$z = d\left\{0.5 + \sqrt{\left(0.25 - \frac{K}{0.9}\right)}\right\} = d\left\{0.5 + \sqrt{\left(0.25 - \frac{0.0413}{0.9}\right)}\right\} = 0.9613d > 0.75d$$

z = **162.5mm**

The required bending reinforcement (A_s) required over the support is:

$$A_{s(required)} = \frac{M}{0.87 f_y z} = \frac{29.52 \times 10^6}{0.87(450)(162.5)} = \mathbf{464.2mm^2}$$

The minimum required reinforcement in any direction is as follows:

$$A_{s(min)} = \frac{0.13}{100} bh = \frac{0.13}{100}(1000)(200) = \mathbf{260mm^2/m}$$

Therefore the top bending reinforcement provided in this case is **Y12-200** (A_s = 565mm^2). In the secondary direction at the top, nominal reinforcement is required. **Y10-300** (A_s = 262mm^2) is provided.

The required area of steel in the span is calculated using the same method as above, and is not shown here. For the span, 376mm^2 of steel is required per meter, therefore **Y12-300** (A = 377mm^2) is provided.

Shear verification

The maximum applied shear stress in the slab is calculated as:

$$v = \frac{V}{bd} = \frac{29.84 \times 10^3}{(1000)(200\text{-}25\text{-}6)} = \mathbf{0.177MPa}$$

The shear that the concrete can resist is as follows:

$$v_c = \frac{0.75}{\gamma_m}\left(\frac{f_{cu}}{25}\right)^{1/3}\left(\frac{100A_s}{b_v d}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4} = \frac{0.75}{1.4}\left(\frac{25}{25}\right)^{1/3}\left(\frac{100\ (565)}{(1000)\ (200-25-6)}\right)^{1/3}\left(\frac{400}{200-25-6}\right)^{1/4}$$

$$= \mathbf{0.461MPa}$$

$\therefore v_c > v$

Therefore no shear reinforcement is required.

<u>Reinforcement layout and bending schedule</u>

The reinforcement layout is given in Figure D.2 and the bending schedule is provided in Table D.1.

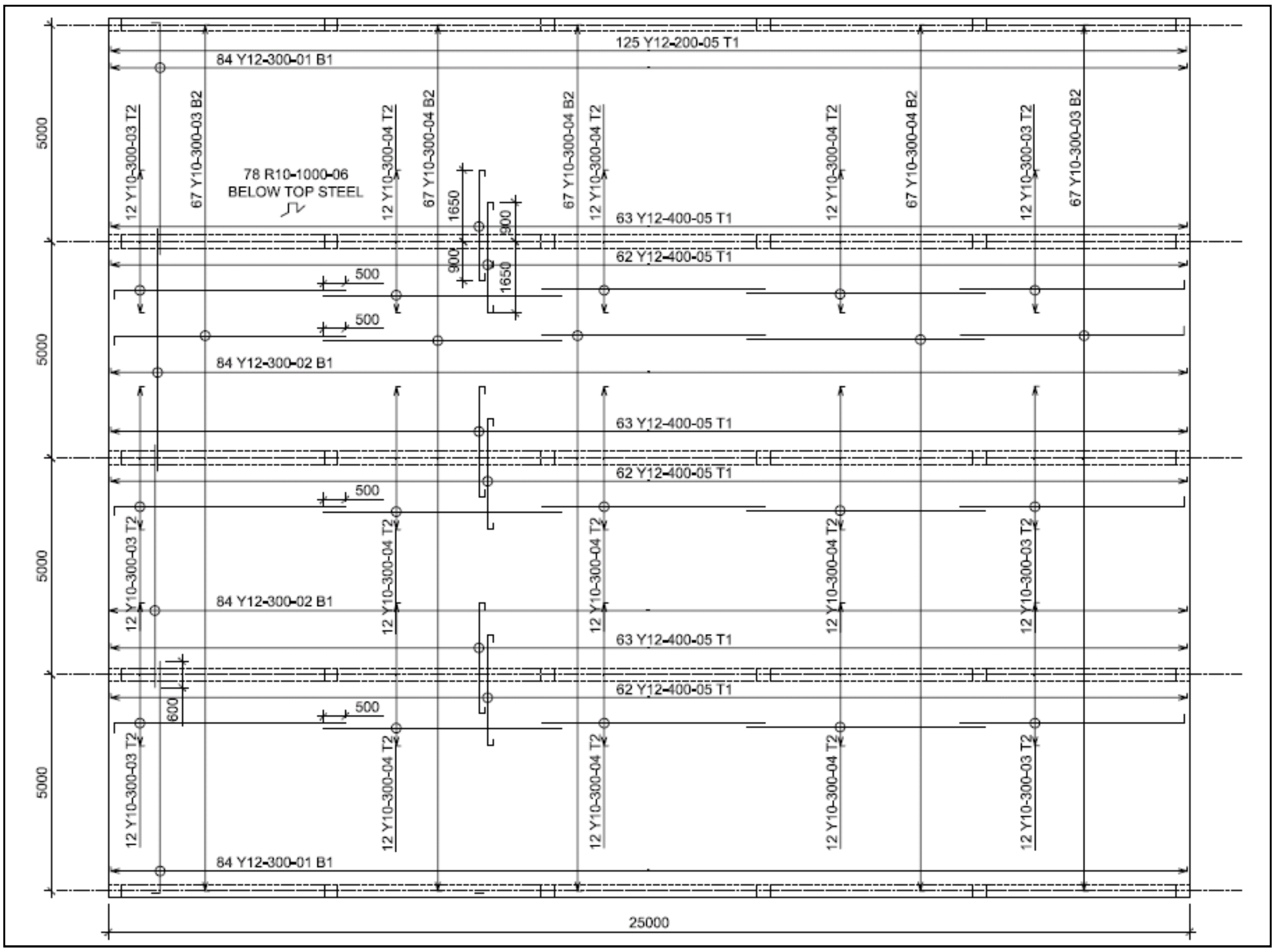


Figure D.2: Floor reinforcement layout

Table D.1: Bending schedule for normally reinforced 5m span slab

Member	Bar mark	Type & size	No	Total	Bending dimensions, etc, to SABS 82:1997						
				No.	Length mm	Shape Code	A mm	B mm	C mm	D mm	E/r mm
Floor slab	01	Y12	168	168	5450	34	5275				
	02	Y12	168	168	5600	20	5600				
	03	Y10	206	206	5400	34	5225				
	04	Y10	309	309	5500	20	5500				
	05	Y12	375	375	3200	55	150	130	2750	130	150
	07	R10	78	78	350	83	130	100	100	100	

Total mass			R8	R10	R12	R16	R20	R25	R32	R40
				17						
Mild steel	**17**	**kg**	Y8	Y10	Y12	Y16	Y20	Y25	Y32	Y40
High tensile steel	**4449**	**kg**		1735	2714					

D.2.4 Serviceability verification

In terms of serviceability, it is necessary to verify that the deflection of the slab is within allowable limits. For the strip of slab in the exterior span, the basic span/effective depth ratio is 24. This limit is adjusted according to the amount of tension steel that is provided in the span versus the amount of steel that is required in the span. The modification factor is calculated as follows:

$$\text{Modification factor} = 0.55 + \frac{(477 - f_s)}{120\left(0.9 + \frac{M}{bd^2}\right)}$$

Where f_s is the design service stress of the tension reinforcement. f_s is calculated as follows:

$$f_s = 0.87 f_y \times \frac{\gamma_1 + \gamma_2}{\gamma_3 + \gamma_4} \times \frac{A_{s,\,req}}{A_{s,\,prov}} \times \frac{1}{\beta_b}$$

$$\therefore\ f_s = 0.87 \times 450 \times \frac{1.1 + 1.0}{1.2 + 1.6} \times \frac{377}{376} \times \frac{1}{1} = 294.4\text{MPa}$$

$$\therefore\ \text{Modification factor} = 0.55 + \frac{(477 - 294.4)}{120\left(0.9 + \frac{23.91}{1000 \times 200^2}\right)} = 1.42 < 2$$

The the allowable span/effective depth is 1.42 x 24 = 34.2

$$\frac{L}{d} = \frac{5000}{200\text{-}31} = 29.6 < 34.2$$

Therefore the dimensions of the slab are within allowable limits of the serviceability.

D.2.5 Quantities

The various span length cases of continuous one-way span continuous slabs were designed according to the method above. Final quantities are summarized in Table D.2 below.

Table D.2: Normally reinforced in-situ slab quantities

Item	Unit	4m span option [170mm]	5m span option [200mm]	6m span option [230mm]	7m span option [270mm]	8m span option [300mm]
Concrete	m^3	85.0	100.0	115.9	136.1	151.2
Mild steel reinforcement	t	0.014	0.017	0.014	0.033	0.033
High tensile reinforcement	t	3.924	4.449	5.358	5.573	7.257
Edge formwork	m^2	15.3	18.0	20.7	24.3	27.0
Soffit formwork	m^2	500	500	504	504	504

These quantities are used to determine the cost of the normally reinforced in-situ option for each span length case. See Section D.7.

D.3 In-situ post tensioned floor

A 1m strip of continuous 3-span post tensioned in-situ floor is designed according to SABS 0100-1:1989. This standard is used (instead of the technical notes available for the design of flat slabs), because a single span floor is designed. Since post tensioned floors typically have large spans, the design of the 7m option is shown here. For the 4m span option, no post tensioned floor is designed. A summary of the slab quantities for the different span lengths is given in Table D.4.

D.3.1 Specifications

The post tensioned floor slab has the following parameters:

- Concrete strength: 30MPa
- Slab thickness: 200mm for the 7m span slab
- Cover to reinforcement: 25mm
- Characteristic force of the tendons (P_k): 260.7kN
- Cross-sectional area of the tendons (A_{ps}): 138.5mm^2
- Force of the tendons at service (P_s): 166.2kN (the jacking force is estimated at 0.75P_k and 15% losses are assumed)
- Characteristic strength of the tendons (f_{pu}) = 1882MPa
- Weight of the tendons: 1.2kg/m

The concrete grade, cover dimension, support dimension and tendon specifications are the same for the remainder of the span lengths.

D.3.2 Preliminary sizing

The pre-compression stress in the concrete is estimated using the following guidelines:

- Pre-compression in the concrete (at service) should be at least 0.7MPa.
- The portion of the load to be balanced by the tendons is chosen to be 70% of the own weight of the floor.

<u>Tendon profile</u>

See the tendon profile in Figure D.3.

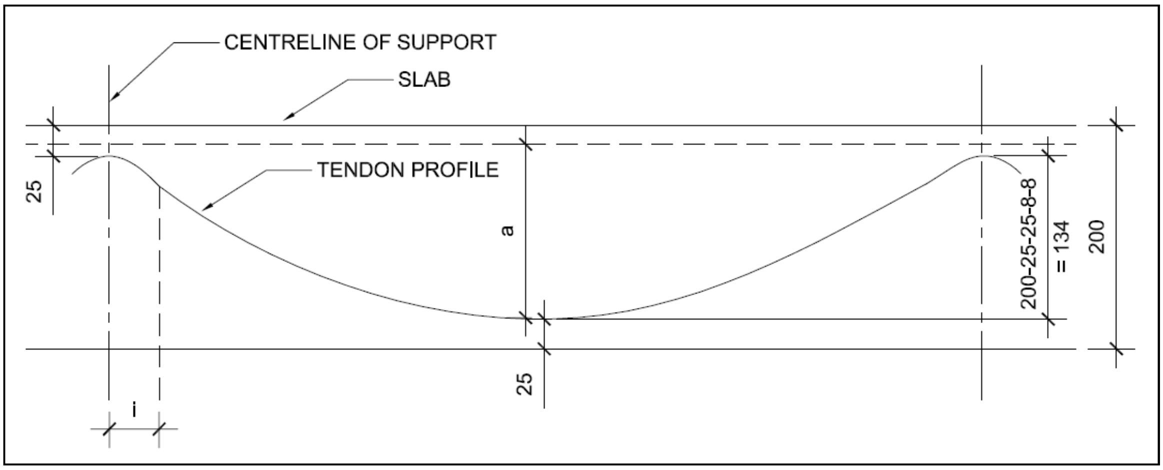


Figure D.3: Tendon profile

The point of inflection (i) of the tendons at the support is estimated as the smallest of:

$$i = \frac{\text{slab thickness + width of support}}{2} = \frac{200+300}{2} = 250\text{mm}$$

Or

i = 0.05 x span length = 0.05 x 7000 = 350mm

Therefore i is taken as **250mm**.

Having a parabola as shown in Figure D.4,

$y = bx^2 + cx$

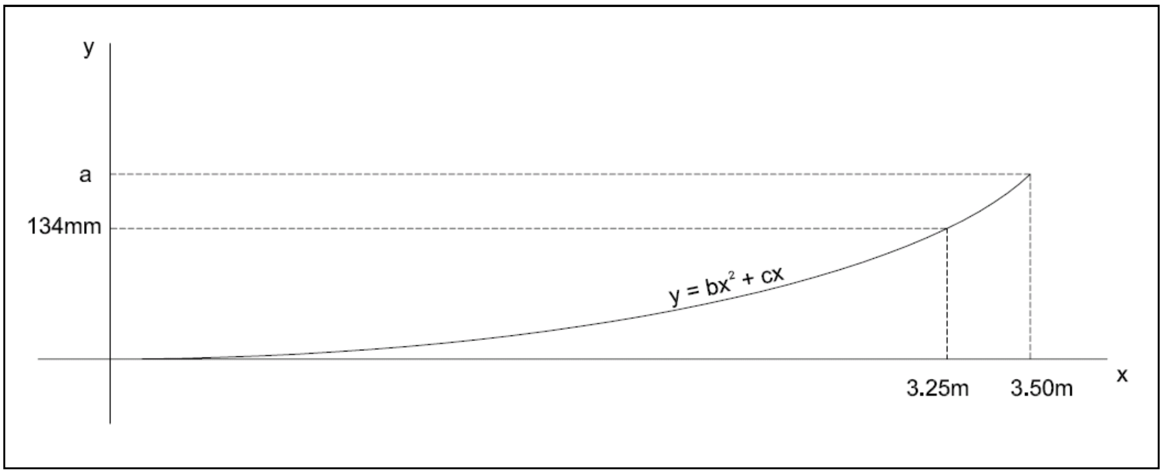


Figure D.4: Parabolic graph

Where x = 0, dy/dx = 0:

$$\therefore \frac{dy}{dx}(0) = 2b(0) + c = 0 \quad \therefore c = 0$$

Where x = 3.25, y = 134:

$$\therefore 134 = b\,(3.25)^2 \quad \therefore b = \frac{134}{3.25^2}$$

Where x = 3.5m, y = a:

$$a = 134 \times \frac{3.5^2}{3.25^2} = \mathbf{155.4mm}$$

Pre-stress force

The portion of the load to be balanced by the tendons (w') is as follows:

w' = 0.7 DL = 0.7 x 24 x 0.20 = **3.36 kPa**

The pre-stress force in the span drape is as follows:

$$F = \frac{w'l^2}{8a} = \frac{3.36 \times 7^2}{8 \times 0.1554} = \mathbf{132.43\ kN/m}$$

Tendons required

With a service force of 166.2kN, tendons are spaced at 0.833m intervals to obtain a force of 199.4kN/m. Therefore 1.2 tendons are provided per meter width of slab.

Concrete pre-compression

The pre-compression in the concrete (f_{cu}) is as follows:

$$f_{cu} = \frac{n\ P_s}{bd} = \frac{1.2 \times 166.2 \times 10^3}{1000 \times 200} = 0.9972\text{MPa} > 0.7\text{MPa}$$

The pre-compression in the concrete is within allowable limits of 0.5MPa and 1MPa. Therefore the preliminary design comprises of a 200mm slab with tendons spaced at 0.833m intervals.

D.3.3 Loading

Loading on the 1m strip of slab includes either ultimate load or serviceability load combined with the distributed load of the tendons. For simplicity, it is assumed that the tendons create an equally distributed upward load (w_{up}) on the floor over the length of the span and an equally distributed downward load (w_{down}) between the support and the inflection point (i). See Figure D.5.

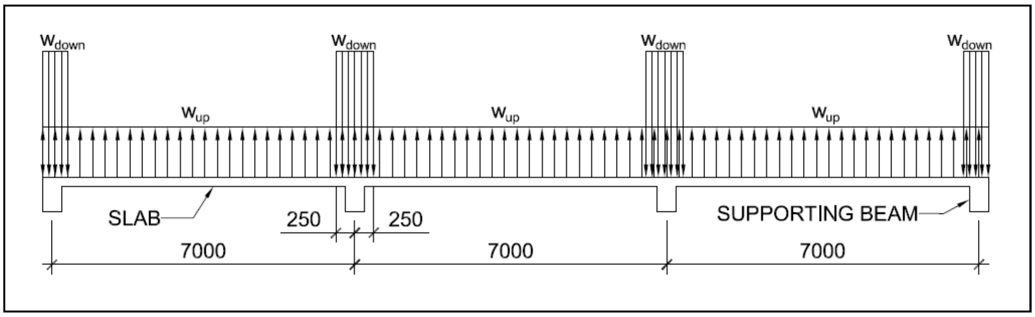


Figure D.5: Loading due to tendons

For the most conservative design, moments caused due to the loading are determined for maximum ultimate limit state (ULS) and minimum serviceability limit state (SLS).

Load due to own weight and live load

w_{ULS} = 1.2 (Self Weight) + 1.6 (Live Load) = 1.2 (24 x 0.20) + 1.6 (2.5) = **9.76 kN/m**

w_{SLS} = 1.0 (Self Weight) + 1.0 (Live Load) = 1.0 (24 x 0.20) + 1.0 (2.5) = **7.30 kN/m**

Load due to stressed tendons

The upward and downward loads of the tendons are determined below.

$$w_{up} = \frac{8\ M_{up}}{l^2} = \frac{8\ F\ a}{l^2} = \frac{8 \times 1.2 \times 166.2 \times 0.1554}{7^2} = \mathbf{5.06\ kN/m}$$

$$w_{down} = \frac{8\ M_{down}}{l^2} = \frac{8\ F\ (\text{slab thickness} - \text{cover} - \text{tendon radius} - 134])}{l^2}$$

$$\therefore w_{down} = \frac{8 \times 1.2 \times 166.2 \times (0.200 - 0.025 - 0.008 - 0.134)}{(2 \times 0.25)^2} = \mathbf{210.6\ kN/m}$$

Moments

Applied moments at the first interior support and in the first interior span are determined.

The maximum and minimum ultimate and serviceability limit state moments are determined according to the Southern African Institute of Steel Construction (2008). This method is similar to the method used in Section D.2.2. The maximum moment at the first internal span and the minimum moment at the first interior support are as follows:

$M_{max} = -\ 0.081\ w\ l^2$; $M_{min} = -\ 0.121\ w\ l^2$

Prokon is used to determine the applied moments due to the stressed tendons. The bending moment diagram due to the tendon load is given in Figure D.6.

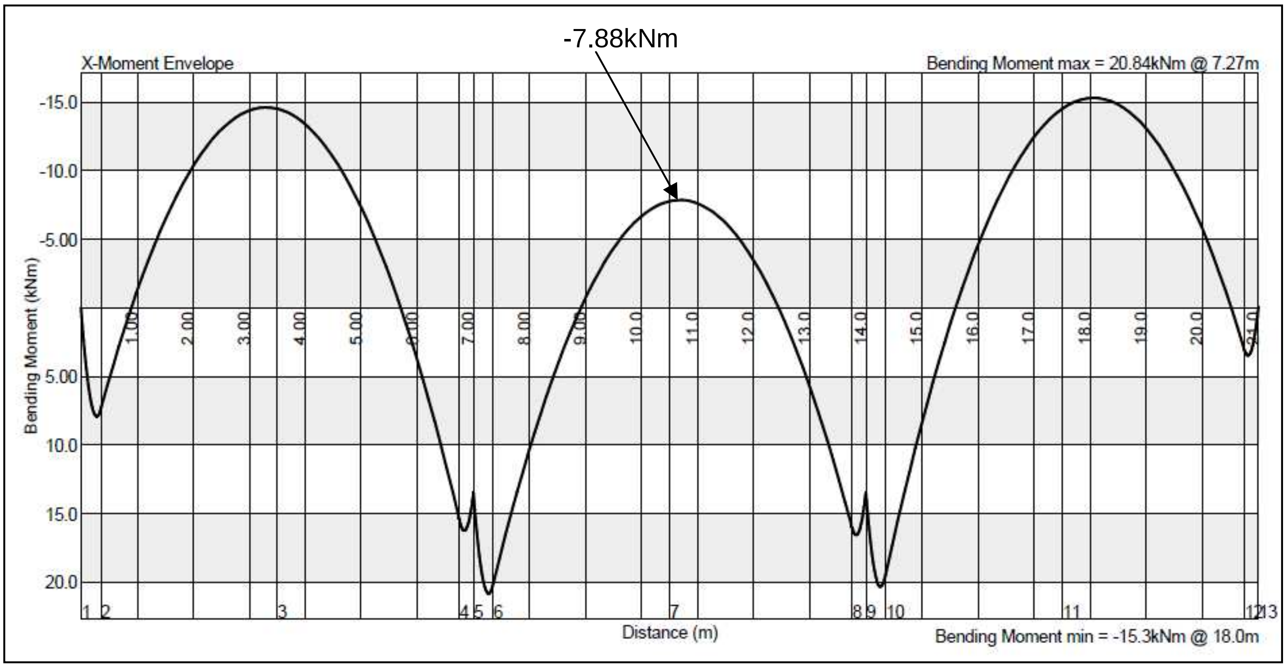


Figure D.6: Bending moment diagram due to tendon loading

The moments obtained as well as the maximum and minimum combined moments required are summarized in Table D.3.

Table D.3: Combined moments at interior span and first interior support

Load case	M_{span} [kNm/m]	$M_{support}$ [kNm/m]
ULS (using DL and LL)	38.73	-57.87
SLS (using DL and LL)	28.97	-43.28
Tendons	-7.88	20.84
ULS + Tendons	**30.86**	**-37.03**
SLS + Tendons	**21.09**	**-22.44**

D.3.4 Maximum tensile stress at serviceability limit state

Elastic section modulus

The elastic section modulus for the 1m strip of floor slab is as follows:

$$z_{el} = \frac{bh^2}{6} = \frac{1000 \times 200^2}{6} = \mathbf{6.667 \times 10^6\ mm^3}$$

Allowable tensile stress

The maximum allowable tensile stress in the concrete is as follows:

$f_{t(allowable)} = -0.45\sqrt{f_{cu}} = -0.45\sqrt{30} = \mathbf{-2.46MPa}$

Tensile stress in span

The maximum concrete tensile stress in the span is as follows:

$$f_t = \text{pre-compression} - \text{stress due to loading} = f_{cu} - \frac{My}{I} = f_{cu} - \frac{M}{z} = 0.997 - \frac{21.09 \times 10^6}{6.667 \times 10^6}$$

$$= \mathbf{-2.17MPa} < f_{t(allowable)} \quad \therefore \text{okay}$$

Tensile stress at support

Similar to the tensile stress in the span,

$$f_t = f_{cu} - \frac{M}{z} = 0.997 - \frac{22.44 \times 10^6}{6.667 \times 10^6} = \mathbf{-2.37MPa} < f_{t(allowable)} \quad \therefore \text{okay}$$

D.3.5 Maximum compressive stress at serviceability limit state

Allowable compressive stress

The maximum allowable compressive stress in the concrete is as follows:

$f_{c(allowable)} = 0.33 f_{cu} = 0.33 \times 30 = \mathbf{9.9MPa}$

Compressive stress In span

The maximum concrete compressive stress in the span is as follows:

$$f_c = \text{pre-compression} + \text{stress due to loading} = f_{cu} + \frac{My}{I} = f_{cu} + \frac{M}{z} = 0.997 + \frac{21.09 \times 10^6}{6.667 \times 10^6}$$

$$= \mathbf{4.16MPa} < f_{c(allowable)} \quad \therefore \text{okay}$$

Compressive stress at support

Similar to the compressive stress in the span,

$$f_c = f_{cu} + \frac{M}{z} = 0.997 + \frac{22.44 \times 10^6}{6.667 \times 10^6} = \mathbf{4.36MPa} < f_{c(allowable)} \quad \therefore \text{okay}$$

Therefore the design is within the allowable limits of the maximum tensile and compressive concrete stresses.

D.3.6 Design for excess tensile stress at serviceability limit state

<u>Excess tensile stress in span</u>

With f_t = -2.17MPa and f_c = 4.16MPa, the distance (e) to the maximum tensile force in the section is as follows:

$$e = \text{thickness of section} \times \frac{|f_t|}{|f_t|+f_c} = 200 \times \frac{2.17}{2.17+4.16} = \mathbf{68.48mm}$$

The maximum tensile force in the section (F_T) is as follows:

$$F_T = \text{width of section} \times {}^1\!/_2\,|f_t|\,(e) = 1000 \times {}^1\!/_2 \times 2.17 \times 68.48 / 1000 = \mathbf{74.20kN}$$

The area of the additional untensioned reinforcement required, due to the tensile force, is as follows:

$$A_s = \frac{F_t}{{}^5\!/_8\,f_y} = \frac{74.20 \times 10^3}{{}^5\!/_8 \times 450} = \mathbf{264mm^2}$$

However, the minimum area of untensioned steel required for post tensioned sections, is 15% of the cross-sectional area of the concrete. Therefore, the following nominal untensioned steel is required:

$$A_{s\,(min)} = \frac{0.15}{100}A_c = \frac{0.15}{100} \times 1000 \times 200 = \mathbf{300\ mm^2}$$

Therefore **Y10-250** (A_s = 314mm^2) is supplied as bottom reinforcement.

Nominal reinforcement with an area of 0.13% of the area of the concrete section **(Y10-300)** is provided in the secondary direction.

<u>Excess tensile stress at support</u>

With f_t = -2.37MPa and f_c = 4.36MPa, the distance (x) to the maximum tensile force in the section is as follows:

$$x = \text{thickness of section} \times \frac{|f_t|}{|f_t|+f_c} = 200 \times \frac{2.37}{2.37+4.36} = \mathbf{70.38mm}$$

The maximum tensile force in the section (F_T) is as follows:

F_T= width of section x $^1/_2$ $|f_t|$ (x) =1000 x $^1/_2$ x 2.37 x 70.38 / 1000 = **83.36kN**

The area of additional untensioned reinforcement required due to the tensile force, is as follows:

$$A_s = \frac{F_t}{{}^5/_8\, f_y} = \frac{83.36 \times 10^3}{{}^5/_8 \times 450} = \mathbf{297mm^2}$$

However, a minimum of area of **300mm²** untensioned steel is required (as calculated for span). Therefore **Y10-250** (A_s = 314mm²) is supplied as top reinforcement. Nominal reinforcement with an area of 0.13% of the area of the concrete section **(Y10-300)** is provided in the secondary direction.

D.3.7 Check ultimate limit state

Tendon stresses

The effective length of the tendons is as follows:

$$l_e = \frac{l}{3} = \frac{21}{3} = \mathbf{7m}$$

The stress in the tendons at service (f_{pe}) is as follows:

$$f_{pe} = \frac{166.2 \times 10^3}{138.5} = \mathbf{1200MPa}$$

The stress where the tendons fail (f_{pb}) is as follows:

$$f_{pb} = f_{pe} + \left(\frac{7000}{{}^{l_e}/_{d'}}\right)\left(1 - \frac{1.7\, f_{pu}\, A_{ps}}{f_{cu}\, b\, d'}\right) = 1200 + \left(\frac{7000}{{}^{7000}/_{167}}\right)\left(1 - \frac{1.7 \times 1882 \times 1.2 \times 138.5}{30 \times 1000 \times 167}\right)$$

$$= 1349.3 \text{ MPa} > 0.7f_{pu} = 1318.1\text{MPa}$$

Therefore f_{pb} is taken as **1318.1MPa**

Moment of resistance due to tendons

The lever arm (x) for the moment resistance is as follows:

$$x = 2.47 \left(\frac{f_{pu}\ A_{ps}}{f_{cu}\ b\ d'}\right)\left(\frac{f_{pb}}{f_{pu}}\right) d' = 2.47\left(\frac{1882 \times 1.2 \times 138.5}{30 \times 1000 \times 167}\right)\left(\frac{1318.1}{1882}\right) 167 = \mathbf{18.04mm}$$

The moment of resistance is as follows:

$$M_u = f_{pb}A_{ps}\, n\, (d' - 0.45x) = 1318.1 \cdot 1.2 \cdot 138.5\ (167 - [0.45 \cdot 18.04]) / 10^6 = \mathbf{34.81kNm}$$

$$M_u < |M_{min}| = 37.03kNm$$

And $M_u > M_{max} = 30.86kNm/m$

Therefore additional top reinforcement is required in the post tensioned slab at supports in order to comply with the ultimate limit state conditions. This reinforcement must resist a moment of 2.26kNm. Following the procedure in Section D.2.3, the reinforcement required is 35mm^2. However, Y10-250 (A_s = 314mm^2) is provided for serviceability and therefore no additional reinforcement is required.

D.3.8 Deflection verification

According to serviceability limit state requirements, the maximum allowable deflection of the floor strip is L/300, which is 23.33mm for the 7m span option. The maximum elastic deflection is determined using Prokon.

The long term modulus of elasticity for the slab is:

$$E_{long} = \frac{E_{short}}{1+\phi}$$

Assuming 60% humidity,

$$E_{long} = \frac{28}{1 + 1.25} = 12.44GPa$$

Using Prokon, the elastic deflection is determined for the serviceability limit state by taking into account the distributed DL and LL, together with the upwards and downwards loads of the post tensioning cables. The maximum deflection is:

$$\Delta_{max} = 9.18mm < 23.33mm$$

Therefore the post tensioned slab dimensions are sufficient for deflection restrictions of the serviceability limit state.

D.3.9 Quantities

Quantities for the different span lengths are given in Table D.4.

Table D.4: Post tensioned slab quantities

Material	Unit	5m span option [150mm]	6m span option [180mm]	7m span option [200mm]	8m span option [230mm]
Concrete	m^3	75.0	90.7	100.8	115.9
Post tensioning cables	kg	504	576	630	696
Anchors	No	42	40	60	58
Mild steel reinforcement	t	0.017	0.014	0.022	0.019
High tensile reinforcement	t	3.128	3.899	3.421	4.064
Edge formwork	m^2	13.5	16.2	18.0	20.7
Soffit formwork	m^2	500	504	504	504

D.4 Hollowcore specification

The size of the required single span prestressed hollowcore panels are selected from specifications obtained from a manufacturer (Queripel, 2011). Depending on the loading and the span length, the required depth is determined for the hollowcore panels. In the case of the 5m span floor with a live load of 2.5kPa, 150mm thick panels with 12 x 5mm wires are required. The panels and prestressing strand required for the floors with the different span lengths are given in Table D.5. A 50mm screed is included in the hollowcore floor design.

Table D.5: Hollowcore quantities

Span	Hollowcore panel depth	Prestressed steel strand
4m	120mm	12 x 5mm wires
5m	150mm	12 x 5mm wires
6m	150mm	7 x 5mm wires and 5 x 9.53mm strand
7m	200mm	9 x 5mm wires and 3 x 9.53mm strand
8m	200mm	12 x 9.53mm strand

According to these quantities and rates obtained from a manufacturer, the cost of the hollowcore panels is estimated in Section D.7.

D.5 Rib-and-block floor

The elements and quantities required for the 5m span floor are given. Data for the design is obtained from a manufacturer (Chetty, 2011). Final quantities for the different span lengths are presented in Table D.6.

D.5.1 Design example

Lintels (ribs)

Ribs are spaced at 550mm intervals. Over a width of 25m, 47 lintels are required. The total length of the lintels is 940m.

Blocks

Small, medium and large blocks are available. Depending on the span length, the size of the blocks is chosen. For the 5m span slabs, medium sized blocks are required. 9 blocks fit into a square meter, therefore 4500 blocks are provided for a 500m^2 floor area.

Y12 bars

2 Y12 bars are prescribed for every 2m interval in the direction perpendicular to the ribs. Over 20m, 20 Y12 bars are required. For the 20x25m floor, 3 bars splice over the 25m direction. Therefore a total length of 524m of Y12 is required, which weighs 462kg.

Mesh

Mesh Reference 141 is required in the top of the rib-and-block floor system. With a 30% overlap, 46 sheets of mesh are required for a 500m^2 floor area.

Total mass

The mass of the rib-and-block materials are required for the estimation of the transport cost. This is priced separately in the rib-and-block floors considered. Information on the mass of the rib-and-block floor is provided by the manufacturer. For medium sized blocks, the own weight of the floor system is 323kg. Therefore the ribs and blocks have a total weight of 162t for the 500m^2 floor.

The mass of the required Y12 bars is 462kg and the mesh weighs less than 1t. Therefore the total mass of the precast items required is estimated at 164t.

Installation

The installation of the rib-and-block items are also priced separately. Installation of rib-and-block floors is measured in terms of area. 500m^2 of rib-and-block flooring has to be installed.

Edge formwork and topping

An in-situ topping forms part of the rib-and-block floor. The thickness of the topping depends on the size of the blocks used. In order to add the required 60mm topping on the medium sized blocks, 5m^2 of edge formwork is required as well as 30m^3 of 25 MPa concrete.

D.5.2 Quantities

Quantities were calculated following the above procedure for the different span lengths. Note that the maximum span length of the rib-and-block floors is 7.5m and therefore a span of 8m is not listed as an option. Quantities for the remainder of the span lengths are given in Table D.6.

Table D.6: Rib-and-block quantities

Item	**4m Span**	**5m Span**	**6m Span**	**7m Span**
Lintels	940m	940m	960m	945m
Blocks	4500 Small	4500 Medium	4536 Large	4536 Large
Y12 Sag Bars	462kg	462kg	458kg	490kg
Mesh	46 sheets	46 sheets	46 sheets	46 sheets
Total Mass	144t	164t	187t	187t
Installation	500m^2	500m^2	504m^2	504m^2
Edge Formwork	5m^2	6m^2	6m^2	6m^2
Concrete Topping	27.5m^3	30m^3	32.8m^3	32.8m^3

Since both the 6m span option and the 7m span option requires the same block size (large), material quantities for these options are equal. These items are priced to determine the cost of the rib-and-block floor for varying span lengths. Refer to Section D.7.

D.6 Prices of items

As mentioned earlier, material prices of the in-situ items were obtained from quantity surveyors (Du Toit, 2011; Berry, 2011) and prices for the precast elements are obtained from precast manufacturers (Chetty, 2011; Queripel, 2011). All the rates used in this study are listed in Table D.7.

Table D.7: Prices for in-situ and precast items

Type	Item	Unit	Price	Person provided
In-situ items	Concrete for slabs: 25/19	m^3	R900	Du Toit
	Concrete for slabs: 30/19	m^3	R950	
	High tensile reinforcement	t	R8250	
	Mild steel reinforcement	t	R8000	
	Post tensioning, including cables, stressing and anchors	kg	R70	Berry
	Horizontal formwork for slabs with thickness ≤250mm	m^2	R100	Du Toit
	Horizontal formwork for slabs with thickness >250mm	m^2	R110	
	Vertical formwork for slabs	m^2	R60	
Hollowcore floor	Hollowcore panels: 120mm	m^2	R400 – R500	Queripel (prices vary, depending on wiring patterns)
	Hollowcore panels: 150mm	m^2	R430 – R530	
	Hollowcore panels: 200mm	m^2	R510 – R610	
	Hollowcore panels: 250mm	m^2	R550 – R850	
Rib-and-block floor	Lintels	m	R60	Chetty
	Blocks	No.	Small: R9 Medium: R11 Large: R13	
	Y12 sag bars	kg	R10	
	Mesh	No. of sheets	R350	
	Transport	11t	R1166 within 35km	
	Installation	m^2	R100	

D.7 Cost comparison

Using the quantities and prices above, the rate per m^2 for each option was determined for the varying span lengths. Costs are summarized in Table D.8.

Table D.8: Rates for different floor system options

Floor system	4m	5m	6m	7m	8m
Normally reinforced in-situ slab	R 322/m^2	R 358/m^2	R 400/m^2	R 450/m^2	R 506/m^2
Post-tensioned slab	n/a	R 368/m^2	R 404/m^2	R 438/m^2	R 486/m^2
Hollowcore floor	R 425/m^2	R 450/m^2	R 490/m^2	R 550/m^2	R 600/m^2
Rib-and-block floor	R 418/m^2	R 443/m^2	R 475/m^2	R 475/m^2	n/a

Appendix E

COST AND TIME MODEL SCHEME

A Scheme is prepared to allow for a cost comparison between different structural options. This Scheme can be used by a researcher, company or institution that wants to find out how the construction of different types of structures would compare in terms of cost and time.

E.1 Background

Project teams need a decision making tool to decide between precast and in-situ concrete construction for any given project. In order to assist with this decision making process, the costs of the different methods as well as its project durations have to be compared. It is assumed that the site conditions of the project under consideration are suitable for any of the different construction methods.

A cost model study for commercial buildings was published by The Concrete Centre (2007). In the study undertaken in the United Kingdom (UK) by four professional consultants, the construction duration and cost were compared of two different buildings. In this study, different options were investigated for structural floors. Comparisons were drawn between construction programmes, the cost of materials (including finishes) and other project costs. Although the study is based on specific projects, it is a meaningful investigation to provide project teams with an indication of the cost comparison of different structural floor options.

In order to perform a similar study for commercial and multi-storey residential buildings in South Africa, a scheme is proposed here for a cost and time comparison between different concrete construction methods for specific projects. Similarities and differences to methods in the UK are pointed out and structural systems that can be investigated are given. This study can be performed with the assistance of certain professionals mentioned later on.

E.2 Aim

The main objective of this scheme is to compare the cost and time implications of different construction methods on a structural project. Attention is given to the effect of the choice of structural system on the cost of other elements such as cladding, ceiling finishes and staircases. All the costs of the different construction methods, including the impact of the different project programmes are summarized to give the overall project costs. Overall costs of a specific project can be compared for different construction methods. This specific comparison can be taken into consideration in the decision making process of construction methods for any other project and the significance (or insignificance) of the possible savings would be proved by this study.

E.3 Motivation

According to the study carried out in the UK by The Concrete Centre (2007), the relevant structural options lead to overall project cost that vary within 4% between the different options. Some of the methods and factors in South Africa are unlike those in the UK, but the comparison of the overall costs is expected to be in the same order for all the different options. Should it be proved by this scheme that the difference in the overall project cost for different construction methods in South Africa is also relatively small, it can be assumed that the decision making process should depend on factors other than cost.

E.4 Resources

In the UK, the cost model study was carried out by The Concrete Centre (2007) in conjunction with the following team of professionals:

- Allies and Morrison – architectural design
- Arup – structural design
- Davis Langdon LLP – quantity surveying
- Mace – programming

For this study to be performed in South Africa, a team of professionals is also required. Input from professionals is vital for valuable results and it is suggested that the following professionals be involved:

- Project leader – lead the study and make the comparison
- Architect – architectural design
- Precast manufacturer – programming and costing of precast elements
- Structural engineer – structural design
- Contractor – construction programme and constructability
- Quantity surveyor – costing
- Subcontractors – lift manufacturer, plumber, electricians and mechanics

E.5 Input

E.5.1 Structural systems

Structural options in the study undertaken by The Concrete Centre (2007) are listed below.

- Flat slab
- Post tensioned flat slab
- Composite slab
- Steel and hollowcore
- In-situ and hollowcore
- Slimdek
- Post tensioned band beams (long-span)
- Long-span composite

Chapter 3 shows the types of structural systems used in South Africa. It was found that for concrete frames, flat slabs are the floor system that are the most often constructed in South Africa. Post tensioned flat slabs, load bearing bricks with precast floors and steel frames with precast floors are also used. Precast beams are only constructed where it is necessary to reach long spans without temporary support and therefore it is not considered as an option in this study. The same applied to precast columns, which is very rarely constructed in South Africa.

As found in Chapters 2 and 3, the precast floor systems used in South Africa are hollowcore panels and rib-and-block floor systems. Precast applications in South Africa are mostly limited to floor systems. Therefore different support structures are considered with the options being in-situ floors, hollowcore floors and rib-and-block floors. The options are summarized in the figures below. One or more of the different support structures can be considered in the comparison.

- Slabs supported on load bearing brickwork:

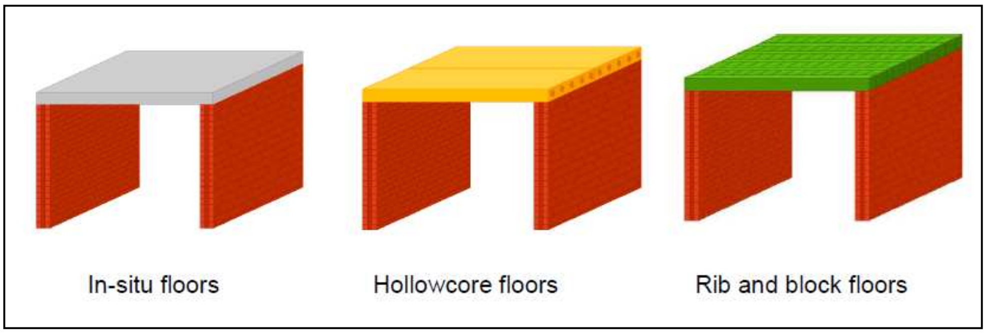


Figure E.1: Load bearing brickwork floor structures

- Slabs supported on concrete frames:

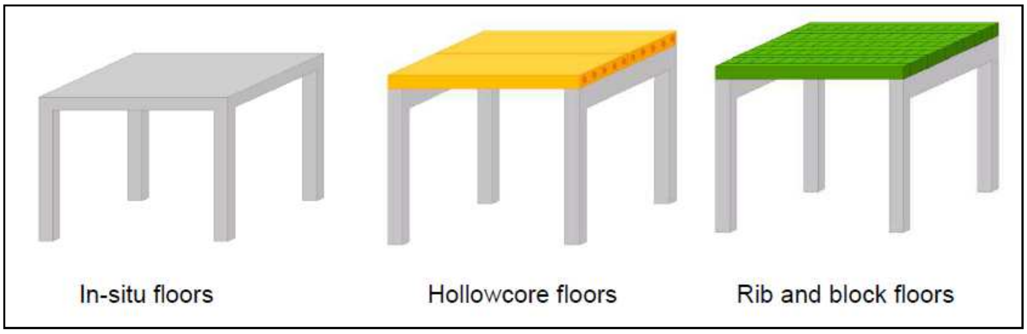


Figure E.2: Floor systems on concrete frames

- Slabs supported on steel frames:

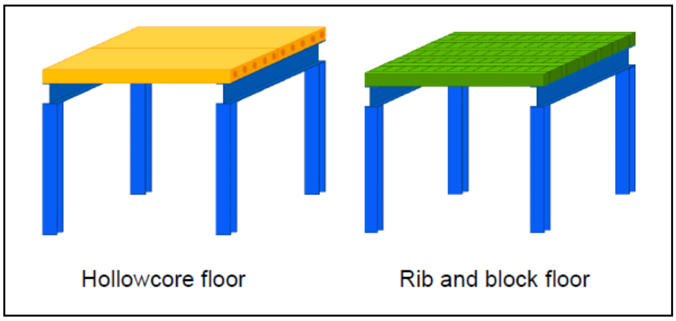


Figure E.3: Floor systems on steel frames

E.5.2 Project and drawings

For the purpose of this study, the choice of the project(s) should be performed by the project leader. The project leader can also require input from the rest of the professional team for a sensible project choice(s). One or more projects can be chosen. Projects should be of a typical nature, such as a typical office block or a typical apartment block. It is recommended that the location of the project be within a 120km radius from a metropolis, where Precast Manufacturers are available and precast elements would typically be considered as a structural option. For a complete study, it is suggested that the areas of study include one project in a big metropolis, such as Johannesburg, one in a medium-sized metropolis, such as Cape Town or Durban and one in a smaller city, such as Bloemfontein or Polokwane.

Two projects were chosen for the study performed by The Concrete Centre (2007). A three-storey office building was selected in an out-of-town business park location in the South East of the UK and also a six-storey office building located in central London.

After the project(s) has been selected, the necessary dimensional requirements have to be specified by the mechanical and electrical engineer before drawings are prepared. The architect is responsible for the architectural layouts, a precast manufacturer provides the layout plans of the precast floor panels and the structural engineer produces the construction drawings.

E.5.3 Project time comparison

Project times for the relevant options investigated by The Concrete Centre (2007) are summarized in their report. A breakdown of the time for the different construction activities is also given in the abovementioned report in the form of Gantt charts.

For a similar study in South Africa, the design time and lead time for manufacturing would not have such a significant effect on a contract or project duration. Unlike in the UK, projects in SA are often of a fast track nature. Construction on site usually runs in parallel with design in the office – for instance the site establishment is performed while the foundations are being designed.

The same applies to precast elements which would not be manufactured before the start of the project and therefore the time of fabrication is not added to the total project time. According to Surridge (2011), a construction site is very rarely or never held up by the manufacturing process of precast elements.

Also, having a smaller industry, precast elements are typically manufactured much faster in the smaller South African market than in the UK. According to Bensalem (2011) hollowcore panels that they manufacture in the UK take 3 to 8 weeks to manufacture and install, depending on their workload. Surridge (2011) indicated that for hollowcore panels manufactured in South Africa, the time required for manufacturing and installation is more or less 2 weeks.

Therefore South African project duration estimations would vary from those in the UK. With the chosen projects for South Africa, a contractor and Precast Manufacturers (of hollowcore and rib-and-block elements) will need to estimate the construction times for the activities.

E.5.4 Costing items

From the construction drawings, the quantity surveyor can obtain quantities and estimate the cost of the necessary items. Subcontractors such as the precast manufacturer, lift manufacturer, plumber, electrician and mechanic would be involved in the pricing of specific items.

Costs of the different items of importance in the study performed by The Concrete Centre (2007) are given as an example below. These items form part of the cost of the frame structure. Basic rates obtained for South African in-situ slabs, hollowcore panels and rib-and-block floors are provided in Table D.5 in Appendix D.

Table E.1: Rates used in the UK comparison (The Concrete Centre, 2007)

Item	Unit	Rate
Concrete in walls	m^3	£125
Concrete in suspended slabs, beams and columns	m^3	£115
Reinforcement	t	£820
Formwork to walls	m^2	£32
Formwork to soffits of suspended slabs	m^2	£31
Formwork to beams and columns	m^2	£42
Hollowcore panels: 150mm deep	m^2	£46
Hollowcore panels: 200mm deep	m^2	£48
Hot rolled steel sections	t	£1390

An example of the different items of the buildings that were considered in the UK comparison and estimated costs for the relevant options is given in Table E.2.

Some of the costs, for instance the cost of the lifts, are the same for any structural floor option, but it is included anyway. The importance of including these costs in the comparison is to develop an estimate of the total sum of the project so that the relevance of each costing item can be appreciated.

Time-related cost (preliminaries and general cost) is included in the list of costs and therefore different construction times would reflect on the cost of each of the options. Contingencies, overheads and profit are also included in the list of costs.

TableE.2: Items contributing to the building cost (The Concrete Centre, 2007)

Item	Flat slab (£)	In-situ + hollowcore (£)	Steel + hollowcore (£)
Substructure	199,480	202,641	195,452
Frame / upper floors	546,827	591,645	643,704
Roof finishes	241,280	241,208	241,208
Stairs	63,000	63,000	63,000
External cladding	1,166,600	1,187,720	1,199,980
Internal cladding	141,230	145,255	156,630
Wall finishes	51,010	49,684	52,240
Ceiling finishes	274,432	274,432	274,432
Fittings	125,308	125,308	125,308
Sanitary	60,000	60,000	60,000
Mechanical	208,890	208,890	208,890
Electrical	1,285,834	1,285,834	650,567
Lifts	70,000	70,000	70,000
BWIC	172,470	172,470	172,470
Contingency	394,658	398,692	406,907
Preliminaries	735,000	755,000	715,000
Overheads and profit	383,505	388,175	392,840
TOTAL	**£6,775,263**	**£6,857,765**	**£6,940,180**

E.6 Factors influencing the model

As mentioned in the report on the study performed by The Concrete Centre (2007), the cost is determined at a specific time. Obviously it is dependent on the economy and inflation. In South Africa, the cost of precast elements could be up to three times more expensive in times of high construction activity than what the same elements would cost in times of little construction activity (Anonymous supplier).

Furthermore, material prices are likely to fluctuate, for instance the price of reinforcement almost doubled from 2007 to 2008 and in 2010 it was almost back where it was in 2007. These fluctuations are not possible to estimate and therefore this model may be very time specific.

E.7 Implementation

A table of the responsibilities to perform a cost comparison is given in Table E.3 below:

Table E.3: Scheme task division

Discipline	**Task(s)**
Project manager	Choose type, size and location of building Final comparisons of alternatives
Architect	Architectural design Layout planning
Structural engineer	Layout planning Structural design
Precast manufacturer	Layout planning Programming Costing
Subcontractors	Layout planning Programming Costing
Contractor	Programming and conceptual layout (for constructability)
Quantity surveyor	Quantifying and costing

Appendix F

LIFETIME COST COMPARISON

F.1 Project details

As an example, the lifetime cost of an in-situ construction project is compared to that of a HCC project to demonstrate the effect of construction period on the total life time project costs. The design time and cost is assumed to be equal for the two projects. Also, the construction and maintenance cost of the two structures are assumed to be equal. The only difference in the lifetime of the projects in this example, is the construction duration. The required yearly income (at the start of the use phase of the building) that is required for breakeven is determined for both projects. In this example the following fictional values are used:

- Construction cost is R80,000,000 (paid in equal monthly instalments over project duration) for the material;
- Construction project running cost is an additional R1,000,000 per month (this is more or less 25% of the total construction cost, which may be unrealistically high; a case where the project running cost is more or less 10% of the total construction cost is considered later in this Appendix)
- Construction duration of in-situ construction project: 24 months
- Construction duration of HCC project: 22 months
- Maintenance of structure: R20,000 per year and an additional R50,000 every fifth year
- Monthly interest rate over the lifetime: 1%
- Use phase of structure: 20 years
- Yearly income increase with 15% every fifth year

Based on Figure 16, Figures F.1 and F.2 graphically present the times and values of the two projects. Equation 1 is used to determine the present values of the two projects.

F.2 In-situ project lifetime cost calculation

Based on Figure 16, Figure F.1 graphically presents the times and values of the income and expenses during the lifetime of the project, except for the expenses during the design phase. Equation 1 is used to determine the present values of the construction cost, maintenance cost and income.

The monthly payments to the contractor is R80,000,000/24 +R1,000,000 = R4,333,333. The yearly income increases after every 5 years by 15%, therefore if it is x in the first 5 years, it is 1.15x in years 6 to 10, 1.3225x in years 11 to 15 and 1.5209x in years 16 to 20.

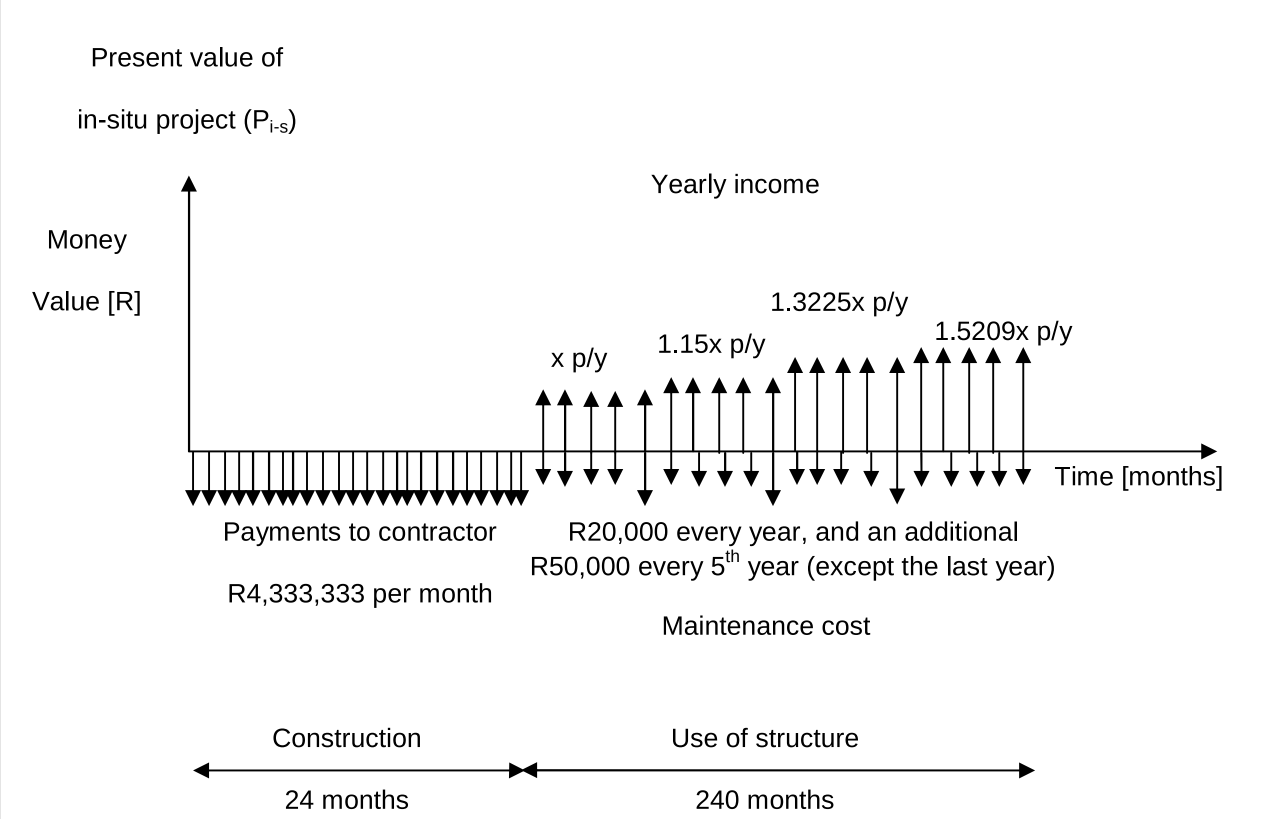


Figure F.1: Schematic presentation of an example in-situ project (excluding the planning phase)

The present value of the construction cost (P_c) is as follows:

$$P_c = A\left[\frac{(1+i)^n - 1}{i\,(1+i)^n}\right] = -4{,}333{,}333\left[\frac{(1+0.01)^{24} - 1}{0.01\,(1+0.01)^{24}}\right] = \mathbf{-R92{,}054{,}671}$$

The present value of the maintenance cost after the first year of usage (P_{m1}) is as follows:

$$P_{m1} = F\left[\frac{1}{(1+i)^n}\right] = -20{,}000\left[\frac{1}{(1+0.01)^{36}}\right] = -R13{,}978$$

The present value of all 20 years' maintenance is calculated similarly and the total figure is:

$$\mathbf{P_{m(total)} = -R156{,}585}$$

Similar to the calculation of the maintenance cost, the present value of the income for the first year of use of the structure (P_{i1}) is:

$$P_{i1} = F\left[\frac{1}{(1+i)^n}\right] = x\left[\frac{1}{(1+0.01)^{36}}\right] = 0.6989x$$

The present value of all 20 years' income is: $\mathbf{P_{i(total)} = 6.3856x}$

The required yearly income (x) for breakeven of the in-situ project is:

x = R14,440,571

F.3 Hybrid concrete construction project lifetime cost calculation

Similar to the in-situ project, the income and expenses in the lifetime of the HCC project is presented in Figure F.2. Monthly payments to the contractor for the HCC project during the construction phase are R80,000,000/22 + R1,000,000 = R4,636364. The values of the yearly income and maintenance in the use phase of the structure are the same than that of the in-situ project. However, the use phase of the HCC project starts 2 months earlier than that of the in-situ project due to less construction time for the HCC project.

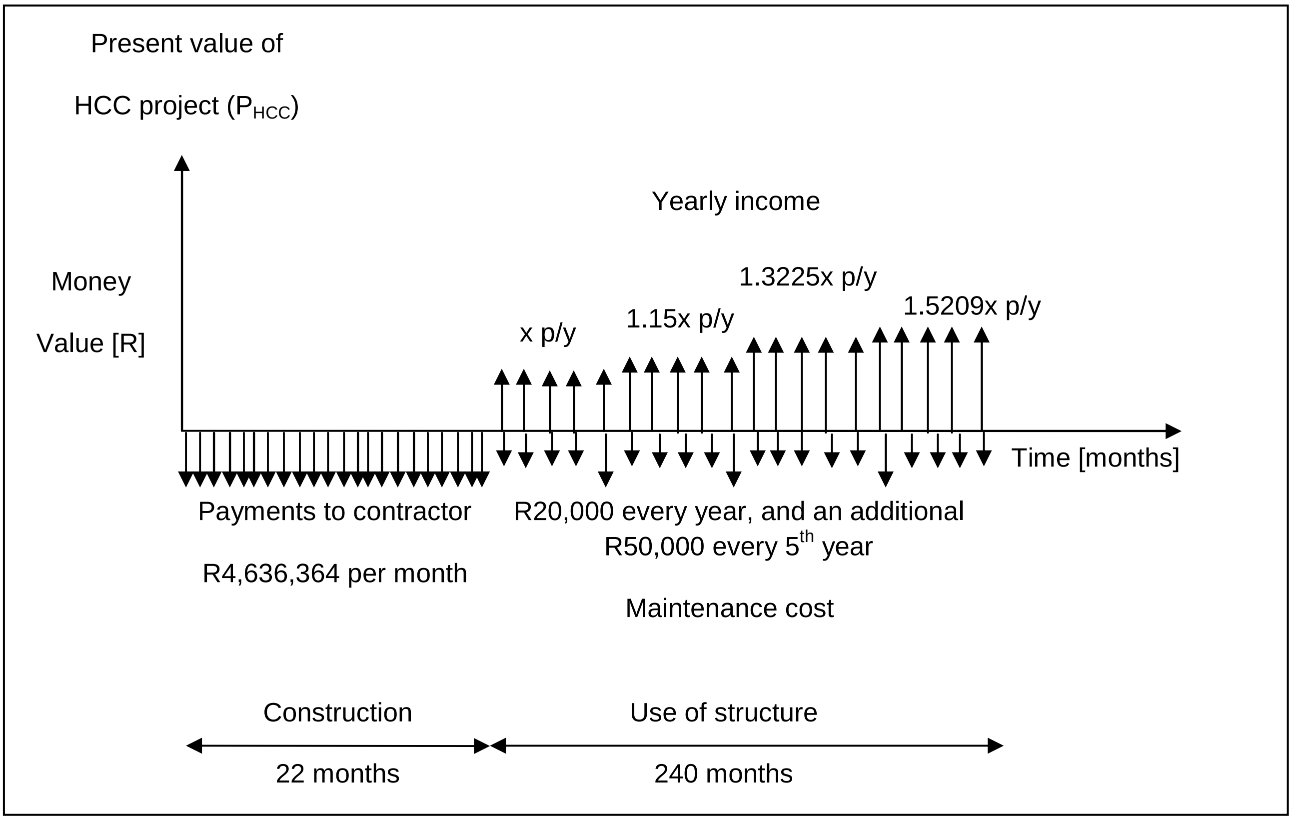


Figure F.2: Schematic presentation of lifetime cost of example HCC project (excluding the planning phase)

The total required yearly income (x) for the HCC project is calculated similarly to that of the in-situ project. This income for the HCC project is **x = R14,018,046**, which is less than the required yearly income for the in-situ project.

F.4 Comparison of required income for in-situ project and hybrid concrete construction project

For the in-situ project, a yearly income of R14,440,571 is required at the start of the use phase in order to breakeven. This income required for the HCC project is only R14,018,046. For the HCC project, yearly income of R422,525 less than the in-situ project is required for breakeven of the present project value. This is a difference of 3% in the yearly income at the start of the use phase.

F.5 Sensitivity of the comparison

The sensitivity of the comparison is tested by using a lower (more realistic) project running cost of R350,000 per month. This adds up to more or less 10% of the construction project cost. Other values are the same as for the previous calculation.

Results are as follows: for the in-situ project, a yearly income of R12,278,165 is required at the start of the use phase in order to breakeven. This income required for the HCC project is only R12,056,208. For the HCC project, yearly income of R221,957 less than the in-situ project is required for breakeven of the present project value. This is a difference of 2% in the yearly income at the start of the use phase.

Therefore, if the project running cost in this example is 10% of the total project cost, instead of 25% of the total construction cost, the required yearly income of the HCC project is 2% (instead of 3%) lower than that of the in-situ project for break even.

By adjusting different parameters of this comparison in a further study, the sensitivity of the comparison to each parameter can be determined.

Appendix G

CONCRETE CONSTRUCTION TOLERANCE SPECIFICATIONS

G.1 South African Standard

Table G.1: Geometric tolerances for South African concrete work (Table 11, SANS 2001-CC1:2007)

Elements or components above foundations	Permissible deviation [mm]		
	Degree of accuracy		
	III	II	I
1a) Position on plan of any edge or surface measured from the nearest grid line or agreed centre line	± 25	± 15	± 5
1b) Linear (other than cross-sectional) dimensions	± 30	± 20	± 10
2) Cross-sectional dimensions	+20, -10	+15, -5	+5, -5
3) Level (deviation from designated level with reference to the nearest transferred datum (TD) of the upper or lower surface, as might be specified, of any slab of other element or component)	+10, -20	+5, -15	0, -10
4) Verticality, per meter of height,	5	5	5
subject to a maximum of	70	50	30
5) Out-of-squareness of a corner or opening or element such as a column for short side length			
a) ≤ 0.5m	±10	±5	±3
b) >0.5m, ≤ 2m	±20	±15	±10
c) > 2m, ≤ 4m	±25	±20	±15
6) Exposed concrete surfaces:			
a) Flatness of plane surface	10	5	3
b) Abrupt changes in a continuous surface	10	5	2
7) Exposed concrete surface to be plastered:			
a) Flatness of plane surface	15	10	Not
b) Abrupt changes in a continuous surface	10	5	Stated

G.2 European Standard

Table G.2: European Class 1 geometric tolerances (ENV 13670-1:2000)

Type of deviation	Where	Permitted deviation
1a) Straightness of beams in plan		The larger of: L/600 or 20mm
1b) Distance between adjacent beams		The larger of L/500 or 15mm, but not more than 40mm
2) Cross sectional dimensions with cross-sectional dimension d	d < 150mm	±10mm
	d = 400mm	±15mm
	d > 2500mm	±30mm
3a) Levels of adjacent floors at supports		±15mm
3b) Level of adjacent beams		±(10 ± L/500)mm
3c) Level of upper floor	H ≤ 20m	±20
	20 < H < 100m	+5(H+20)
	H ≥ 100m	±0.2(H+200)
4a) Inclination of a column at any level		The larger of h/300 or 15mm
4b) Total inclination for n storeys	n > 1	50mm or $\Sigma h/(200n^{1/2})$
4c) Curvature of column		The larger of h/300 or 15mm
5a) Deviation between centre lines for columns and walls	t is the column or wall width	The larger of t/30 or 15mm
6) Flatness of moulded / smooth surface		
a) Global	L = 2m	9mm
b) Local	L = 0.2m	4mm
7) Flatness of rough surface		
a) Global	L = 2m	15mm
b) Local	L = 0.2m	6mm

G.3 Comparison of applicable tolerance specifications

In order to see how the South African Standard compares to the European Standard, the allowable tolerances for typical elements according to these two Standards are compared in Table G.3. The degree or class that normally applies in general construction is given as the specification in this example. This is Degree of Accuracy 2 for South African projects and Class 1 Tolerances for European projects.

Table G.3: Example comparison of tolerance specification in SANS 2001-CC1:2007 and ENV 13670-1:2000

Deviation	**SANS 2001 Degree 2 specification**	**ENV 13670 Class 1 specification**	**Conclusions on how SANS compare to ENV in this example**
1a) Beam edge along length of a 6m beam 1b) Linear distance between adjacent beams spaced 7m	15mm 15mm	20mm 15mm	More conservative Similar
2) Depth of a 600mm deep beam	+15mm, -5mm	±15mm	More conservative
3) Levels of adjacent floors with floor-to-floor distance 3300m,	+5mm, -15mm	±15mm	More conservative
4) Inclination of a 3m column	15mm	15mm	Similar
5) Deviation between consecutive columns of dimension 300x300mm	±5mm	15mm	More conservative
6) Local flatness of exposed floor surface	5mm	4mm	Comparable
7) Global flatness of unfinished floor surface	10mm	15mm	More conservative

From the conclusions in the Table above, it is clear that the South African Standard (SANS 2001-CC1:2007) is comparable to the European Standard (ENV 13670-1:2000) and is even in some cases more conservative than the European Standard.

Appendix H

INTERNATIONAL LABOUR PRODUCTIVITY INDICES

Table H.1: International labour productivity indices (rounded to nearest 1000) according to World Bank statistics (2011)

Country	Labour productivity index in 2008
Australia	50,000
Argentina	28,000
Bahrain	14,000
Belgium	55,000
Brazil	13,000
Canada	49,000
Chile	30,000
China	10,000
Croatia	24,000
Denmark	46,000
Egypt	13,000
Finland	51,000
Germany	43,000
India	7,000
Italy	46,000
Japan	46,000
Malaysia	26,000
The Netherlands	47,000
Norway	52,000
Portugal	30,000
South Africa	12,000
Sweden	50,000
Switzerland	43,000
United Arab Emirates	21,000
United Kingdom	52,000
United States of America	65,000
Zimbabwe	2,000

Appendix I

MATERIAL INPUT CALCULATIONS

Material input for the different construction methods are determined and summarized in Table F.3. Designs are obtained from Appendix D, where different floor options were designed for the purpose of a cost comparison. The floors have different span lengths with a live load of 2.5kPa. One-way span is used for a fair comparison.

I.1 Normally reinforced in-situ floor

For the in-situ slab, quantities of materials are obtained from Appendix D. These quantities are for the total floor area. In Table I.1 below the quantities per square meter of floor area are determined.

Table I.1: Normally reinforced in-situ slab quantities

Span (m)	Floor area (m^2)	Concrete (m^3)	Concrete (m^3/m^2)	Steel reinforcing (t)	Steel reinforcing (kg/m^2)
4	500	85.0	0.170	0.014 + 3.924	7.876
5	500	100.0	0.200	0.017 + 4.449	8.932
6	504	115.9	0.230	0.014 + 5.358	10.659
7	504	136.1	0.270	0.033 + 5.573	11.123
8	504	151.2	0.300	0.033 + 7.257	14.464

I.2 Post tensioned floor

The mass of the post tensioned tendons is 1.2kg/m. Therefore its weight is obtained by multiplying the length of tendons required by 1.2. Furthermore, the weight of anchors are assumed to be 2.1kg, which includes a plate with a mass of 1.5kg, a nut with a mass of 0.22kg and a coupler with a mass of 0.34kg (Thread bar 950, 2011). Quantities for the post tensioned floors are given in Table I.2.

Table I.2: Post tensioned floor quantities

Span (m)	Floor area (m^2)	Concrete (m^3)	Concrete (m^3/m^2)	Steel reinforcing (t)	Steel (kg/m^2)
5	500	75.0	0.150	0.017 + 3.128 + 0.605 + 0.088	7.676
6	504	90.7	0.180	0.014 + 3.590 + 0.605 + 0.084	8.518
7	504	100.8	0.200	0.022 + 3.421 + 0.756 + 0.126	8.581
8	504	115.9	0.230	0.019 + 4.064 + 0.835 + 0.121	9.998

I.3 Hollowcore floor

The panels chosen for the design in Appendix D are given in Table I.3. The material for this option is also calculated per square meter of floor area in this table.

Concrete material for the hollowcore panels is calculated by using the manufacturer's specification for the area of the cross section of the panels. This area is multiplied with the length to obtain the volume of concrete.

The mass of the steel reinforcing is calculated by assuming a volumetric mass of 7800kg/m^3.

Table I.3: Hollowcore floor quantities

Span (m)	Panel depth (mm)	Area of 1.2m panel (m^2)	Concrete without 50mm screed (m^3/m^2)	Concrete with 50mm screed (m^3/m^2)	Wiring in 1.2m panel	Steel reinforcing (kg/m^2)
4	120	0.108507	0.090	0.140	12 x 5mm wires	1.532
5	150	0.124674	0.104	0.154	12 x 5mm wires	1.532
6	150	0.124674	0.104	0.154	7 x 5mm wires and 5 x 9.53mm strand	2.540
7	200	0.148970	0.124	0.174	9 x 5mm wires and 3 x 9.53mm strand	3.212
8	200	0.148970	0.124	0.174	12 x 9.53mm strand	5.564

I.4 Material Input

The material input of the in-situ floor in Table I.1, of the post-tensioned floor in Table I.2 and of the hollowcore floor in Table I.3 is summarized in Table I.4 below.

Table I.4: Material input comparison

Span (m)	In-situ		Post tensioned		Hollowcore		
	Concrete (m^3/m^2)	Steel (kg/m^2)	Concrete (m^3/m^2)	Steel (kg/m^2)	Concrete without 50mm screed (m^3/m^2)	Concrete with 50mm screed (m^3/m^2)	Steel (kg/m^2)
4	0.170	7.876	n/a	n/a	0.090	0.140	1.532
5	0.200	8.932	0.150	7.676	0.104	0.154	1.532
6	0.230	10.659	0.180	8.518	0.104	0.154	2.540
7	0.270	11.123	0.200	8.581	0.124	0.174	3.212
8	0.300	14.464	0.230	9.998	0.124	0.174	5.564