

Identifying opportunities for leveraging industry 4.0 technology in petrochemical engineering, procurement, and construction projects in South Africa

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Mini-dissertation accepted in partial fulfilment of the requirements for the degree [Master of Business Administration](#) at the North-West University

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Graduation: June 2023

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ABSTRACT

Engineering, procurement and construction projects (EPC) are notorious for cost and schedule overruns. With the declining profit pool of the petrochemical industry in South Africa, EPC contractors need to answer the call to reduce the capital expenditure of petrochemical plants by increasing the efficiency of capital project execution.

The manufacturing sector enjoyed high productivity gains with the introduction of Industry 4.0 in the German public-private sector. On the contrary, the construction sector saw marginal increases in productivity, which is partly the effect of the delayed adoption of technology. This study aimed to identify opportunities to leverage Industry 4.0 technology against the challenges faced by the petrochemical EPC sector in South Africa.

The study's primary objective was to derive a theoretical framework for leveraging Industry 4.0 technology to address challenges in the South African petrochemical EPC sector that result in cost and schedule overruns in EPC projects. To derive the framework, the study consulted the literature available to identify recurring challenge themes faced in engineering and construction projects. As a secondary objective, causation research was conducted to determine the factors that influenced the recurring themes. The literature was further reviewed to uncover the potential applications of Industry 4.0 technology in EPC projects.

To validate the challenge themes and to identify additional challenges true to the geographic demarcation, the researcher conducted semi-structured interviews with experienced project professionals within the petrochemical EPC sector in South Africa. The challenge themes were validated, and as secondary objectives, the current state of digitalisation and the perceived barriers to technological innovation within the petrochemical EPC sector in South Africa were determined.

The study finds that the challenges faced by the petrochemical EPC sector in South Africa are fundamentally the result of poor communication through the various and complex interfaces in the project functions. A framework is presented wherein increased collaboration between project stakeholders is promoted, and communication is enhanced by leveraging Industry 4.0 technologies. Building Information Modeling (BIM) is deemed the technology that would form the foundation of the technological shift of the petrochemical EPC sector in South Africa. It is proposed that BIM strategies be developed in close collaboration with the owners of petrochemical plants in South Africa to achieve standardisation in implementing BIM throughout the South African EPC sector.

Addressing the challenges faced in the South African EPC sector will not be possible with technology as the only change source. The author notes that even though the findings show enormous potential within Industry 4.0 technology, a parallel cultural shift is required among project stakeholders to create an EPC environment characterised by trust and transparency. Therefore, an integrated approach to project delivery is implemented as part of the framework, which promotes contractual agreements that reward project stakeholders for achieving their shared objectives, is characterised by shared risk rather than shifted risk, and promotes collaboration between project parties.

Charles Darwin famously said: "It is neither the strongest, nor the most intelligent of a species that survives, but the one that is most adaptable to changes". The South African petrochemical EPC industry is changing, and EPC contractors need to answer the call to reduce the capital expenditure of petrochemical plants.

Key words: Petrochemical, EPC, Industry 4.0, Building Information Modeling, Internet of Things, Integrated project delivery, Virtual reality, Augmented reality, Big Data, Blockchain

ACKNOWLEDGEMENTS

I would like to thank everyone that had a part in supporting me through these two years of growth and challenges. I wouldn't have been able to do it without your support.

Thank you to each participant of this study for being willing to share your experience and time with me.

To my study leader, Prof. Leenta Grobler, thank you for your patience, your support, and your advice. Without your guidance, the completion of the study wouldn't have been possible.

Recce and Mia, thank you for keeping me awake with your snoring in your bed behind me through the long nights of working on this study.

To my family and my in-laws, thank you for every message of encouragement and for the support to both me and Michelle during these two years.

To my mother and father: Thank you for making me who I am. Thank you for always being there to support me, thank you for believing in me and thank you for always keeping me in your prayers.

To my wife, Michelle: you are my home, my place of happiness and the source that drives me to be better each day. Thank you for your unconditional love and support. Thank you for all the wisdom during this time and sacrificing so much to make this as easy as possible for me. You are my rock and I love you.

I would like to thank the Lord for answering my prayers and giving me the opportunity to enrich my life through this process, for giving me the talents, strength, and endurance to complete this process and for blessing me with grace throughout.

TABLE OF CONTENTS

ABSTRACT	I
ACKNOWLEDGEMENTS	III
CHAPTER 1 NATURE AND SCOPE OF STUDY	1
1.1 Introduction	1
1.2 Problem statement	4
1.3 Research objectives	5
1.3.1 Primary objective	5
1.3.2 Secondary objectives.....	5
1.4 Contribution of the study	5
1.4.1 Theoretical contribution	5
1.4.2 Practical contribution	6
1.5 Scope of the study.....	6
1.5.1 Field of study	6
1.5.2 Industry under investigation	6
1.5.3 Geographical demarcation.....	6
1.6 Limitations of the study	6
1.7 Layout of the study.....	7
1.7.1 Chapter 1.....	7
1.7.2 Chapter 2.....	7
1.7.3 Chapter 3.....	8
1.7.4 Chapter 4.....	8

1.7.5	Chapter 5.....	8
1.7.6	Chapter 6.....	8
CHAPTER 2 LITERATURE REVIEW.....		9
2.1	Introduction	9
2.2	EPC projects	9
2.2.1	Context of the EPC industry.....	10
2.2.2	The soft root cause for the underperforming EPC business	12
2.2.2.1	Poor performance in the execution of projects	12
2.2.2.2	Poor productivity growth compared to other industries and sectors	14
2.2.2.3	Delayed adoption of digitalisation	15
2.2.3	Global repetitive challenges resulting in delays and cost overruns.....	16
2.2.3.1	Changes in project scope	18
2.2.3.2	Design errors and discrepancies in design documents	20
2.2.3.3	Poor interface management and communication	21
2.2.3.4	Construction material delays.....	22
2.2.3.5	Poor productivity of construction labour	23
2.2.3.6	Delays in decision making and approvals by the owner	24
2.2.3.7	Poor planning and scheduling.....	26
2.2.3.8	Delays in multi-discipline engineering design.....	29
2.2.3.9	Rework	29
2.3	Uncovering the potential of Industry 4.0 technology	31
2.3.1	Digitalisation of EPC projects.....	33

2.3.1.1	The internet of things and industrial internet of things	35
2.3.1.2	Building information modelling	36
2.3.1.3	Big data, cloud analytics and smart sensors	42
2.3.1.4	Machine learning	43
2.3.1.5	Autonomous things and hyper automation.....	44
2.3.1.6	Extended reality	46
2.3.1.7	Blockchain	47
2.3.2	Partnering and integrated project delivery.....	48
2.3.3	Integrated supply chains.....	49
CHAPTER 3 RESEARCH METHODOLOGY		50
3.1	Empirical study.....	50
3.1.1	Research paradigm (Figure 3-1, Layer 1)	51
3.1.2	Research approach (Figure 3-1, Layer 2)	51
3.1.3	Methodological choice (Figure 3-1, layer 3)	51
3.1.4	Research strategy (Figure 3-1, layer 4)	52
3.1.5	Time horizon (Figure 3-1, layer 5).....	52
3.1.6	Study population and sampling (Figure 3-1, layer 6).....	52
3.1.7	Designing the measuring instrument (Figure 3-1, layer 6).....	53
3.1.8	Collection of data (Figure 3-1, layer 6).....	53
3.1.9	Statistical analysis (Figure 3-1, layer 6)	54
3.1.10	Reliability and validity	54
CHAPTER 4 DATA ANALYSIS		56

4.1	INTRODUCTION	56
4.2	DEMOGRAPHIC DESCRIPTION	56
4.2.1	Highest academic qualification of participants	56
4.2.2	Years of experience in the South African petrochemical EPC sector	56
4.2.3	Roles of participants in the South African petrochemical EPC sector.....	57
4.3	THE CURRENT CHALLENGES FACED IN SOUTH AFRICAN PETROCHEMICAL EPC PROJECTS	58
4.3.1	Introduction.....	58
4.3.2	Challenges faced during the engineering design phase.....	58
4.3.3	Challenges faced during the procurement phase.....	59
4.3.4	Challenges faced during the construction phase.....	60
4.3.5	Validation of Table 2-1 in the South African context.....	61
4.3.6	Discussion of findings	62
4.3.6.1	Engineering phase.....	62
4.3.6.2	Procurement phase	62
4.3.6.3	Construction phase.....	63
4.4	CURRENT STATUS OF DIGITALISATION WITHIN THE PARTICIPANTS' EPC ENVIRONMENTS	64
4.4.1	Information flow and communication systems.....	64
4.4.2	Supply chain and procurement automation.....	65
4.4.3	Data capturing and analytical usage of captured data.....	66
4.4.4	Discussion of findings	67
4.4.4.1	Information flow	67

4.4.4.2	Procurement.....	68
4.4.4.3	Data capturing and analytics.....	68
4.5	PERCEIVED BARRIERS OF TECHNOLOGICAL IMPLEMENTATION.....	68
CHAPTER 5	THEORETICAL FRAMEWORK	70
5.1	INTRODUCTION	70
5.2	IMPLEMENTING 4IR TECHNOLOGY TO ADDRESS IDENTIFIED CHALLENGES.....	71
5.2.1	Changes in project scope	71
5.2.2	Design errors and discrepancies in design documents	73
5.2.3	Poor interface management and communication	75
5.2.4	Construction material delays.....	77
5.2.5	Poor productivity of construction labour	78
5.2.6	Delays in decision making and approvals by the owner	80
5.2.7	Poor planning and scheduling.....	82
5.2.8	Delays in multi-discipline engineering design.....	83
5.2.9	Rework	84
5.3	4IR TECHNOLOGIES AND THEIR POTENTIAL VALUE	86
5.4	IDENTIFIED CONNECTIONS BETWEEN THE PROBLEMS FACED AND THEIR FACTORS OF INFLUENCE	87
5.5	INTRODUCTION OF A THEORETICAL FRAMEWORK OF 4IR TECHNOLOGY IMPLEMENTATION	88
5.5.1	Horizontal integration of project stakeholders	89
5.5.2	Vertical networking partnerships	90

5.5.3	Segment integration.....	90
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS		92
6.1	INTRODUCTION	92
6.2	EVALUATION OF STUDY OBJECTIVES	92
6.2.1	Primary objective	92
6.2.2	Secondary objectives.....	92
6.3	MANAGERIAL IMPLICATIONS OF THE STUDY	93
6.4	OVERALL STUDY LIMITATIONS.....	94
6.5	OPPORTUNITIES FOR FUTURE RESEARCH.....	95
6.6	CONCLUSION	95
BIBLIOGRAPHY.....		96
ANNEXURE A		112
ANNEXURE B		115

LIST OF TABLES

Table 2-1: Repetitive problems in EPC projects worldwide	17
Table 2-2: Summary of the causes of project scope changes.....	18
Table 2-3: Summary of the causes of design errors	20
Table 2-4: Summary of the factors influencing interface management.....	22
Table 2-5: Summary of the factors influencing construction material delays	23
Table 2-6: Summary of the factors influencing construction labour productivity	24
Table 2-7: Summary of the factors influencing decision making	26
Table 2-8: Summary of the factors influencing project planning and scheduling	28
Table 2-9: Summary of the factors influencing rework	30
Table 2-10: The five common practices of successful digitalisation implementation	34
Table 2-11: BIM applications that could be applied to petrochemical EPC projects	37
Table 2-12: Machine learning applications on construction projects	43
Table 2-13: Autonomous things in construction projects.....	46
Table 2-13: Autonomous things in construction projects.....	47
Table 4-1: Challenges faced in the engineering phase	58
Table 4-2: Frequency statistics of challenges faced in the engineering phase.....	58
Table 4-3: Challenges faced in the procurement phase.....	59
Table 4-4: Frequency statistics of challenges faced in the procurement phase	59
Table 4-5: Challenges faced in the construction phase	60
Table 4-6: Frequency statistics of challenges faced in the construction phase	61
Table 4-7: Rating system of digitalised information flow	64

Table 4-8: Ratings of digitalised information flow	64
Table 4-9: Frequency statistics of identified digitalised information flow ratings	64
Table 4-10: Rating system of digitalised procurement	65
Table 4-11: Ratings of digitalised procurement.....	65
Table 4-12: Frequency statistics of identified digitalised procurement ratings	66
Table 4-13: Rating system of data capturing and analytics	66
Table 4-14: Ratings of digitalised information flow	66
Table 4-15: Frequency statistics of identified data capturing ratings	67
Table 5-1: 4IR opportunities for addressing changes in project scope	71
Table 5-2: 4IR opportunities for addressing design errors	73
Table 5-3: 4IR opportunities for addressing poor interface management and communication .	75
Table 5-4: 4IR opportunities for addressing construction material delays	77
Table 5-5: 4IR opportunities for addressing poor productivity of construction labour	78
Table 5-6: 4IR opportunities for addressing delays in decision making and approvals.....	80
Table 5-7: 4IR opportunities for addressing poor planning and scheduling	82
Table 5-8: 4IR opportunities for addressing delays in multi-discipline engineering design	83
Table 5-9: 4IR opportunities for addressing rework	84
Table 5-10: Opportunities for a 4D BIM-based application for project quality management	85
Table 5-10: Potential benefit ratings of 4IR technologies	86

LIST OF FIGURES

Figure 1-1: International Energy Outlook 2021 primary energy consumption.....	1
Figure 1-2: Muted recovery scenario of the petrochemical value pool	2
Figure 1-3: Cost and schedule overruns occurred on EPC projects.....	3
Figure 1-4: Schematic layout of the study.....	7
Figure 2-1: Typical key roles in large capital projects	10
Figure 2-2: Typical lifecycle for a construction project	10
Figure 2-3: Oil price data from 1970 to March 2022.....	11
Figure 2-4: Capex of top 100 Oil & Gas Companies & Brent, USDBN (LHS), USD/bbl (RHS) .	12
Figure 2-5: Historical performance for projects with budgets >US\$1 billion	13
Figure 2-6: Global labour-productivity growth per sector.....	15
Figure 2-7: 4IR technology applications to supply chain proximity	49
Figure 3-1: The research onion model derived for this study	50
Figure 4-1: Highest academic qualifications of participants	56
Figure 4-2: Participants' experience in the petrochemical EPC sector	57
Figure 4-3: Participants' roles in the petrochemical EPC sector.....	57
Figure 4-4: Frequency statistics of challenges faced in the engineering phase.....	59
Figure 4-5: Frequency statistics of challenges faced in the procurement phase	60
Figure 4-6: Frequency statistics of challenges faced in the construction phase	61
Figure 4-7: Frequency statistics of identified digitalised information flow ratings.....	65
Figure 4-8: Frequency statistics of identified digitalised procurement ratings.....	66
Figure 4-9: Frequency statistics of identified data capturing ratings.....	67

Figure 4-10: Five stages of adoption	69
Figure 5-1: Framework methodology	70
Figure 5-2: The Macleamy curve	72
Figure 5-3: 4IR opportunities for addressing changes in project scope.....	73
Figure 5-4: 4IR opportunities for addressing design errors	75
Figure 5-5: 4IR opportunities for addressing poor interface management and communication	76
Figure 5-6: 4IR opportunities for addressing construction material delays	78
Figure 5-7: 4IR opportunities for addressing poor productivity of construction labour	80
Figure 5-8: 4IR opportunities for addressing delays in decision making and approvals	82
Figure 5-9: 4IR opportunities for addressing poor planning and scheduling.....	83
Figure 5-10: 4IR opportunities for addressing delays in multi-discipline engineering design	84
Figure 5-11: 4IR opportunities for addressing rework	86
Figure 5-12: 4IR opportunities for addressing rework	87
Figure 5-13: Influential connections between the identified challenges.....	88
Figure 5-14: Proposed 4IR enabled EPC framework.....	89

KEY TERM DEFINITIONS

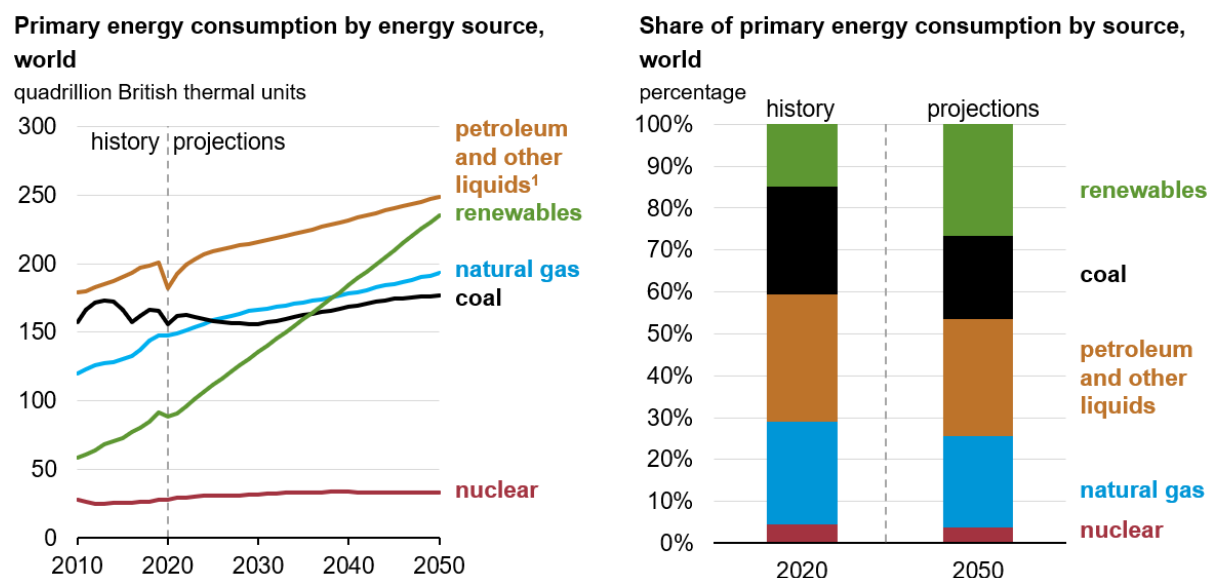
Term	Definition
4IR	Industry 4.0, also referred to the fourth industrial revolution
AEC	Architecture, engineering and construction
AI	Artificial intelligence
AR	Augmented reality
AuT	Autonomous things
BIM	Building information modeling
CPM	Critical path method
EPC	Engineering, procurement and construction
EPCM	Engineering, procurement and construction management
EU	European Union
ICT	Information and communication technology
IIoT	Industrial internet of things
IoT	Internet of things
IPD	Integrated project delivery
IT	Information technology
ML	Machine learning
R&D	Research and development
RPA	Robotic process automation
US	United States of America
VR	Virtual reality
XR	Extended Reality

CHAPTER 1 NATURE AND SCOPE OF STUDY

1.1 Introduction

The International Energy Outlook 2021 (IEO, 2021:4) projections show that the world will continue to rely on petroleum and liquid fuels as its largest energy source until at least 2050. A 29% rise in liquid fuels consumption demand is projected from 2021 to 2050 (IEO, 2021:4), which will require existing petrochemical operations to develop sustainable strategies to undergo emission reduction whilst maintaining economic growth (Chou *et al.*, 2019:11). Figure 1-1 below is a graphical representation of the worldwide primary energy consumption by energy source and the share of primary energy consumption by source according to the International Energy Outlook 2021 (IEO, 2021:4):

Figure 1-1: International Energy Outlook 2021 primary energy consumption

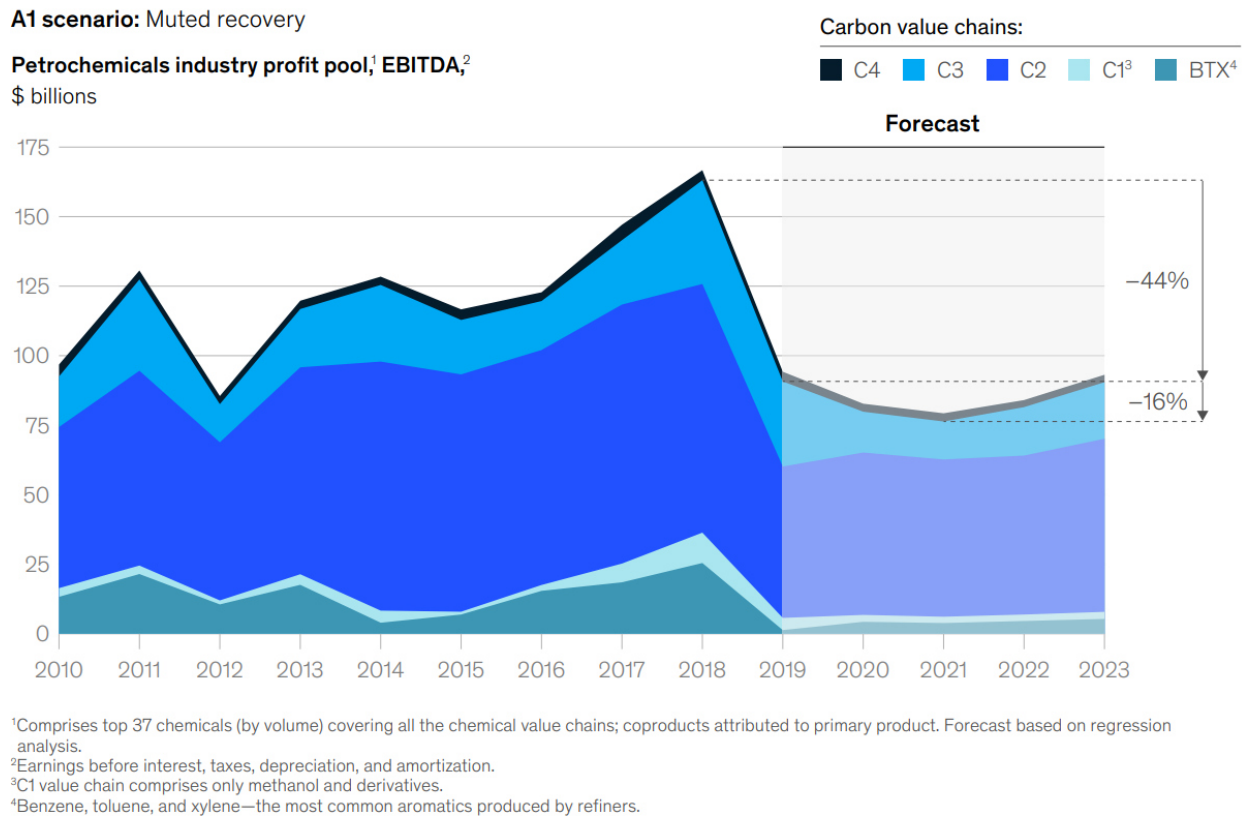


Source: IEO (2021:4)

The profitability of operations in the petrochemical, energy and associated industries have been severely impacted by the financial crisis of 2008 and the oil price crash of 2014 (Wagner, 2020:2245). More recently, the Covid 19 pandemic hit the world like a storm in 2020 and impacted every economic sector (Norouzi, 2021:14338). Global petrochemical market prices declined in tandem with crude oil, the primary raw material of the petrochemical industry (Saputera *et al.*, 2020:1354). The World Energy Outlook's net-zero emissions scenario as proposed in Cozzi *et al.* (2020:8) and the increase in emission regulations worldwide will put further pressure on the profitability of petrochemical operations. Subsequently, the engineering, procurement, and construction (EPC) business built on the investments of the petrochemical industry will be

influenced (Wagner, 2020:2245). Due to the effect of the Covid-19 pandemic on the economic demand for the petrochemical industry, Malik *et al.* (2020:5) posed a muted recovery scenario where the Covid-19 pandemic led to a negative impact of 16% on the petrochemical value pool that will not be recovered until 2023 (refer to Figure 1-2).

Figure 1-2: Muted recovery scenario of the petrochemical value pool



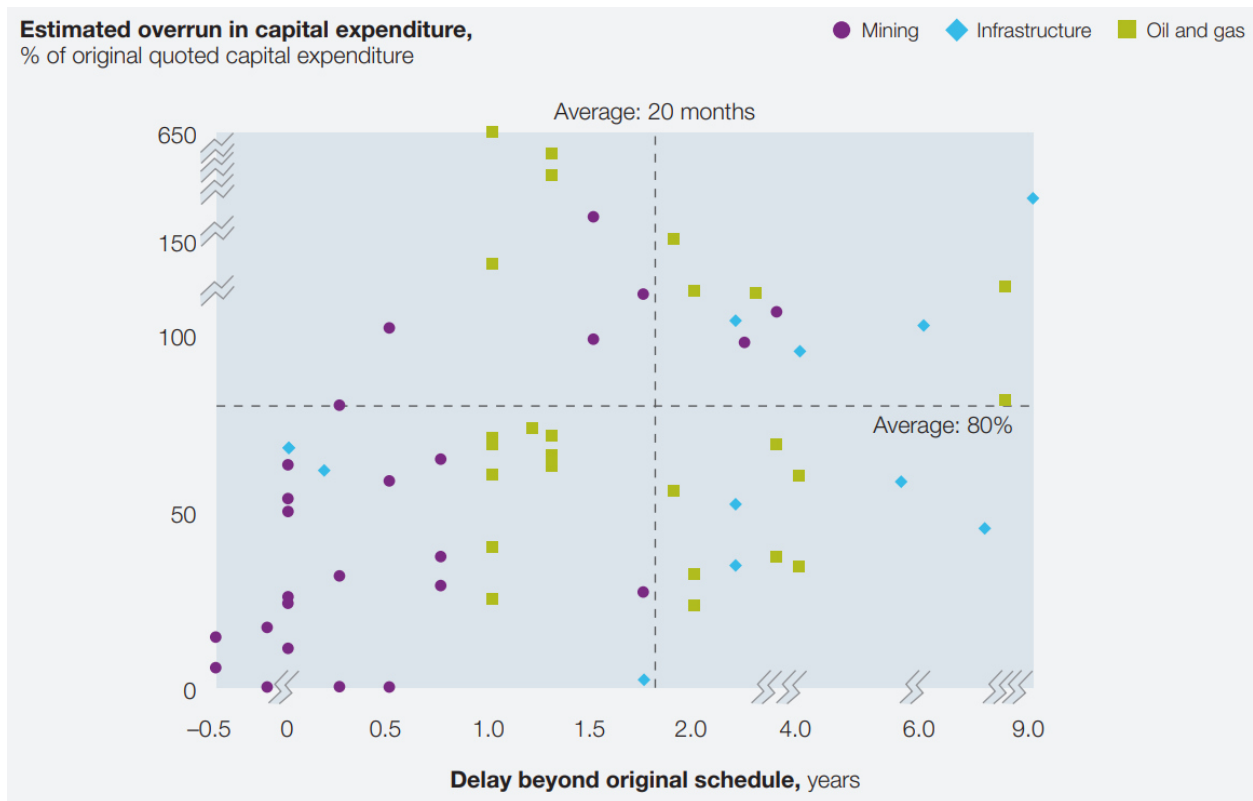
Source: Malik *et al.* (2020:6)

With a declining profit pool, pressure is exerted on the capital expenditure of the petrochemical industry. Ritsche *et al.* (2019:6) found that the world's need for industrial plants is nevertheless growing and stated: "The world population is growing; industrial production output will continue to grow on a global scale, and the need to build new production facilities will do, too. The backlog of ten lost years for the EPC industry is immense. Brownfield investments to revamp existing facilities add to this huge market. The engine of EPC business has started up again. But nothing will be the same as before 2008. Because the traditional business model in EPC has no future."

Construction project costs and time overruns generally depend on the project location, type, industry, and time of construction among other factors (Habibi *et al.*, 2019:2). According to Sabharwal and Pada (2020:1) for capital projects over \$1 billion in value reports show that 98% of projects occur cost overruns or delays, where the average cost increase is 80% of the original value, and the average slippage is 20 months behind the original project schedule. Similarly

Agarwal, Chandrasekaran, *et al.* (2016:2) found that across all asset classes, large projects frequently take 20% longer to complete than anticipated and cost up to 80% more than anticipated. Figure 1-3 displays the cost and schedule overruns occurred on mining, infrastructure and oil and gas projects captured in the Global Projects Database:

Figure 1-3: Cost and schedule overruns occurred on EPC projects



This study will aim to identify opportunities to leverage 4IR technology to address challenges currently identified in the petrochemical infrastructure projects industry in South Africa. This study is particularly interested in the following four pillars of 4IR and its relevant technologies:

1. *Vertical networking*: The automated exchange and collection of data from production processes transformed into valuable information for remote stakeholders (Pérez *et al.*, 2015:1). Vertical networking uses hyperconnected things to react swiftly to demand fluctuation, stock levels and detected faults (Schlaepfer *et al.*, 2015:7).
2. *Horizontal integration*: The combination of different information systems to generate value-creating networks that are integrated and optimised in time to ease information transparency (Rivera *et al.*, 2021:693). Horizontal integration enables risks to be managed by the most competent party on the value chain and not a party that will add contingent money to their cost, without defining the appropriate risk mitigation measures (Ritsche *et al.*, 2019:23).
3. *Through engineering*: Applying cross-disciplinary engineering through the entire value chain and across the life cycle of the product from production to the client (Schlaepfer *et al.*, 2015:8).
4. *Exponential technologies*: The use of automation solutions that is both cognitive and autonomous. Increased autonomy potentially can be achieved by leveraging artificial intelligence (AI), advanced robotics and sensor technology (Schlaepfer *et al.*, 2015:9).

With South Africa's largest oil refinery announcing an impending shutdown early in 2022 and two smaller refineries being offline due to incidents since 2021, questions will start to arise regarding fuel security. South Africa now has only had two coal-to-petroleum refineries producing fuel in an economy in dire need of growth. With the South African government's national economic recovery plan (2021:8) placing emphasis on infrastructure development and energy security, it is crucial to get South Africa's petrochemical operations profitable and up to world operation standards. This will require the expertise of an EPC execution contractor of the future.

1.2 Problem statement

Oil, gas, and petrochemical projects have attracted the attention of researchers due to their features, complexity, and capital requirements (Afsharhotli & Yitmen, 2020:4273; Hatmoko & Khasani, 2020:1). Project schedule and budget adherence are two critical indicators of successful project completion. However, delays and cost overruns are not uncommon for many projects worldwide (Rui *et al.*, 2018:677). EPC projects involves many resources with different interests and backgrounds. The basic trio consists of owners, design professionals, and contractors, with the supporting team consisting of subcontractors, material suppliers, bankers, insurance and

bonding firms, attorneys, and public agency officials (Maskuriy *et al.*, 2019:4). The integration of these resources is critical to make EPC projects successful and keeping to original budgets and schedules. Industry 4.0 introduced systems that are becoming more intelligent, improving, and learning constantly, with the flexibility to adapt swiftly to changing environments. Industry 4.0 further increases resource efficiency by the integration of humans and technology (Tvenge & Martinsen, 2018:261).

The current method of executing EPC projects is under scrutiny due to its unsuccessful attempts to improve efficiency to avoid the EPC status quo that is characterised by high probability of cost overruns and schedule extensions. This study aimed to investigate the opportunity to use Industry 4.0 technology to address the current problems faced by EPC stakeholders. Industry 4.0 technology can possibly provide the needed opportunity to integrate the resources in all phases of EPC project execution allowing flexible planning and accurate execution.

1.3 Research objectives

1.3.1 Primary objective

The primary objective of this study is to derive a theoretical framework for leveraging Industry 4.0 technology to address challenges in South African petrochemical EPC projects by using primary and secondary data.

1.3.2 Secondary objectives

1. Determining the factors contributing to the challenges faced in South African petrochemical EPC projects
2. Determining the current state of digitalisation in the South African petrochemical EPC sector
3. Determining the current hurdles of implementing technology in EPC projects
4. Identifying methods of enhanced collaboration between EPC project stakeholders

1.4 Contribution of the study

1.4.1 Theoretical contribution

The study will aim to add to the current theoretical research on possible applications for Industry 4.0 technology to address challenges in the South African petrochemical EPC sector.

1.4.2 Practical contribution

The study aimed to give South African context to the implementation of Industry 4.0 technology in the EPC sector, which can alleviate capital expenditure of petrochemical infrastructure projects. South Africa must achieve fuel security in its recovering economy. More efficient and cost-effective EPC project execution can enable petrochemical operations to achieve higher profit margins and serve the continuously growing demand for liquid fuels and chemicals.

1.5 Scope of the study

1.5.1 Field of study

The field of study encompasses EPC projects. These projects include multi-discipline engineering and construction services.

1.5.2 Industry under investigation

This study will focus on EPC contractors delivering services within the petrochemical industry in South Africa.

1.5.3 Geographical demarcation

This study will focus on the EPC contractors within the borders of the Republic of South Africa.

1.6 Limitations of the study

The population used in the study will be the major contributor to this study's limitations. The study population is described in Section 3.1.6. The population emits the following as determining factors on population inclusion:

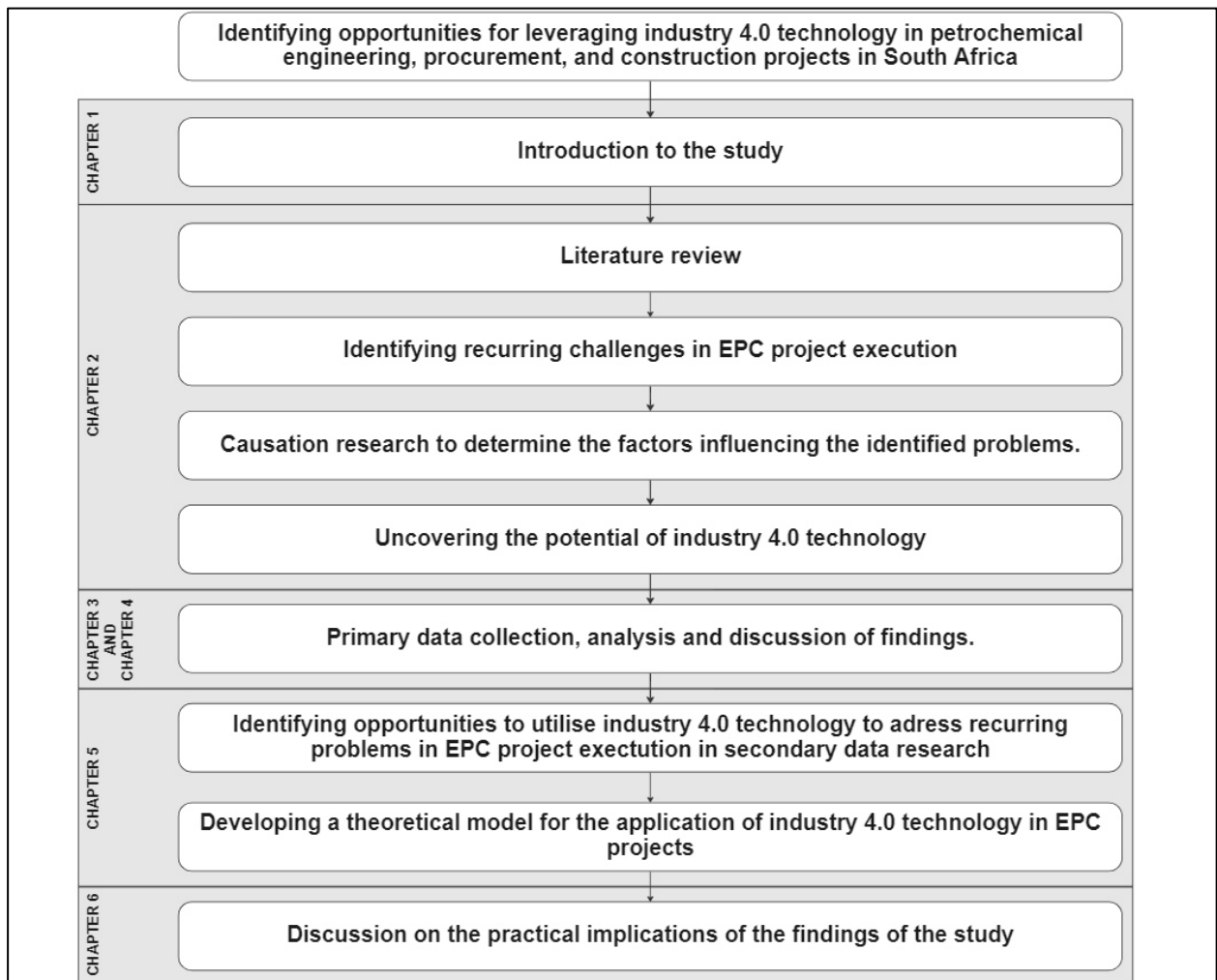
1. Gender
2. Age group
3. Race
4. Area of practice in South Africa

The interpretivist qualitative data gathered will be from a small sample of the population and will not fully represent the population. The time constraints of this study make more extensive samples impractical, and hence the research will not be deemed representative of the entire population. It should be emphasized that a convenience sample strategy was utilised because of the time restrictions of this investigation.

1.7 Layout of the study

Figure 1-4 below displays the research roadmap utilised for this study.

Figure 1-4: Schematic layout of the study



1.7.1 Chapter 1

Chapter 1 consist of an introduction, a discussion of the problem statement, the objectives of the research, and the study's contribution.

1.7.2 Chapter 2

Literature reviews should provide a precise analysis of what is known and not known about the research topic (Saunders *et al.*, 2019:75). The literature review of this study aimed to make use of secondary data to gain insight into the following main topics:

1. The context of the EPC industry

2. Identification of global repetitive problems in the execution of EPC projects
3. Identifying the potential of applying Industry 4.0 technologies to address the experienced problems

1.7.3 Chapter 3

Chapter 3 explains the research methodology followed to the reader and how the research is designed.

1.7.4 Chapter 4

Chapter 4 will display the primary data research findings of data collected in interviews and explain how the data was analysed. The problems identified in the global context of EPC projects in Chapter 2 will be verified in the South African context.

1.7.5 Chapter 5

Chapter 5 will give insight into a theoretical model that is introduced to display the potential of the identified Industry 4.0 technologies in addressing the challenges faced by the EPC industry in South Africa.

1.7.6 Chapter 6

Chapter 6 will conclude the study, summarise the findings and identify future opportunities for research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

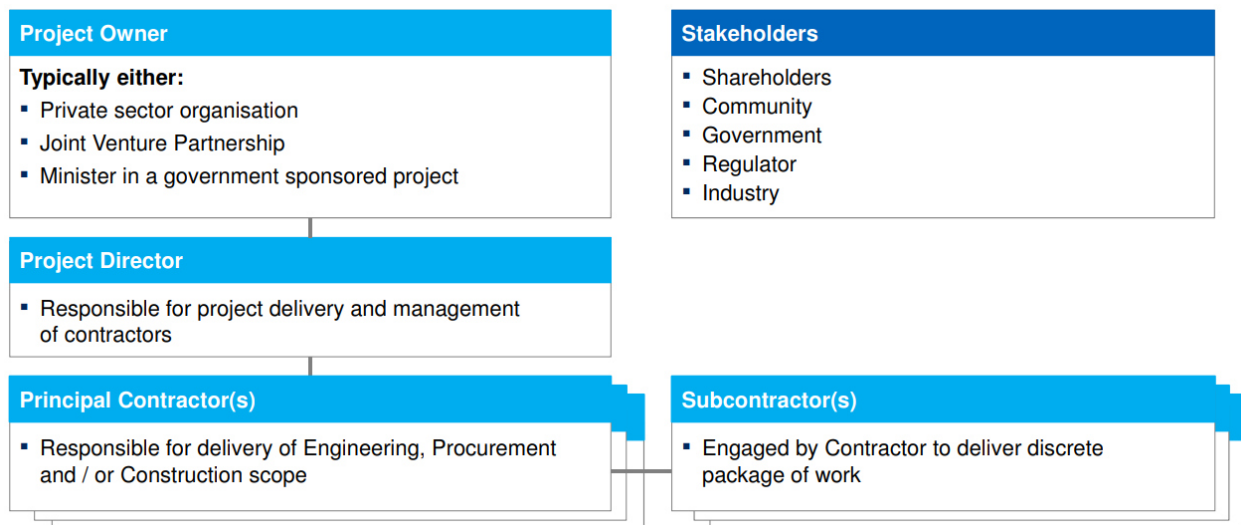
This Chapter will review the current literature on the three main aspects of EPC services: engineering, procurement, and construction. This review will first aim to identify the challenges within each element of EPC projects and then identify available Industry 4.0 technologies to leverage against the identified challenges.

2.2 EPC projects

Engineering, procurement, and construction contracts (EPC) and engineering, procurement, and construction management (EPCM) contracts have become the delivery method of choice in infrastructure projects worldwide (Loots & Henchie, 2007:1; Yang *et al.*, 2019:1). For a long time, the most popular method for owners to procure major construction projects, mainly those financed by project-based financing, has been to procure turnkey contracts with a fixed price, lump-sum payment known as EPC projects (Loots & Henchie, 2007:1). As part of an EPC contract, the EPC contractor is responsible for all materials and equipment supply, design, engineering, procurement, construction, and installation activities, as well as commissioning, start-up, training, and acceptance testing (Loots & Henchie, 2007:2; Schramm *et al.*, 2010:33; Wagner, 2020:2246). EPC projects are typically large and complex and are executed in many industry segments, including, but not limited to, industrial plants, oil and gas, mining, power generation or large infrastructure (Ritsche *et al.*, 2019:8; Wagner, 2020:2246). As part of EPCM contracts, the EPCM contractor develops all designs, performs procurement, acts as the owner's representative, and manages all construction contracts and processes on their behalf (Loots & Henchie, 2007:5; Schramm *et al.*, 2010:35). For this study, the focus is placed on EPC projects as the life cycle of the two contract types is the same, except the areas of responsibility as noted.

The typical key roles in large capital project are displayed in Figure 2-1 (P.10):

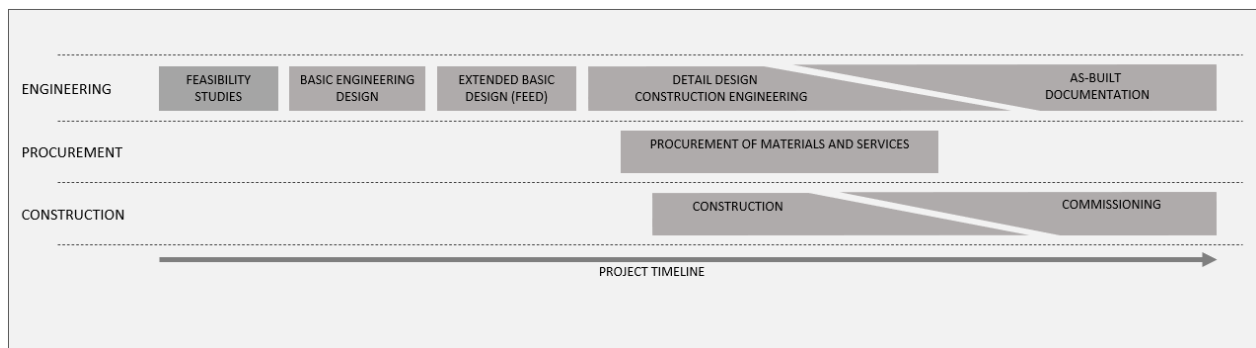
Figure 2-1: Typical key roles in large capital projects



Source: Knox *et al.* (2017:8)

Each EPC project has three distinctive phases: engineering (design), procurement and construction (Kabirifar & Mojtahedi, 2019:7). Figure 2-2 schematically displays the typical project lifecycle of a construction project:

Figure 2-2: Typical lifecycle for a construction project

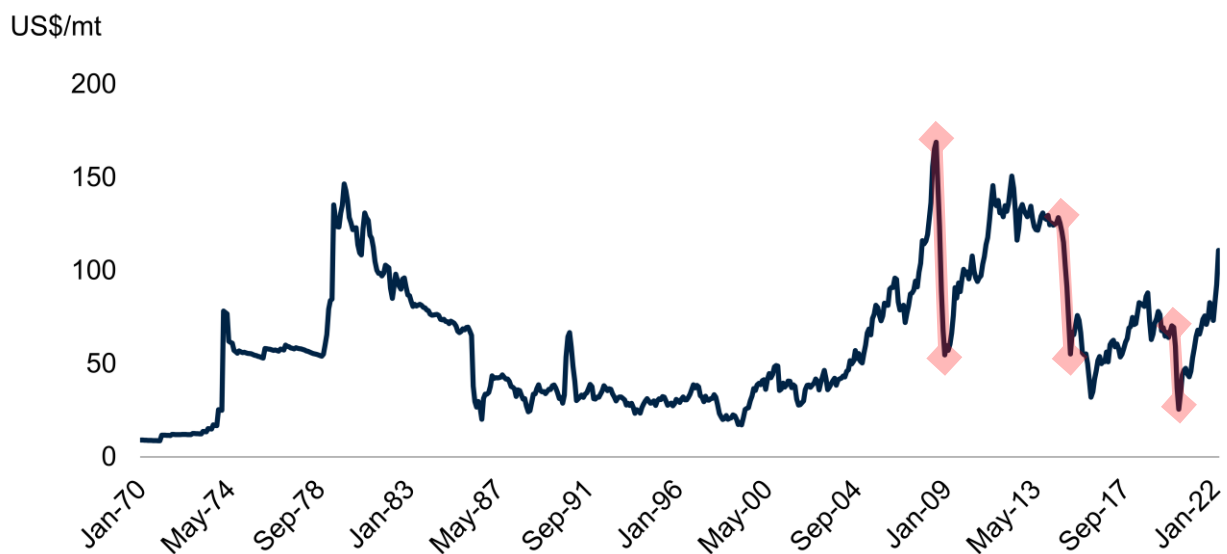


Source: Adapted from Schramm *et al.* (2010:34).

2.2.1 Context of the EPC industry

In 2008 the oil price rose to an unprecedented high. The extensive rise in commodity price was driven by the rapidly increasing demand in developing economies and the decrease in production by the Organisation of the Petroleum Exporting Countries (Wagner, 2020:2246). The oil price then collapsed due to the worldwide recession triggered by the 2008 financial crisis shown in Figure 2-3 (P.11).

Figure 2-3: Oil price data from 1970 to March 2022



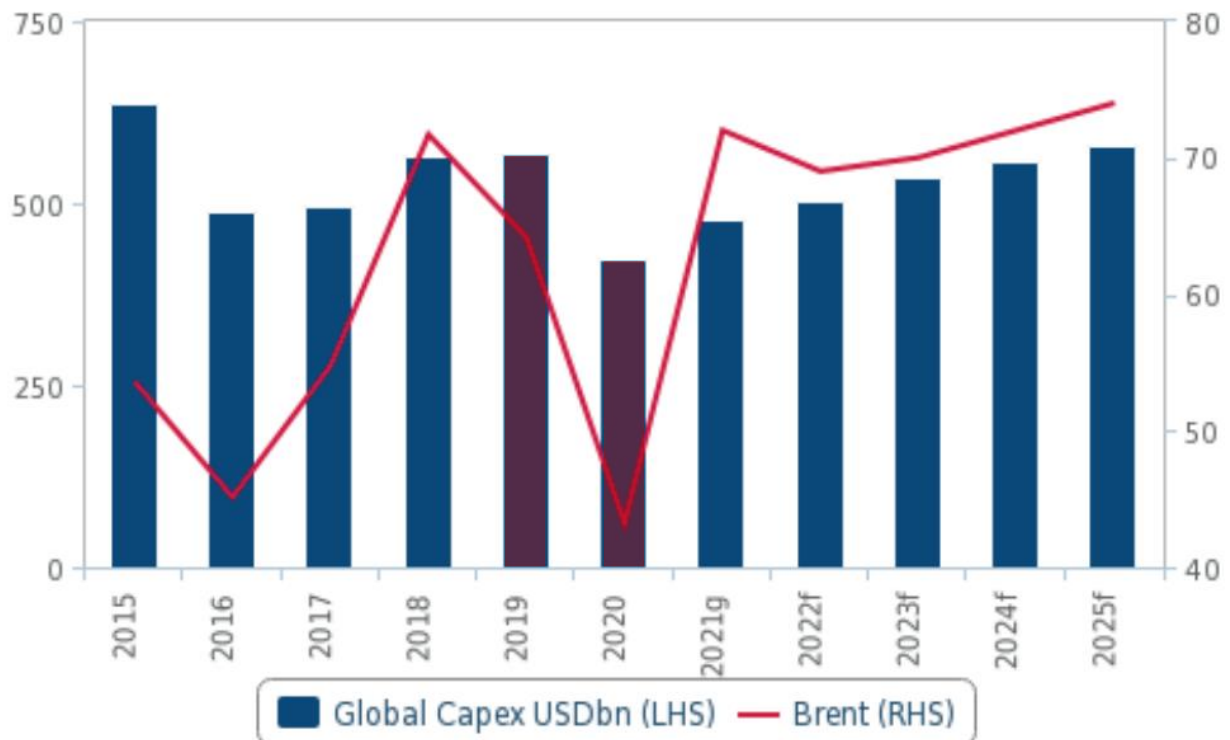
Source: World Bank Group. (2022:11)

The oil prices recovered to levels above 100-125 USD between 2010 and 2014 before suffering another steep decline in 2014. This decline resulted from the same economies that fuelled the oil price with their massive demand in the years before and then struggled to maintain their growth. The high oil prices from 2010 to 2014 triggered North America to expand its upstream extraction capabilities, further contributing to the negative effect of the low demand. The low demand was finally coupled with Saudi Arabia exploiting its resources with high production levels, contributed to the demise of the oil price (Wagner, 2020:2246). Before the oil price recovered to above 100 USD, the Covid 19 pandemic started. Bourghelle *et al.* (2021:48) found that the Covid 19 pandemic negatively impacted the oil price in at least two ways. Firstly, it led to a demand shock as the global demand for crude oil was reduced. Secondly, it led to a supply shock as the pandemic triggered a trade war between the major oil producing nations Saudi Arabia and Russia (Bourghelle *et al.*, 2021:48). This led to the lowest oil price since the late 1990's in April 2020. The oil price since recovered to the level of 110 USD in March 2022. The volatility in commodity prices keeps the pressure on investors to plan their businesses based on continuously low commodity prices, which exerts pressure on capital and operational expenditure (Wagner, 2020:2246).

As a consequence of the low oil and the low prices of commodities such as natural gas, owners put their investments on hold. A dramatic decline was subsequently experienced in the order intake for EPC companies relying on orders from the owners of industrial plants (Wagner, 2020:2246). Fitch Solutions. (2021:6) reported a 25.9% decline in capital expenditure by the top

100 oil and gas companies and draws a comparison of the influence of the oil price on capital expenditure (see Figure 2-4).

Figure 2-4: Capex of top 100 Oil & Gas Companies & Brent, USDBN (LHS), USD/bbl (RHS)



Source: Fitch Solutions. (2021:5)

After more than a decade of low demand for the EPC business, the good news is that the market is starting up again. The backlog of EPC projects is immense, and the growing world population will feed the demand for new capital projects (Wagner, 2020:2247). To capitalise on the increased demand of EPC project contractors, the focus should return to improving the management systems encapsulated within EPC projects.

2.2.2 The soft root cause for the underperforming EPC business

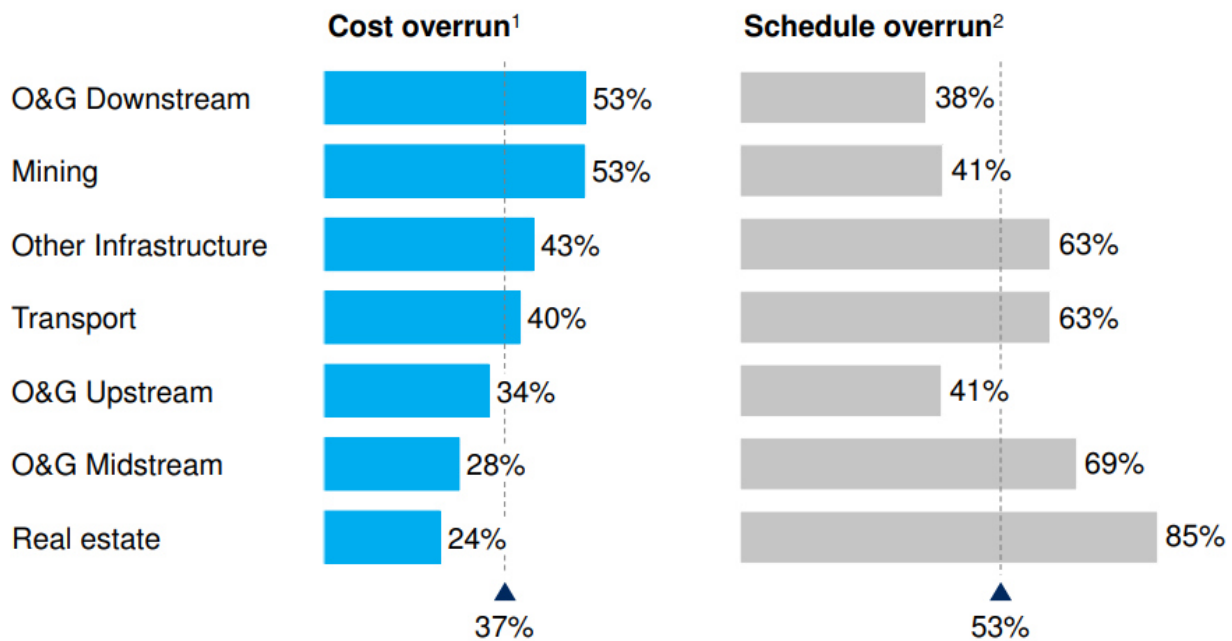
2.2.2.1 Poor performance in the execution of projects

The on-schedule and within-budget completion of large capital projects is the exception and not a norm. Knox *et al.* (2017) reviewed a dataset of over 500 global resource and infrastructure projects above \$1 billion. Only five percent of these projects were completed within their original budget and schedule. For the completed projects in this dataset, cost overruns were 37 per cent on average, and schedule overruns were 53 per cent on average. The magnitude of the cost and schedule overruns varies from sector to sector, but the oil and gas downstream business that

deals with refining petrochemical products suffered the most, with an average of 53 per cent cost overrun (see Figure 2-5).

Figure 2-5: Historical performance for projects with budgets >US\$1 billion

N=274



¹ Cost overrun = (actual cost – budgeted costs) / budgeted cost

² Schedule overrun = delivery delay / budget duration

Source: Knox *et al.* (2017:11)

Knox *et al.* (2017:11) commented on these massive losses: “The failures in the core processes of project under-performance are well understood: post project reviews generally audit the systems, process, and project management root causes for overruns. However, the disruptive influence of failures in project leadership, ineffective culture of the project organisation, failed mechanisms of collaboration between multiple parties involved—and their increasing importance as the scale and complexity of projects increase—are typically not examined to the same extent.”

Boston Consulting Group. (2016:14-15) pointed out the following underlying causes of this unimpressive track record:

1. *Lack of innovation and delayed adoption* – the benefits of research and development (R&D) are in the long term, whereas the cost arises in the present. This mismatch is ill-suited to the project business and therefore receives less attention than in other industries.
2. *Informal processes or insufficient rigour and consistency in process execution* - It is common for construction companies to adopt processes that are not mature. It appears that companies

usually pay more attention to defining the final product than to planning the construction process.

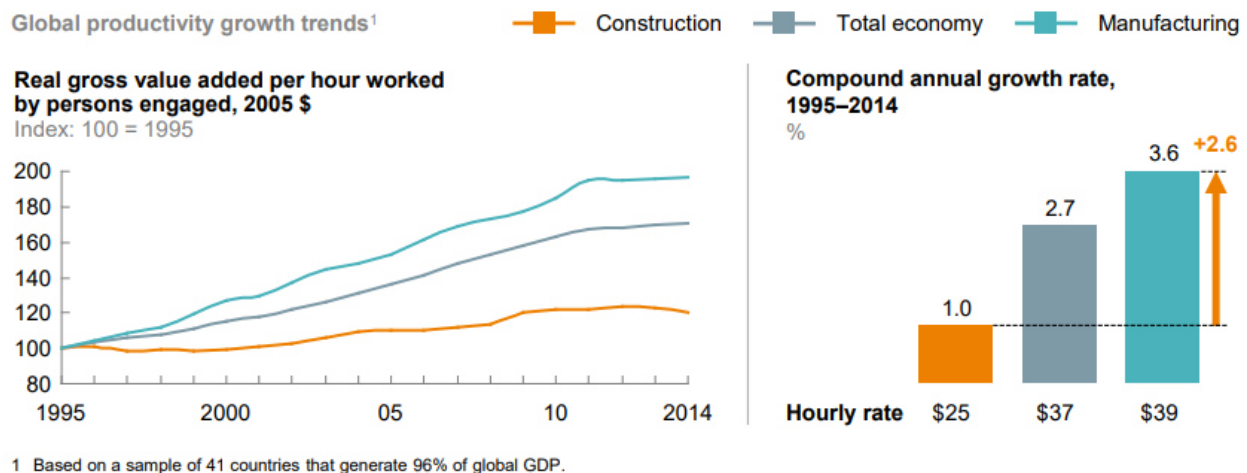
3. *Insufficient knowledge transfer from project to project* - Even though every construction project has unique characteristics, the fundamental execution processes remain the same. The lessons learned from previous projects can often be incorporated into new projects. To institutionalise such a process formally is often neglected. Due to this, past project experience is often lost, making the project manager's individual expertise crucial.
4. *Weak project monitoring* - Manufacturing industries continuously collect large quantities of data and track operations. As a result, a car manufacturer, for example, can quickly identify the root cause of an issue and implement solutions. Few project execution entities are tracking their operations to this extent.
5. *Little cross-functional cooperation* - It is common for the conventional construction process to be sequential, reflecting input from the project owner, designers, constructors, and critical suppliers at various stages. There is a lack of sophistication in this setup, which makes agile construction planning impossible. The current project execution methodology seldom makes it easy for all stakeholders along the value chain to fully contribute to design and planning.
6. *Little collaboration with suppliers* - It is common for large contractors to have long-term relationships with key suppliers. However, final decisions are often still made ad hoc, on a project-by-project basis.
7. *Conservative company culture* - The corporate culture in the construction business is often conservative and functions in a rather traditional atmosphere. The common perception is that construction companies are not sufficiently progressive or forward-thinking.
8. *Shortage of young talent and people development* - People's perceptions of the construction sector as an employer are generally negative, with inadequate gender diversity and limited job stability (due to the industry's cyclical nature). As a result, engineering and construction businesses frequently struggle to find qualified candidates to join their teams. Construction organisations participate in internal people-development efforts less regularly and more unsuccessfully than businesses in other industries.

2.2.2.2 Poor productivity growth compared to other industries and sectors

Over the previous few decades, productivity has increased steadily, increasing by between 50 and 70 per cent for the economy as a whole in the last 20 years (Wagner, 2020:2248).

Manufacturing has been the industry with the highest productivity gain, nearly doubling its real gross added value per hour of labour between 1995 and 2014 (Barbosa *et al.*, 2017). During the same period, productivity in the construction industry showed only modest growth (see Figure 2-6).

Figure 2-6: Global labour-productivity growth per sector



Source: Barbosa *et al.* (2017:4)

2.2.2.3 Delayed adoption of digitalisation

The construction industry is notorious for the delayed adoption of technological advances (Hautala *et al.*, 2017:340). Research and development (R&D) investment in the construction sector is very low compared to the economic impact thereof (Hampson *et al.*, 2014:4). The European Commission Joint Research Centre (2022:4) reports that this is the persisting reality with the construction industry R&D accounting for less than 1% of the R&D expenditure in the European Union (EU) and the United States of America (US) in 2020. The construction R&D expenditure decreased by 0.3% in the EU and 11.5% in the US. The construction sector is one of the most important industrial sectors, yet considerable underinvestment in R&D is at odds with its economic significance (Oesterreich & Teuteberg, 2016:123). Oesterreich and Teuteberg (2016:123) further confirmed the findings of Boston Consulting Group. (2016:14-15) in Section 2.1.1.1 by describing the root cause of low R&D investment in the construction industry in five points:

1. *Complexity*: Due to a large number of interconnected processes, subprocesses, and project stakeholders (engineer, contractor, subcontractors, customer, suppliers) participating at various phases and locations, construction projects are complicated endeavours.

2. *Uncertainty*: Because each construction project is a time-bound, site-specific venture, there is a lack of complete specifications for systems and sub-systems, as well as uniformity of materials, work, and teams on construction sites, creating an unpredictable environment.
3. *Fragmented supply chain*: High supply chain fragmentation is caused by many small and medium-sized businesses with similar goods and services and insufficient resources for investing in new technology.
4. *Short-term thinking*: The decentralised organisation of construction contractors, and the temporary nature of construction projects is a barrier to innovation.
5. *Culture*: The construction sector is renowned for having a robust, inflexible culture and for being extremely resistant to change.

2.2.3 Global repetitive challenges resulting in delays and cost overruns

Research in EPC projects points out many problems resulting in schedule delays and cost overruns (Pham & Hadikusumo, 2014:22). Although there is a wealth of literature available, a sample set of 20 studies investigating the factors contributing to schedule and cost overruns in the global context of engineering and construction projects were analysed, and the most repetitive elements were summarised. Table 2-1 (P.17) contains a summary of repetitive problems that have cost and schedule impact in each phase of engineering and construction projects worldwide:

Table 2-1: Repetitive problems in EPC projects worldwide

		Pham and Hadikusumo (2014)	Pourrostam and Ismail (2012)	Atsharghoti and Vitnen (2020)	Alhajri and Alshibani (2018)	Le-Hoi et al. (2008)	Kabirifar and Mojtabedi (2019)	Yang et al. (2019)	Ahmed et al. (2003)	Mahamid (2016)	Salama et al. (2008)	Tahmasebina and Song (2022)	Long (2021)	Hatmoko and Khasani (2019)	Pall et al. (2016)	Fallahnejad (2013)	Kazemi et al. (2020)	Rugaishi and Bashir (2015)	Sweis et al. (2018)	Amarkhil et al. (2021)	Rachid et al. (2019)
1)	Changes in project scope		X	X	X	X	X		X			X	X	X	X	X	X	X	X	X	
2)	Design errors and discrepancies in design documents	X	X				X	X		X		X	X		X	X			X	X	
3)	Poor interface management and communication	X			X			X		X			X	X	X	X	X	X		X	
4)	Construction material delays				X		X			X	X	X		X	X	X		X	X	X	
5)	Poor productivity of construction labour				X	X				X	X	X	X	X	X		X	X		X	
6)	Delays on decision making and approvals by the owner	X	X					X			X	X	X		X			X	X	X	X
7)	Poor risk management	X	X				X		X			X	X					X	X	X	X
8)	Delays in multi-discipline engineering design	X	X		X		X	X						X		X		X			X
9)	Rework	X			X	X		X		X							X		X		

2.2.3.1 Changes in project scope

Changes in the project scope are the most repetitive phenomenon impacting project cost and schedule according to the sample of studies described in Table 2-1. In today's complex business environment, where project owners' requests and expectations can constantly change, unexpected project scope changes impact project performance in terms of cost, schedule, and quality (Wang & Ko, 2012:423). Different types of change events can occur in projects due to differences in the geographical and natural environments, political concerns, economic crises, technological advances, project characteristics, technical tasks, skill levels of design teams, and project management knowledge levels (Afsharghotli & Yitmen, 2020:4273):4273. Design changes are often required if deliverables are omitted or misrepresented (Afsharghotli & Yitmen, 2020:4274).

Projects that involve the design of petrochemical process plants include mechanical, chemical, and other facilities that alter the matter or composition of feedstocks (solids, liquids, or gases) to produce different products. Each processing unit is like an assembly line; the previous unit's output becomes the next unit's input. As a result, a change to the operation or equipment of one process can affect the design of its successors (Long, 2022:1). When integration projects are performed, there is an additional element of discovery of additional required work when existing equipment is opened for inspection, which is a significant area of concern given the advancements in the accuracy of forecasting equipment status and in-operation inspections (AlHamouri *et al.*, 2021:1118). The industry average for scope expansion from scope freeze to integration project completion, according to Hansen and Schroeder (2016:3), is 19%. Because considerable quantities of work are added after the budget is created, the authors blame inadequate scope definition prior to project execution for this high degree of scope expansion.

Researchers identified a variety of reasons for design changes occurring during the lifecycle of an EPC project. Table 2-2 below contains a summary of these reasons:

Table 2-2: Summary of the causes of project scope changes

Change origin	Description	Summary
Client related changes	Change in objectives	There is a substantial positive link between project scope modifications and frequent design revisions (Memon <i>et al.</i> , 2011:59). Research studies on managing changes in construction projects revealed that many projects experience late design revisions because of the client's persistently shifting requirements. In a typical project, this led to a 30% employee time wastage (Maherry, 2012:27).

Change origin	Description	Summary
	Financial challenges	A change in the owner's financial situation may cause the owner to give the design team instructions to concentrate on lean design and fit for purpose in order to lower project expenses (Maherry, 2012:27).
	Inadequate project objectives	The quantifiable requirements that must be satisfied for the project to be deemed successful should be listed in the project objectives. At a minimum, the objectives must include cost, schedule, and quantity metrics. The design team may not be in alignment as a result of inadequate project objectives, which could lead to modifications in the design (Maherry, 2012:29).
	Change in specifications	Design teams must correctly interpret the specifications specified in the contract documents when presented with this situation. Design adjustments may be necessary due to incorrect understanding and presentation of the specifications. Maherry (2012:30) noted that throughout the industry, the phrase "defective specifications" is frequently used to describe specifications that contain mistakes and/or omissions. The following are examples of typical defective specifications: • Copied specifications • Expired specifications • Generic specifications • Impractical specifications • Multiple specification interpretations
Consultant related changes	Design changes	These are the reasons for design adjustments that the consultant explicitly requests or that are necessary as a result of the consultant's failure to meet specific project-related requirements (Maherry, 2012:30).
	Errors and omission in design	Because the designs provided by the designers are either incomplete or inconsistent with the site conditions, construction contractors frequently have to postpone the work on site and even redo it (Maherry, 2012:31).
	Conflicting information in contract documents	
	Inadequate details on drawings	
	Lack of consultant's knowledge of available material and equipment	Selecting trustworthy and experienced designers is essential to minimizing erroneous decisions or assumptions made at the design stage that can later necessitate design adjustments (Patrick, 2009:8).

Change origin	Description	Summary
Equipment vendor related design changes	Material and equipment changes	The design team often has to change the process equipment it had previously chosen since the equipment vendor did not match the design requirements. It is also known to have a detrimental effect on the design of succeeding systems when materials and equipment are not known to be readily available (Maherry, 2012:34).

2.2.3.2 Design errors and discrepancies in design documents

The complexity and concurrent nature of industrial EPC projects make them prone to errors (Elsherbiny, 2021:3). Approximately 75% of the project cost is influenced by design quality, directly affecting contractor profits. Various factors can cause design errors and design changes, including geological survey errors, insufficient design capability, compressed design time, and the inability to meet owner requirements (Liu *et al.*, 2020:2). According to studies, rework resulting from design flaws raises the project contract values by 5-20% (Barber *et al.*, 2000:3; Love & Edwards, 2004:209). Despite multiple studies, the exact costs associated with design errors that on-site workers need to be aware of are frequently unknown. The exact cost's rare availability is rarely calculated at the project level and is not formally calculated at the company level (Lopez & Love, 2012:585). Table 2-3 contains a summary of the literature regarding the origins of design errors.

Table 2-3: Summary of the causes of design errors

Error origin	Summary
Loss of biorhythm	Every person has a biorhythm, which consists of their mental, emotional, and physical states (Lopez <i>et al.</i> , 2010:402). An individual's biorhythm is influenced by their experiences in and out of the workplace, affecting their capacity to handle work responsibilities (Love <i>et al.</i> , 2010:651). Designers and engineers are frequently pressured to fulfil unreasonable deadlines, which can lead to stress and exhaustion (Love <i>et al.</i> , 2010:651). Particularly, cognitive fatigue brought on by a severe workload may be a factor in the recurrence of mistakes (Love <i>et al.</i> , 2009:427).
Adverse behaviour	People's behavioural characteristics are greatly influenced by the organisational cultures in which they work (Minato, 2003:297). The manner wherein a person makes a mistake and how it is addressed afterwards are grounded in the organisation's implicit and unspoken standards and values (LePine <i>et al.</i> , 2004:883). Using competitive tendering may lead to businesses agreeing to take on work at the lowest cost. This may lead to design firms engaging in opportunistic conduct to increase profitability by neglecting design audits, reviews, and verifications (Lopez & Love, 2012:585).

Inexperienced design consultants	Errors in design documentation are influenced by factors such as inadequate knowledge, aptitude, and the ability to carry out specific tasks (Minato, 2003:297). According to research by Josephson and Hammarlund (1999:681), design errors are often the result of the designer's lack of knowledge and experience.
Schedule pressure	There is a tendency for organisations to neglect duties to complete their work more quickly when they are under schedule pressure from clients to design and document. This frequently leads to contract documentation problems, which have been noted as a significant source of dispute in construction projects (Love <i>et al.</i> , 2011:403).
Inadequate quality assurance	Design consultants' resistance to quality assurance significantly contributes to producing substandard documentation. Even when design businesses have quality procedures in place, they hardly ever perform audits, inspections, and verifications because they believe it is time- and money-consuming and requires much effort. (Love <i>et al.</i> , 2000:570).
Ineffective interface management and integration of the design team	Interface management and communication will be discussed in detail in Section 2.2.3.3.

2.2.3.3 Poor interface management and communication

Interface management is described by Zheng (2022:198-199) as the "management of communications, relationships, and deliverables among two or more interface stakeholders". Technology, environmental factors, and stakeholders' interfaces can cause a project to become complex. These interfaces are often difficult to manage to achieve predefined goals and objectives (Remington & Zolin, 2011:116). Schlumberger Business Consulting conducted a ten-year study on exploration and production capital expenditures and found that larger oil and gas projects experienced higher cost overruns (Rostand, 2012:23). It is possible to explain this positive correlation by the fact that the number of interfaces and the complexities of these interfaces increases as the project size increases. Higher costs will be incurred when project activities and interfaces are not properly integrated (Davies *et al.*, 2009:106). The structural design of the tank foundation and the sizes of the input pipes, for instance, are significantly affected by changes in tank capacity in an oil refinery project (Shen *et al.*, 2018:1). Due to the interdependence of these components' functions during the design and construction phases, the flow and exchange of information, including technical specifications, resources, spacing, and scheduling data, used in the subsequent changes, should be well coordinated and integrated among the pertinent stakeholders across their interface boundaries (Shen *et al.*, 2018:1). EPC projects require intensive communication among project stakeholders from planning to commissioning due to their complexity and uncertainty; interface management has a significant contribution to collaboration throughout the process and improve the performance of EPCs (Shokri *et al.*, 2016:4). Zheng (2022:198-199) identified factors that impact interface

management. Table 2-4 below contains a summary of five factors found to have a significant impact on interface management:

Table 2-4: Summary of the factors influencing interface management

Factor	Summary
Design changes	Design changes was discussed in Section 2.2.3.1 For every design change, a line of communication is opened wherein various stakeholders require the change to be communicated and understood to proceed with the necessary change actions
Misunderstanding of design documents	There are evident difficulties that adds to a project's potential for complexity, like a lack of understanding of the design intent, design documents, and drawings (Paik <i>et al.</i> , 2022:2226)
Errors in design documents	Design errors are discussed in Section 2.2.3.2. Design errors often lead to physical construction interfaces to be mismatched and causes significant delay until a solution is designed.
Designers did not take constructability into account	Because the designs provided by the designers are either incomplete or inconsistent with the site conditions, construction contractors frequently have to postpone the work on site and even redo it (Maherry, 2012:31).
Poor inter-departmental communication	Any construction project's success is strongly dependent on efficient channels for communicating information to various stakeholders. Due to the interdisciplinary nature of these projects' work environments, which necessitate constant collaboration between members of several organisations, effective communication during them is frequently difficult (Abbas <i>et al.</i> , 2019:4972).

2.2.3.4 Construction material delays

The process of strategically controlling the flow of materials, components, and completed goods from supplies through the manufacturing process and on to consumers or end users, as well as the related information flows, is known as supply chain management (Yeo & Ning, 2002:256). Oil and gas infrastructure development by EPC contracting strategies involves a complicated supply chain (Joshi *et al.*, 2017:1). The supply chain consist of global stakeholders (Saad *et al.*, 2014:70) that interact and conduct transactions using a linear supply chain paradigm (Agarwal, Sharma, *et al.*, 2016:1). The multiplicity of stakeholders causes supply chain inefficiencies and when it comes to promoting information exchange and coordinating the activities among relevant organisations, the management of supply chains is arguably ineffective (Gammelgaard *et al.*, 2019:11). Due to the complexity of the linear supply chain and the variety of the stakeholders, there is a risk of information loss and ambiguity which causes supply chain delays and construction rework (Gammelgaard *et al.*, 2019:11). Durdjev and Hosseini (2019:30) identified factors that leads to material delays in construction projects. Table 2-5 (P.23) contains a summary of five factors found to have a significant impact on interface management:

Table 2-5: Summary of the factors influencing construction material delays

Factor	Summary
Design changes	Design changes was discussed in Section 2.2.3.1.
Errors in design documents	Design errors are discussed in Section 2.2.3.2.
Interface management between designer and supplier	Interface management are discussed in Section 2.2.3.3.
Unreliable suppliers	One of the primary causes of delays in construction projects, which lead to higher expenditures, has been identified in the literature as being a scarcity of materials and unreliable deliveries (Assaf & Al-Hejji, 2006:351; Tommelein, 1998:281). To support decision-making in production planning and control in the construction industry, the availability of precise and continuously updated data and information is becoming a necessity. This data is not always available, and procurement decision-makers often do not have a broad understanding through data what the current material market supply chain has to offer. Similarly, designers do not have real-time data to identify material equivalents that fall within the project budget and schedule objectives.
Material lead times	

2.2.3.5 Poor productivity of construction labour

The general definition of "productivity" is maximising output while optimising input (Hamza *et al.*, 2022:413). Productivity is, therefore, a measure of the value-added output versus the input required to achieve the output (Borcherding, 1977:73; Yi & Chan, 2014:214). One of the essential components of labour productivity that needs careful consideration for efficient project delivery in the construction sector is the performance of skilled personnel. Low performance from skilled personnel has been identified as a critical element that lowers the productivity of ineffective construction projects (Zannah *et al.*, 2017:1). The units of work placed or produced per man-hour are referred to as the construction labour productivity (Bekr, 2016:92). The overabundance of unskilled workers and the shortage of skilled workers are the two main characteristics of the South African labour market (Windapo, 2016:2).

Hamza *et al.* (2022:416) ranked the top repetitive factors throughout a large set of literature influencing low productivity in construction labour which in summary is set out in Table 2-6 (P.24):

Table 2-6: Summary of the factors influencing construction labour productivity

Factor	Summary
Poor labour supervision, management, and planning	Supervision and labour management is an important virtue to ensure productivity, safety and quality of construction activities (Venkatesh & Natarajan, 2019:408). It is expected of management to plan labour allocation to specific tasks, whereafter supervision needs to ensure that these tasks are executed. Failure to manage and supervise construction labour was deemed to negatively impact labour productivity (Bekr, 2016:95).
Shortage of materials	Lack of materials significantly lowers the productivity of construction efforts. Usually, labourers squander their time on unproductive tasks because there is not enough or any material available (Bekr, 2016:65). Material delays significantly contribute to the shortage of materials and the influencing factors on material delays are discussed in Section 2.2.3.5.
Communication or coordination problems and misunderstanding	Dixit <i>et al.</i> (2017:652) report that one of the primary reasons for delays in construction projects is poor site coordination, which has an immediate impact on construction labour productivity. The author notes that communication and coordination directly relate to interface management, as discussed in Section 2.2.3.3.
Design change and design errors	Design changes, design errors, and the overall management of engineering drawings were determined to significantly impact labour productivity (Dai <i>et al.</i> , 2009:180; Iyer <i>et al.</i> , 2008:180). Design changes and design errors and their influencing factors are discussed in Section 2.2.3.1 and Section 2.2.3.2.
Shortage of skilled labour	International patterns imply that the lack of skilled workers is a worldwide issue. Globally, nations, businesses, and organisations frequently voice their concern about a lack of qualified workers in various spheres of their economies (Mateus <i>et al.</i> , 2014:63). The labour in the construction sector, in general, is low-skilled, rotates among jobs often, is getting older on average, and has low turnover. This is primarily due to the industry's lack of appeal to young and skilled personnel due to safety, wages and working conditions (Yap <i>et al.</i> , 2019:35).

In addition to the above (Bekr, 2016:65) indicated that productivity in the construction industry is significantly impacted by the delays and expenses associated with rework. Rework on deficient tasks is a widely researched factor and will be discussed in detail in Section 2.2.3.10.

2.2.3.6 Delays in decision making and approvals by the owner

Project management strategies are essentially decision-oriented due to their roots in operations research and decision science (Kwak & Anbari, 2009:436). Decision-making becomes an information-intensive process in an ever-changing project environment. This results in decision-making having a critical influence on the duration of projects (Dayan *et al.*, 2011:470). It is

challenging for a single decision-maker to address complicated project decision problems based on the limited information possessed because of the intense dependencies among distinct project responsibilities. Collaborative decision-making groups, in which professionals build close working relations and contribute their views to obtain an informed judgment, are extensively relied upon by many organisations (Wen *et al.*, 2018:2). While group decision-making benefits from multidisciplinary knowledge, it also presents difficulties for timely decision-making, which is especially important for adjusting to changes in project environments (Eweje *et al.*, 2012:642). Firstly, the coordination and communication between many decision-makers may take a long time and cause the decision to be delayed (Dayan *et al.*, 2011:470). Secondly, as group size increases, it becomes more difficult to quickly develop trust and mutually agreeable goals, which are necessary for knowledge sharing and attaining consensus within decision-making groups (Buvik & Rolfsen, 2015:1485). Thirdly, the ad hoc nature of project decisions results in the lack of a properly defined implementation routine and could further result in a disorganised decision-making process (Bergman *et al.*, 2012:22).

The complicated decision-making procedures that govern oil and gas projects are characterised by risks, uncertainties, and opportunities (Castillo & Dorao, 2013:48). A project's timeline is unquestionably affected by delaying the acceptance of some crucial documentation or procrastinating options for an extended period of time without a clear roadmap (Alhajri & Alshibani, 2018:6). The effect of stakeholder decisions on project efficiency has been the subject of numerous studies. Al-Khalil and Al-Ghafly (1999:105) reasoned that decisions are often delayed due to the owner's technical staff having insufficient expertise in handling technical matters. McWhirter and Shealy (2017:4) found that cognitive biases, systematic errors, and predictable estimating errors are strongly related to uncertainty and risk and can negatively affect project decisions in several ways. These effects can have exceptionally high stakes for complex and multi-stakeholder infrastructure decisions.

According to (Kahneman, 2011:54), humans have two different ways of thinking when making decisions: a quick, intuitive system one and a slower, more analytical system two. While it's generally accepted that tasks move from system two to system one over time, these thought patterns are complementary rather than exclusive (Gulati *et al.*, 2021:1535). The efficient transfer of information and knowledge, therefore, directly impacts the transfer of decision-making from system 2 to system one. When a decision-maker is comfortable with the information received and within previous experience can relate to a decision, decision-making can more easily be transferred from system two to system one.

Garland (2009:15) noted that only primary project stakeholders, not all stakeholders, should make up whatever decision-making body is established for the project, as big committees rarely result in effective decisions. When the appropriate stakeholders are not represented in the decision-making forum and/or the project ownership is unclear or divided, difficulties in decision-making can arise. As a result, there may be displeased stakeholders and confusion regarding who is responsible for making decisions.

The factors influencing the quality and speed in which decisions are made are summarised in Table 2-7 below:

Table 2-7: Summary of the factors influencing decision making

Factor	Summary
Change in project scope	The resulting new work and rework on a project that experienced changes in scope tend to keep the team members busier than normal (Wang & Ko, 2012:430). The more changes occur on projects, the busier the decision-making authorities get to analyse and approve the changes.
Coordination of between decision making stakeholders	Multiple decisions that have an impact on a variety of project-related characteristics constitute collaborative decision management in complex designs. Due to the multidomain nature of these operations, various stakeholders, including project managers, engineers, planners, supply chain managers, and quality engineers, must be involved (Jaber <i>et al.</i> , 2015:475). Owners of decisions must oversee the decision-making process and form temporary decision teams while identifying pertinent project expertise. Since these teams are frequently not adequately set up, many actors attend numerous meetings but are ineffectively connected to the impact and conclusion of the decisions made (Jaber <i>et al.</i> , 2015:475).
Communication between decision making stakeholders	Lack of communication results in a lack of information, which causes rework and, as a result, affects decision-making because of the required information not being transferred (Zhong <i>et al.</i> , 2022:6).
Insufficient information provided to make decisions	The transfer of knowledge and information between project stakeholders often leads to misunderstanding when analytical decisions are required, which subsequently leads to bad- or delayed decision-making (Williams & Samset, 2010:45).
Shortage of technical knowledge	Al-Kharashi and Skitmore (2009:21) argued that owners are often so reliant on consultants that they are unaware of the technical detail of experienced issues which limits the client's capacity to make decisions that might help the construction process.

2.2.3.7 Poor planning and scheduling

Numerous academic and professional research initiatives have been carried out that have improved project scheduling and cost control (Ruwanpura *et al.*, 2006:20). Although the

petrochemical industry has implemented advanced planning techniques, technology, and processes, the sector still has difficulties completing projects that meet performance standards (AlHamouri *et al.*, 2021:1127).

The critical path method (CPM) was created to plan conventional construction projects by utilising a list of tasks in a work breakdown structure. CPM serves as the standard requirement for contract schedules in the petrochemical EPC industry in South Africa. Using the sequence of tasks with zero total levitation, this technique calculates the project's completion time in the shortest possible amount. As a result, if the critical route task execution times vary, so does the project completion time. In many businesses and sectors, this strategy is still the primary planning method (Taghipour *et al.*, 2020).

Due to their failure to incorporate risk and other aspects present in projects and whose absence can lead to inaccurate schedule projections, traditional planning methods like CPM are receiving criticism from researchers (Mongalo & Lee, 1990). According to (Kelleher, 2003:38-39), the CPM's drawbacks include:

1. An excessive amount of implementation effort.
2. The misuse of logic.
3. Excessive reliance on specialists.
4. Ignorance of the needs of field employees.

The CPM may be helpful to contractors in analysing progress status and updating activity data. Still, it may not be as beneficial for supporting other crucial elements like corrective actions and locating execution issues (Deacon & Van der Lingen, 2015:79). Although the owners and managers of contracting organisations understand the benefits of utilising CPM, contractors are unable to do so since the critical path does not accurately reflect reality (Hegazy & Menesi, 2010:1078). Menesi (2010:2) argued that the CPM algorithm is founded on two idealistic assumptions during the project planning stage: that resources are infinite and that the project deadline is unconstrained.

Planning and scheduling are essential to understanding project performance in contexts that are competitive and where infrastructure and construction projects are being executed. To ensure that projects accomplish their objectives, both activities must be handled appropriately and effectively (AlNasseri & Aulin, 2015:58). The definition and organization of a wide range of activities, as well as the estimation and allocation of the most cost-effective resource deployment, are all part of the planning and scheduling procedures, which are vital throughout the life cycle of construction projects (Ahuja & Thiruvengadam, 2004:19). Without thorough knowledge about the task being planned, scheduling cannot succeed. Additionally, a flawed planning process could

diminish the value of schedules, resulting in an unregulated flow of project progress (Andersen, 1996:93).

Table 2-8 below summarises the factors influencing project planning and scheduling:

Table 2-8: Summary of the factors influencing project planning and scheduling

Factor	Summary
Poor risk modelling	Risk management in construction projects has many flaws that impair its efficiency as a project management function and, ultimately, the performance of projects. The reductionist approach that has been used for many years to control risk in construction projects yields substandard results and lowers the efficiency of project management, planning and scheduling (Serpella <i>et al.</i> , 2014:654). Risk is frequently managed through the application of floats (time) or contingencies (money) that is not based on a comprehensive risk analysis, which is recurrently insufficient to cover the consequences of risks that do occur during the project lifecycle (Serpella <i>et al.</i> , 2014:654).
Insufficient knowledge within planning and scheduling team on project activities	Due to the complexity of construction project management, project managers and practitioners must possess specific planning and scheduling knowledge or awareness. In order for project stakeholders and practitioners to effectively transfer, measure, analyse, and rectify the implementation of project plans and schedules, acquiring such knowledge is required for a well-defined project planning methodology (AlNasseri & Aulin, 2015:68).
Impractical sequencing of activities	Planners find it challenging to understand the reasoning behind activity sequences or decide whether or not certain constraints may be eased because CPM-based schedules lack a sequencing rationale. Therefore, assigning roles and statuses to events is only possible in the planner's mind (Koo <i>et al.</i> , 2007:423). The lack of understanding of all construction project activities and an individual's cognitive bias can often lead to planners sequencing construction activities impractically. When alteration to activity sequencing is then required within CPM-based scheduling tools, this process is often time-consuming and error-prone (Koo <i>et al.</i> , 2007:423).
Inaccurate activity duration estimation	Average productivities are typically provided as an aid in estimating activity duration. Still, these averages frequently need to be updated to adjust to the unique characteristics of a task or site (Hendrickson <i>et al.</i> , 1987:288). Due to the exposure of construction projects to several uncontrollable risk variables, variations in activity duration do occur (Dawood, 1998:41).
Poor monitoring and control of the schedule	The activities for project control, monitoring, and the resulting update of the project schedule are frequently performed manually. This results in the delay of the consequence of deviations being incorporated in project schedules (Isaac, 2016:1). The resulting delay in reacting to the deviation can pose significant threats to the project schedule as mitigation measures are often imposed too late.

Planning and scheduling are a function of the input of various stakeholders in an EPC project. Taking the complexity of petrochemical EPC projects into account, emitting to capture multi-discipline information in a project schedule often leads to overrun planned schedules and costs.

2.2.3.8 Delays in multi-discipline engineering design

Engineering-related delays can be attributed to several factors, which can be divided into three categories: design development, preparation and/or approval of construction drawings, and project party changes (as discussed in Section 2.2.3.1). Marzouk *et al.* (2008:316) described the reasons for design development delays as follows:

1. Inability of the designer to complete design duties due to a lack of resources, including software and labour.
2. Delays in the owner's preliminary documents being delivered to the designer.
3. Incompleteness of the owner-prepared preliminary documentation.
4. Delay in responding to inquiries or proposals from the designer.
5. Alterations made during the development phase to meet the needs of the owner.

Marzouk *et al.* (2008:318) further described the reasons for the preparation and/or approval of construction drawings delays:

1. Delays in submitting construction drawings to the owner for approval.
2. Errors and emissions on construction drawings.
3. Delays in the approval process.
4. Delays in responding to clarification requests.

The ability to make engineering decisions is crucial to the success of construction projects (Tan *et al.*, 2021:1). Since decisions are inherently judgments based on information, insufficient information will always lead to bad decision-making (Elonen & Artto, 2003:401).

2.2.3.9 Rework

Love (2002:18) defined of rework as "the needless effort of redoing a procedure or job that was implemented improperly the first time". It is a challenge frequently faced in engineering and construction projects since rework often contributes to cost and schedule overruns (Love & Edwards, 2013:1121). Rework, on average, accounts for 52% of overall cost overruns and can result in a 22% surge in schedule overrun (Love, 2002:18). Latent circumstances that exist inside the organisational and project systems have been linked to rework (Love *et al.*, 2009:322). These latent conditions may include inadequate training, resources, and a lack of a quality management

focus at the organisational level. At the project level, a lack of monitoring, a competitive tendering process, and a contracting strategy provide favourable circumstances for mistakes (Love *et al.*, 2009:323). Latent conditions, therefore, lay dormant within a system until an error becomes known. Without exception, latent conditions arise from strategic decisions taken by senior management, government, regulators, designers and critical decision-makers (Roberts & Bea, 2001:179).

High-quality welding performance, for instance, also known as weld integrity, is essential for minimising rework costs, preserving project safety, and guaranteeing general product quality (Ji & AbouRizk, 2018:1). The labour of inspectors and pipe fitters, as well as the additional material expenses connected with fixing non-conforming welds and replacing damaged pipes, leads to direct project costs overruns and delays (Megow *et al.*, 2011:200). Ji and AbouRizk (2018:489) noted that a critical element in the successful administration of construction projects is quality management. Yet, due to their failure to implement a project quality plan, inspection, and test plans, design consultants and construction contractors experience a significant negative impact on project performance throughout the construction project industry.

Table 2-9 below summarises the factors influencing rework on construction and engineering projects.

Table 2-9: Summary of the factors influencing rework

Rework origin	Description	Summary
Design related rework	Design changes and design errors	Design changes and errors, as described in Section 2.2.3.1 and Section 2.2.3.2, could significantly impact rework. Love and Edwards (2013:1127) found that the lack of design audits, reviews and verifications and the distribution of incorrect information and preliminary engineering documents led to rework in oil and gas projects.
	Design interface management	Interface management, as described in Section 2.2.3.3, could significantly impact rework. Love and Edwards (2013:1127) found that inadequate interface management between engineering consultants and fabricators contributed substantially to the rework required to complete projects.
Construction related rework	Construction interface management	Interface management as described in Section 2.2.3.3 could have a significant impact on rework. Love and Edwards (2013:1127) found that inadequate interface management between contractors contributed significantly to the rework required to complete projects.

Construction quality	Love and Edwards (2013:1127) found that oil and gas construction projects suffered high rework rates due to:
Construction errors and damage during construction	• Absence of quality assurance and controls during construction • Re-fabrication owing to failure to meet the requirements of the engineer • Work left incomplete • Inadequate training • Inadequate matching of individual to task • Misunderstanding of tasks brought on by the lack of knowledge and experience.

2.3 Uncovering the potential of Industry 4.0 technology

By utilising progressive technology, the fourth industrial revolution (4IR), fuelled by digitalisation, is altering industries and increasing their efficiencies (Oesterreich & Teuteberg, 2016:122). 4IR can be distinguished as a phrase that is mainly used in popular science in many contexts, in contrast to many other classic manufacturing ideas like advanced manufacturing or lean production, which have been extensively established in the scientific literature (Brettel *et al.*, 2014:37). This multidimensional concept, created by the German Federal Government to support its high-tech policy, combines several multidisciplinary concepts without a clear demarcation (Lasi *et al.*, 2014:239). Researchers further defined 4IR technically as the rising digitalisation and automation of the industrial environment together with the development of a digital value chain to enable communication between goods and their environment and business partners (Lasi *et al.*, 2014:239; Schmidt *et al.*, 2015:2). As a result, concurrent planning of products and production procedures enhances product quality and cuts down on time to market (Oesterreich & Teuteberg, 2016:122). Lasi *et al.* (2014:239) recommended the following three key characteristics required for the implementation of 4IR:

1. *Horizontal integration through value networks*: Closer collaboration with value chain partners across corporate borders is made possible by integrating information technology (IT) systems, processes, and data flows between diverse businesses, including customers, suppliers, and other external partners.
2. *Through engineering*: Reduced internal operational expenses due to end-to-end digital engineering integration along the entire value chain to enable highly customisable products. As a result, the value chain must be digitally integrated using cyber-physical systems.
3. *Vertical integration and networked manufacturing systems*: Creation of an intelligent manufacturing environment within the organisation through integrating IT systems, business processes, and data flows from product development to manufacturing, logistics, and sales.

Mischke *et al.* (2021:58) found that the Covid 19 pandemic accelerated the potential productivity growth of the construction industry and forecasts between 1.7% and 2.5% productivity growth from 2019 to 2024. The main contributors to this growth acceleration are forecasted to be modular designing, designing for constructability, standardisation, digitalisation, and automation. The most significant boost to productivity growth may come from the accelerated adoption of digital and industrialised construction techniques and the ensuing increases in operational effectiveness. For example, more digitalised planning processes in building information modelling (BIM) can reduce conflicts, rework, and delays. On-site work procedures, logistics, and quality can be improved using digitally enabled workflow management and computer vision-based progress tracking (Mischke *et al.*, 2021:59). Barbosa *et al.* (2017:101) found that digitisation and automation have the potential to increase construction productivity by 68% across all the sector's asset classes. From this lever alone, Barbosa *et al.* (2017:103) forecasted a potential boost of productivity growth of 0.8 percentage points per year leading to 2024. Ribeiro *et al.* (2020:3) conducted an executive survey wherein two-thirds of the respondents acknowledged that the Covid-19 pandemic accelerated the overall transformation of the construction industry through increased adoption of industrialisation, value-chain control, and digital technologies. Half of the respondents confirmed investment in the line of digital transformation.

There are several areas where 4IR technology has the potential to add value to the construction sector (Oesterreich & Teuteberg, 2016; Ribeiro *et al.*, 2020; Ritsche *et al.*, 2019):

1. *Productivity improvement*: 4IR provides improvements such as automation, real-time inventory management and continuous optimisation that have the potential to increase productivity.
2. *Increased quality*: Production process monitoring, and control enables higher-quality goods and services.
3. *Increased agility*: 4IR allows agile, customer-centric manufacturing through automation and robotics.
4. *Increased production*: The production speed is increased with improved physical-digital-physical integration and product life cycle management.
5. *Safer working conditions*: Workers can have safer and better working circumstances thanks to increasing automation, real-time incident monitoring, better workstation design, and improved job structure.

6. *Improved collaboration:* Collaboration inside and between organisations is improved as data availability is increased and the digital and physical layers are combined.
7. *Sustainable operations:* Operations can become more sustainable through improved resource management, defect reduction, and other environmental benefits.
8. *Innovation:* 4IR enables the development of novel value-creation strategies and employment opportunities, such as through downstream services.

In May 2018, Wagner (2020) launched a research project intending to use desk research to analyse the current situation and significant trends, investigate potential solutions for the company's challenges, and produce actionable advice for investors, owners, and operators, as well as EPC contractors. The project's objective was to provide novel solutions to advance the EPC business model, and subsequently, the term "EPC 4.0" was born. The project focussed on five main areas, namely:

1. Digitalisation
2. Partnering and integrated project delivery
3. Integrated supply chains
4. Agile EPC collaboration and flexible resourcing
5. Project management and competencies

Summarising the finding in these areas, Wagner (2020) projected potential savings of up to 50% of budgeted project cost in evolving EPC projects to EPC 4.0 projects.

2.3.1 Digitalisation of EPC projects

The beginning of the 21st century brought along dynamics of changes that created a new dimension of the economy that is based on information and knowledge. Increased areas of economic existence are permeated by the Internet of Things (IoT), hyperconnectivity, large data sets, cloud solutions, automation, and robotisation. Not all entrepreneurs are aware that the boundaries between what is physical and what is digital are blurring, making the existing ways of managing business processes likely to be insufficient (Łukasz Sułkowski & Morawski, 2017).

With ICT (information and communications technology) access approaching being very common in organisations, the next challenge is to ensure that all organisations, individuals, and governments are using these networks and applications to their full extent. Countries realised that achieving digitisation at advanced levels has significant benefits for the economy, society and functioning of their public sectors (Sabbagh *et al.*, 2012:124). Sabbagh *et al.* (2012:124) noted that South Africa was among the 65 countries that are in the constraint stage of digitisation.

Most independent subcontractors and suppliers used in typical EPC projects are short-term positions or contract workers who have little motivation to adopt new technology and practices. Furthermore, the complexity of EPC projects makes it difficult to standardise and difficult to design procedures and tools that can be used consistently (Brakstad, 2020:20). Koeleman *et al.* (2019:2) reported that despite the challenges faced, an increasing number of companies overcoming these challenges to transform projects and business divisions digitally. Koeleman *et al.* (2019:2) discovered parallels in behaviours that supported digital technology and working ways to overcome obstacles in digital transformation, despite significant variations in these organisations' operating environments. The five common practices of engineering and construction companies that successfully implemented digital technologies were identified as discussed in Table 2-10:

Table 2-10: The five common practices of successful digitalisation implementation

Focussing on addressing problem areas, not installing IT solutions	Companies can boost the possibility that digital technologies will have a positive impact by creating digital use cases that will enable operational adjustments to improve performance first. Three things should be specified in a robust process-centred use case: a process change, the necessary enablers (data and technological tools, capabilities, changes in mandates and duties, legal and contractual requirements, among others), and the projected benefit.
Implementing digital use cases that promotes collaboration	Companies should pay extra attention to projects involving various organisations and disciplines and create digital use cases that facilitate collaboration. For instance, real-time construction site progress data may guarantee that subcontractors raise invoices on time and appropriately.
Reskilling and restructuring engineering teams	Engineering design has seen significant modifications as a result of digital technologies. For instance, generative design tools can significantly shorten the time it takes to produce designs by automatically proposing a variety of design possibilities in accordance with user-defined specifications. It may be argued that the capacity to analyse and improve a generative design product is fast, overtaking the ability to generate an original design. Additionally, with the adoption of modular construction techniques, it is now more crucial than ever to standardise design elements and save them in design libraries for future usage.
Adjusting project baselines to capture value	Many project executives report that their businesses have experienced some productivity gains due to digitisation but have had a little overall financial impact because the cost savings from increased productivity do not offset the expenses of implementing new software and systems. This might happen when managers fail to remove float from the project baseline after productivity-boosting use cases create it during the execution phase. Managers must change baselines to cut down on wasteful time and increase the value to fully benefit the bottom line from digital use cases.
Connect projects to unlock impact across the enterprise	It is simple for business-unit leaders at a typical decentralized engineering and construction company to concentrate on project optimization while ignoring enterprise-wide use cases that could unleash a new wave of value as the

company standardizes its digital tools and platforms across its various business units and shares more project data. The following are typical enterprise-wide use cases for engineering and construction businesses:

- Combining cost and schedule data from several projects and business divisions to improve the precision of future contract bids and consequently raise the margin.
 - Having access to an enterprise-wide resource view will help you load resources more efficiently and react fast to changing project demands.
 - Establishing central storage locations for designs at the element, package, and project levels to enable the reuse of such designs on new projects.
-

Executives and managers must begin with a clear description of how digital technology will add value to the organisation for a digital transformation to be effective. They must devote just as much time to operational change as they do to technological change during the shift, if not more (Koeleman *et al.*, 2019:2). A subset of 4IR technology that can possibly be associated with the digitalisation of EPC projects and the potential benefits thereof will be discussed in paragraphs to follow.

2.3.1.1 The internet of things and industrial internet of things

The Internet of Things (IoT) emerged in the late 1990s and was enabled by wireless and mobile communications, small and powerful computers, sensor technology, and interwoven systems. The early applications included, among other things, an effort to organise and track consumer assets by embedding tiny electronic markers inside the assets that could connect to the internet (Brakstad, 2020:15). Rose *et al.* (2015:1) argue the term IoT generally describes the phenomenon where network connectivity and computing capability are extended to objects, sensors, and everyday household items that are not typically thought of as computers, enabling these devices to generate, exchange, and consume data with little to no human intervention. However, there isn't a solitary, inclusive definition. For example, Kumar *et al.* (2019:1) simply state that IoT is a paradigm that allows internet-based connectivity between electronic gadgets and sensors to improve our quality of life. For most people, the Internet of Things (IoT) refers to household items connected to the internet and can transmit data to improve or simplify daily living. However, it can help firms operate more efficiently by providing a greater viewpoint and more data. Although the technology itself is not innovative, its adoption is. This is principally caused by the accessibility of more affordable and effective wireless components, which are being rapidly incorporated into the goods we use every day (Brakstad, 2020:16).

Industrial Internet of Things (IIoT) refers to a network of intelligent and highly connected industrial components that are used to increase production rates while lowering operational costs by continuously monitoring, effectively managing, and controlling industrial processes, assets, and

operational time (Khan *et al.*, 2020:2). IoT typically refers to consumer-level gadgets like smart home appliances or fitness bands. On the other hand, IIoT as a subset of IoT involves connecting equipment in sectors like oil and gas, power production, or healthcare to the internet where system failure or unanticipated downtime could result in dangerous or life-threatening circumstances (Brakstad, 2020:16). Through the integration of machine sensors, middleware, software, and backend cloud compute and storage systems, IIoT offers the business increased visibility and insight into its operations and assets (Brakstad, 2020:16). Industrial equipment can now be equipped with intelligent sensors, connected to wireless networks, and capable of collecting and exchanging real-time data. Sensors, networks, and analytics make up the three critical infrastructural pillars that support the IIoT. IoT, cloud computing, big data analytics, artificial intelligence, cyber-physical systems, extended reality, human-to-machine, and machine-to-machine communication are some of the enabling technologies that make up these elements (Brakstad, 2020:16). IIoT is taking shape as a result of the foundational components' increased technical maturity and affordability, which enable projects to be commercially successful. This allows the above technologies to be investigated, tested, and combined to determine how to optimise the advantages of IIoT in various projects (Miller, 2018:18).

2.3.1.2 Building information modelling

The creation, storage, and interchange of information about the construction environment among involved parties have increasingly transformed because of new Building Information Modelling (BIM) tools and technology (Kubicki *et al.*, 2019:160). Academia has given various definitions to BIM. A commonly appreciated definition is that BIM is “the digital representation of physical and functional characteristics of a facility” (Majrouhi Sardroud *et al.*, 2021:283). Professor Charles M. Eastman established the idea of BIM in the 1970s (Latiffi *et al.*, 2013:2). Since then, many software developers have created an alternative, effective BIM design software, including Autodesk, Bentley Systems, and Tekla. Since the middle of the 2000s, BIM technologies have been steadily developed. They have begun to be utilised in architecture, engineering and construction (AEC) project to address inefficiencies in the AEC sector (Azhar *et al.*, 2012:1; Panaitescu, 2014:2).

Although the oil, gas, and petrochemical industry (OGPI) is larger and more complicated than the AEC sector, it has shown that employing digital modelling technology to increase cost, time, quality, and efficiency is possible and can be rewarded (Lee *et al.*, 2018:350):350, which is fairly similar to the BIM notion. Majrouhi Sardroud *et al.* (2021:283) did a comprehensive review of the application of BIM technology in the oil, gas, and petrochemical industry. They found that there are limited cases that have implemented BIM in some part of the industry life cycle and that no

cases reported the use of BIM through its entire lifecycle. Additionally, a different study on 28 BIM guidelines from across the world, 83 academic articles, and 101 case studies pertaining to digital modelling in the oil, gas, and petrochemical industry demonstrated the overwhelming number of overlapping applications of BIM in the AEC sector and digital modelling in the oil, gas, and petrochemical industry. The study presented 36 BIM modules that could be utilized with the oil, gas, and petrochemical industry and were comparable to digital modelling tools that is currently in use in the industry (Lee *et al.*, 2018:353). Table 2-11 displays the 25 BIM applications Lee *et al.* (2018:354-368) identified that is applicable to the application of the EPC project life cycle.

Table 2-11: BIM applications that could be applied to petrochemical EPC projects

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
1	Existing conditions modelling: A procedure where a three-dimensional (3D) representation of the current circumstances on a site and the amenities available for the site or a particular section inside a facility is created (Kreider & Messner, 2013:9). It includes modelling of the current ground surface of the structures, the surrounding area, and the infrastructure for project master planning, existing facilities, and assets, existing spaces, building components and equipment, geotechnical elements, and horizontal construction like roadways, raised bridges, walkways, and transportation is developed so that the overall environment of the facilities can be modelled effectively.	x		x	Gather, generate
2	Site analysis: A procedure in which the site location is assessed using BIM or geographic information system (GIS) technologies to determine: 1. The most suitable location for a future project (Bloomberg <i>et al.</i> , 2012:11) 2. The volumes and position (placement, orientation) of the facility(s) on site (Bloomberg <i>et al.</i> , 2012:11)	x			Analyse
3	Cost estimation: BIM may be used in a process to provide an accurate cost estimate, and the cost implications of design changes can be tracked using the BIM, allowing designers to reduce unnecessary cost overruns brought on by project changes (Bloomberg <i>et al.</i> , 2012:14). This process includes cost management, cost tracking and bill of quantities.	x	x	x	Gather, generate, analyse
3 (a)	Cost analysis (5D)/cost and schedule forecast A procedure wherein a 5D BIM is used to link the cost data to a 4D BIM in order to conduct cost analysis and provide a cash flow projection report (Lee <i>et al.</i> , 2018:356).	x	x	x	Analyse, communicate

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
4	Phase planning (4D modelling)/ scheduling Time is introduced as a fourth dimension to the traditional 3D model. Phase planning is a method whereby phased occupancy is efficiently planned using a 4D model, allowing the project team to see and communicate for a better grasp of project milestones and building schedules (Bloomberg <i>et al.</i> , 2012:14). Early project phasing to compare various solutions, detailed phasing to order multi-trade installation, and scheduling for project control are all involved.	x	x	x	Communicate
5	Space program validation A procedure wherein area and program data are taken from BIM to evaluate the space design while the design is being developed. It enables tracking of useable, gross, and rentable space (Lee <i>et al.</i> , 2018:356).	x			Generate
6	Design authoring A procedure wherein interdisciplinary teams use writing tools to provide depth of information to a facility (Hong Kong Construction Industry Council, 2015:17)	x	x	x	Generate
7	Design reviews and constructability reviews A procedure where stakeholders examine a 3D model through various presentation formats and offer their opinion on a variety of design elements validation (Bloomberg <i>et al.</i> , 2012:13). It entails choosing a design from a range of BIM possibilities, communicating the concept visually, and using digital prototypes (Lee <i>et al.</i> , 2018:357).	x			Communicate
8	Modelling For effective coordination, each facility system must be set up as a distinct model connected to a single origin point. It contains an architectural model that consists of structural, interior, material and spatial design, and any other typical models for constructing a facility (Lee <i>et al.</i> , 2018:357).	x			Generate
8 (a)	Civil engineering/infrastructure model A procedure where a civil engineering model is produced to depict infrastructure or civil engineering components that should be distinguished from building models. With the assistance of related technologies like GIS and LiDAR, the civil engineering or infrastructure aspects may incorporate site topography models, landscaping features, and site utilities models (Lee <i>et al.</i> , 2018:357). Models of civil engineering include bridges, main roads, highways, railroads, foundations, and tunnels.	x			Generate
8 (b)	Equipment modelling and maintenance clearance space modelling A procedure wherein equipment models are made to show its location, dimensions, and details. Additionally, it takes into account normal maintenance cycles, replacement procedures, and continuity of operations so that related equipment may be maintained concurrently (Hunt & Betancur, 2016:8)	x			Generate

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
8 (c)	Energy modelling				
	Energy analysis is frequently carried out independently of the BIM due to the time of the analysis and probable model clean-up. It accelerates the simulation process fast with less information from the circumstances of an existing building to create an energy analysis (Hunt & Betancur, 2016:10).	x			Generate
9	Design analysis/engineering analysis				
	A procedure in which the models are employed for structural analysis, lighting analysis, and fire safety analysis, or are simulated using standard analysis tools (Lee <i>et al.</i> , 2018:358).	x			Analyse
9 (a)	Energy analysis				
	A procedure that uses information from BIM to analyse lifespan costs and energy simulation (Lee <i>et al.</i> , 2018:358).	x			Analyse
9 (b)	Accessibility analysis				
	A method of evaluating the practicality and accessibility for all individuals, including those with impairments, utilizing factors such as colours, lighting, acoustics, and other factors that are harder to evaluate than geometrical standards (Lee <i>et al.</i> , 2018:358).	x			Analyse
9 (c)	Proximity analysis				
	A method of using BIM to carry out proximity analysis to establish the ideal travel distance between two regions (Lee <i>et al.</i> , 2018:359).	x			Analyse
9 (d)	Security and circulation analysis				
	An approach where a BIM is simulated using a security and circulation analysis program to examine the circulation locations where the building has defined security zones (Lee <i>et al.</i> , 2018:359).	x			Analyse
9 (e)	Acoustics analysis				
	A method for doing room acoustical analyses and sound insulation estimates using a simulation of BIM and an acoustical analysis program (Lee <i>et al.</i> , 2018:359).	x			Analyse
9 (f)	Mechanical analysis, virtual testing, and balancing system analysis				
	A technique for evaluating a facility's performance against the design requirements. It covers evaluations of a mechanical system's performance, the amount of energy a project consumes, lighting analysis, solar gain analysis, and CFD-based airflow study (Hong Kong Construction Industry Council, 2015:17).	x			Analyse
9 (g)	Sustainability evaluation				
	A procedure where models are used to simulate and validate facility characteristics such as thermal performance, energy use, structural calculations, acoustics, heat flows, Life Cycle Costing (LCC), Life Cycle Analysis (LCA), and environmental sustainability based on the requirements of standard sustainability assessment (Lee <i>et al.</i> , 2018:360).	x	x	x	Analyse

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
9 (h)	Civil engineering analysis A procedure wherein the models of civil engineering components are examined using GPS, LiDAR, and any other types of technologies, such as for the hydraulic design of water supply, sewage, storm water drainage systems, surface analysis, and traffic simulation (Hong Kong Construction Industry Council, 2015:17).	x			Analyse
9 (i)	Signal sighting A procedure that uses BIM to design and test new signalling ideas before fixing (Lee <i>et al.</i> , 2018:360).	x			Analyse
9 (j)	Civil engineering analysis A procedure wherein the models of civil engineering components are examined using GPS, LiDAR, and any other types of technologies, such as for the hydraulic design of water supply, sewage, storm water drainage systems, surface analysis, and traffic simulation (Hong Kong Construction Industry Council, 2015:17).	x			Analyse
9 (k)	Design verification and code validation A procedure where project-specific codes are compared to the model parameters using code validation tools. It also incorporates prescription and functioning validation in addition to compliance checking (Lee <i>et al.</i> , 2018:360).	x			Analyse
10	Design coordination Clashes are manually categorized and reported after clash detection software has been used to analyse the BIM for physical interferences between building systems and components. BIM tools enable automated clash identification analyses for drainage and utility networks (Lee <i>et al.</i> , 2018:361).	x			Analyse
11	Design documents and drawing generation Schematic, design development, construction, and shop drawings are extracted directly from BIM repositories or object libraries through this technique (Lee <i>et al.</i> , 2018:361).	x			Communicate
12	Digital fabrication A method for extracting geometry from the BIM for shop drawings, which may then be supplied to computer numerical control equipment for prefabrication and fast assembly on site (Lee <i>et al.</i> , 2018:361).		x	x	Realise
13	Subcontractor/trade coordination A method whereby a coordinated model is used to help the contractor and the subcontractors examine the design, optimize scheduling, and perform field installation before installation (Lee <i>et al.</i> , 2018:361).		x	x	Realise

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
14	Material management All project deliverables, including prefabricated components and other small construction support materials, are received, tracked, and controlled using a BIM process to assure timely delivery and expectations for quality. (Lee <i>et al.</i> , 2018:362).		x	x	Gather, generate
15	Equipment management A method for using BIM to support construction equipment management, such as scheduling downtime to match project workload, producing maintenance schedules, producing a full service history, and coordinating work (Lee <i>et al.</i> , 2018:361).		x	x	Gather, generate
16	Site and logistics planning A method whereby specific logistic objects are modelled in the BIM and connected to the construction schedule (4D) for both permanent and temporary facilities on site (Lee <i>et al.</i> , 2018:362).			x	Communicate
17	Field construction layout A procedure where layout points are fed into robotic total stations for layout using data from the BIM. In contrast, during building, layout points are recorded in the field and rounded back to the model for proactive quality control (Lee <i>et al.</i> , 2018:362).			x	Communicate
18	Rigging plan A procedure whereby lift plan models are generated through cooperation between the structure engineers and qualified workers on the site, such as the lift supervisor, to convey the lift plan for execution (Lee <i>et al.</i> , 2018:363).			x	Communicate
19	Safety plan BIM can be used to construct safety plans for communication both on and off site, including information about emergency routes and public safety measures, and BIM-based orientation can be used to deliver safety instruction (Lee <i>et al.</i> , 2018:363).			x	Communicate
20	Construction system design A method for improving planning, construction productivity, and safety by modelling complicated systems, such as modular construction components and scaffolding (Lee <i>et al.</i> , 2018:363).			x	Generate, communicate
21	Process tracking An approach that combines mobile computing, laser scanning, and 4D BIM to let project managers properly analyse construction progress and take prompt action if schedule delays emerge (Lee <i>et al.</i> , 2018:363).			x	Gather

No.	BIM use/ description	Project phase			Application
		Engineering	Procurement	Construction	
22	Quality tracking and reporting A method where Field Management software is used to track, task, and report on quality, safety, and documents to the field, commissioning, and handover programs, connected to BIM for project compliance, during the construction, commissioning, and handover process (Lee <i>et al.</i> , 2018:364).			x	Gather, generate, communicate
23	Field supplements BIM data can be used to support field supplements [70] such construction drawings and schedules, as-built documents, and sustainability certification documentation that is presented as part of the project deliverables (Lee <i>et al.</i> , 2018:364).			x	Generate
24	As-built model Record modelling is a technique used to accurately reflect the assets, surroundings, and physical characteristics of a facility. Delivering a record model to the owner or facility manager is the result of all the BIM modelling that was done throughout the project, including linking operation, maintenance, and asset data to the as-built model that is derived from the engineering, construction, 4D coordination models, and subcontractor fabrication models (Lee <i>et al.</i> , 2018:364).			x	Generate
25	Commissioning A methodical procedure to ensure that all project systems interact in accordance with the design intent and the owner's operational requirements (Lee <i>et al.</i> , 2018:364).	x	x	x	Communicate, realise

2.3.1.3 Big data, cloud analytics and smart sensors

Big data refers to vast, diverse, and complicated data sets that are challenging to store, analyse, and visualise for use in subsequent operations or outcomes (Sagiroglu & Sinanc, 2013:42). Big data is currently being used in a variety of disciplines such as developing future national strategies, resolving social issues, enhancing the effectiveness of public enterprises, and boosting the competitiveness of the private sector, for instance through public service innovation (Pencheva *et al.*, 2020:25). There is a tremendous amount of interest in using big data for analytics, both to interpret vast amounts of data using sophisticated statistical and visualisation techniques as well as to create prediction models that guide future decisions leveraging data-driven insights (Siegel, 2013:78).

The development of low-cost, high-performance computer power enables us to find previously undiscovered correlations between data that reveal fresh hidden insights. Predictive analytics is

used in all industries, including banking, retail, oil and gas, manufacturing, and others. Big data and cloud analytics, statistical algorithms, machine learning, and smart sensors enable this (Brakstad, 2020:26). Massive volumes of data are produced by EPC projects at every stage of their life cycle, from planning to operation and maintenance. Due to the complexity of the decision-making processes and the enormous volume of project data created throughout each project stage, many EPC contractors experience difficulties with their projects (Choi *et al.*, 2021:1). Considering the amount, complexity, and speed of the data generation throughout the project's execution, the data are categorised as big data (Bilal *et al.*, 2019:1). The demand for engineering project management systems to use artificial intelligence (AI) in big data technologies is rising in pace with the fourth industrial revolution (Choi *et al.*, 2021:1).

Intelligent sensor data is a crucial source of information for big data analytics in the industrial sector. Intelligent sensors use built-in computing capabilities and data from the physical world to determine whether something is wrong. They offer a more precise collection of environmental data, better monitoring, control systems, and fewer downtime thanks to their predetermined functions dependent on the application (Brakstad, 2020:27).

2.3.1.4 Machine learning

Machine learning (ML) is a developing subset of computing algorithms that aims to imitate human intelligence through environmental learning. They are regarded as the workhorses of the new big data era (El Naqa & Murphy, 2015:13). Data is learned through the predictive model when data analysts enter the gathered data into a system with an incorporated predictive model. The system that reflects all of this automatically evaluates and outputs the final prediction result when a user enters a new document into the system in which such an ML model is embedded (Choi *et al.*, 2021:2).

Research on the application of machine learning on construction projects enjoyed attention globally in recent years. Table 2-12 describes the application of various machine learning research projects:

Table 2-12: Machine learning applications on construction projects

Author	Machine learning application
Zhang and El-Gohary (2016)	A natural language processing (NLP) method based on semantic rules for automated information extraction (IE) from construction regulation documents.
Lee, Yi, <i>et al.</i> (2019)	Research is presented on a variety of methods and the most recent research on IE and NLP methods whereafter

Author	Machine learning application
	Lee <i>et al.</i> applied NLP and IE approaches to create an automated contract risk extraction model for construction projects.
Lee, Yoon, <i>et al.</i> (2019)	An Invitation to Bidder (ITB) risk management model to identify risk indicators during the bidding stage by utilizing Watson AI to stop EPC project cost overruns.
Chua <i>et al.</i> (1997)	A model that used the artificial neural network (ANN) technique to identify the project management elements necessary for a construction project's budget to be met. After adequate training, they indicated, the model may be utilized as a tool for project budget prediction.
Williams and Gong (2014)	A model that makes use of data mining and classification algorithms to foresee the potential for cost overruns during the bidding stage of a construction project.
Zhang <i>et al.</i> (2015)	A big data approach to evaluating bids for construction projects by looking at project cost information.
Matel <i>et al.</i> (2022)	A study on the engineering project cost estimating model using the ANN method.
Ahn <i>et al.</i> (2020)	Performance assessment of the normalized case-based reasoning (CBR) model to enhance the calculation of the initial design cost of a construction project for multi-family homes.
Kim <i>et al.</i> (2018)	The use of Detail Engineering Completion Rating Index System (DECRIIS) to reduce rework during the design phase of offshore EPC projects.

As indicated, numerous studies have lately been conducted that use ML approaches to analyse building and plant projects. Very little research integrates the whole plant project life cycle because the majority of the studies were restricted to individual studies on single project phases (Choi *et al.*, 2021:3).

2.3.1.5 Autonomous things and hyper automation

Automation is using technology to automate and replace operations that previously required humans to perform (Brakstad, 2020:29). No single tool can fully replace humans. When robotic process automation (RPA), ML, and AI are introduced to automation, Haleem *et al.* (2021:1) note that automation is transformed into hyper-automation. The objective of hyper-automation is to boost AI-driven decision-making and decrease human errors through a combination of tools, including RPA, intelligent business management software, and AI. Hyper automation includes functions like thinking, discovering, and building this automation themselves using a combination

of modern digital tools. Automation involves replacing humans with machines to perform physical operations like welding or other operational jobs (Brakstad, 2020:29).

Autonomous Things is the phrase used to describe the gadgets that automate jobs and take the place of humans (AuT). These devices, such as robots, vehicles, drones, smart home appliances, and software, are anticipated to partially or entirely automate the work currently performed by humans (Brakstad, 2020:30). The most relevant technology in the AuT spectrum at the moment is autonomous robots, autonomous vehicles and drones. The AuT aims to equip robots with sensors, AI, and analytical tools to the point where they can carry out activities independently without any direct human interaction. Together, these technologies can gather sufficient data and knowledge to enable data-based decision-making (Brakstad, 2020:30).

Globally, there is also an aerial revolution in addition to Industry 4.0 and EPC 4.0. Drones have become an efficient commercial tool in several industries, particularly construction, enabling on-site safety and project monitoring to the degree that was previously impractical (Brakstad, 2020:30). Multirotor drones, an innovative technology in the modern construction sector, can facilitate construction tasks from observation and inspection to monitoring of safe practices, resulting in time, cost, and injury reductions along with improving quality work (Herrmann, 2016:589). Drone information can be utilised for mapping, land surveys, building inspections, client, and employee visual materials, monitoring on-site operations, security surveillance, and data collection. For instance, drone technology makes it simple to construct 3D representations of large areas or objects, which can then be merged with ground-based laser scanning and traditional surveying (Brakstad, 2020:30). Drones have been utilised thus far in a number of industries, including mining and agriculture. Although drones are still in the exploratory stage and have not yet become widely used in the construction industry, they have the potential to make construction easier, such as by facilitating site observations and structural checks (Li & Liu, 2019:410).

Robotics, which includes intelligent robots, mobile robots, delivery robots, personal robots, and robotic appliances, is the second most important technology in autonomous objects. There are high potential benefits in replacing operations that are very repetitive and exact, like welding, as well as dangerous ones, like using power tools (Brakstad, 2020:31). The ability to operate a robot remotely cuts down on waste, streamlines project work, and lowers the number of specialists required to complete a particular operation. Contractors rated the advantages of robotics, with the top three being a reduction in the need for human labour, cost savings, and increased construction stability. Other benefits included increased productivity, improved quality, improved safety, and decreased waste generated by materials (Struková & Líška, 2012:124). Given that they are

produced in large quantities in a regulated manufacturing environment, prefabricated components are thought to be the easiest construction component to automate. Components made in a workshop are also simple to automate; examples include project-specific structural parts that can be managed in a workshop setting (Elhouar *et al.*, 2019:771). Elhouar *et al.* (2019:771) noted that speciality trades in construction activities continue to be the most difficult to automate since they demand substantial research and development.

Table 2-13 below describes research on the use of autonomous things in construction projects:

Table 2-13: Autonomous things in construction projects

Author	Spectrum	Application
Zhang and Fu (2021)	Robotics	Utilisation of autonomous tower crane in the construction process.
Pérez and He (2021)	Robotics	On-site welding robot implementation on construction projects
Koc and Nguyen (2021)	Robotics	Autonomous excavators and their potential in construction projects
Forch and Karadag (2021)	Drones	Applications for unmanned aerial vehicle (UAV) construction progress monitoring
Prieto <i>et al.</i> (2020)	Robotics	Monitoring construction progress using autonomous robots

2.3.1.6 Extended reality

Extended Reality (XR) refers to a range of experiences that blur the boundary between the real and virtual worlds. It is a collective term for immersive technologies, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies (Alizadehsalehi *et al.*, 2020:3). All real-and-virtual integrated environments, as well as human-machine interactions produced by wearables and computer technologies, are together referred to as XR. Although all forms of virtual experiences fall under this umbrella term, there are significant differences in technology in terms of information processing, data collection, storage capacity, and power (Brakstad, 2020:34).

The term "virtual reality" (VR) describes computer-based technologies that produce lifelike visuals, audibles, and other sensations that depict an immersive environment and replicate a user's physical presence in that environment (Alizadehsalehi *et al.*, 2020). Employees or clients can see the tangible asset visualised rather than just relying on design drawings and models. Along with viewing through VR, adding sensory enhancements like headphones and haptic devices to the VR headgear makes it easier to achieve the immersive experience (Brakstad, 2020:34).

In augmented reality (AR), computer-generated content is superimposed on the real world, so users can superficially interact with it in real time (Li *et al.*, 2018:154). By adding text, audio, or visual elements, for instance, additional levels of information can be added to reality using augmented reality (AR). It makes the blending of a virtual experience with the physical world visible to the user (Brakstad, 2020:34). Table 2-13 displays research examples of the application of VR/AR in construction projects.

Table 2-14: Autonomous things in construction projects

Author	Spectrum	Application
Li <i>et al.</i> (2018)	VR/AR	The use of VR/AR systems in hazard identification, safety education and training, safety inspection, and induction
Fu and Liu (2018)	VR/AR	The application of VR/AR in mitigating project schedule risks
Muhammad <i>et al.</i> (2019)	VR	The application of VR in construction site layout optimisation
Alizadehsalehi <i>et al.</i> (2019)	VR	The application of VR in design and construction education
Sutcliffe <i>et al.</i> (2019)	VR	Enhancing collaboration and collaborative decision making among stakeholders
Romano <i>et al.</i> (2019)	VR	Enhancing the understanding of complex designs
Bille <i>et al.</i> (2014)	VR	Displaying construction geometry for stakeholders to make sense of a project and reach better decision making
Rankohi and Waugh (2013)	AR	Tracking construction progress and identifying defective work

2.3.1.7 Blockchain

Although the construction sector has not yet implemented Blockchain widely, there have been various initiatives to do so via the creation of business models (Elghaish *et al.*, 2020:3). As an example, BIMCHAIN, a plugin for BIM platforms, is proof of concept for integrating BIM into Blockchain (Lamb, 2018:11). Elghaish *et al.* (2020:3) reports on several examples of the adoption of smart contracts in the construction industry, including: delivering the agreed contracts automatically with the ability for parties to update any variations; enhancing copyright for project documentation; and making automated payments among project parties. It also notes that it can function as a platform for claim submission. Therefore, the automation of some construction processes that often depend on several interactions and contributions from project participants will benefit from using smart contracts (Mason & Escott, 2018). In the construction sector, late payments and insolvencies result in numerous claims. Still, smart contracts can considerably limit the consequences (Elghaish *et al.*, 2020:3). Lamb (2018:11) argued that a smart contract is a straightforward and efficient solution that holds promise for corporate growth. Complex transactions can be quite expensive; thus, smart contracts can help lower these overall costs.

Building a dependable cash flow is difficult because of the unpredictability of construction payments, which ultimately results in claims that hinder corporate growth (Elghaish *et al.*, 2021:558). A trust fund, wherein smart contracts have the potential to function as trust accounts that store funds that will be automatically delivered to the intended recipient upon agreed milestones. Given that all embedded data is immutable and decentralized, project participants will trust smart contract outputs (Lamb, 2018:11). Blockchain has the potential to be an objective and consistent contract management tool which could have risk mitigation and financial surety benefits to all project stakeholders.

2.3.2 Partnering and integrated project delivery

Partnering allows EPC contractors to assess design-related aspects of the projects and the surrounding environment from a broad perspective by asking each stakeholder if the projects align with their needs (Lam *et al.*, 2006:460). Project stakeholders are encouraged to contribute to the design, procurement, and construction stages since partnering have a win-win benefit (Wang *et al.*, 2015:2). Critical success factors for partnerships can be divided into two categories: attitude factors, which include shared goals and objectives, attitudes, equity, commitments, and trust; and open communication factors, which include openness, teamwork, effective communication, problem-solving, and prompt responsiveness (Black *et al.*, 2000:424).

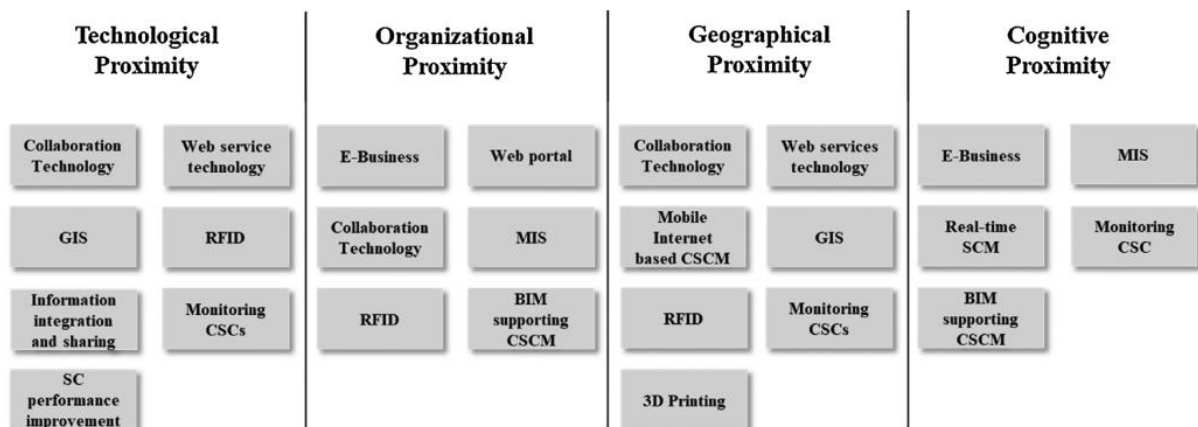
Integrated project delivery (IPD) is a method for managing construction projects that actively incorporates essential players from the beginning of the project timeline, frequently even before the design phase. It is distinguished by a multiparty contractual arrangement that often permits project stakeholders to share risks and rewards (El Asmar *et al.*, 2013:1). El Asmar *et al.* (2013:13) found that IPD has excelled in measures for quality, communication, and change performance, it has been demonstrated. The quality aspect was found to possibly be the most meaningful metric that IPD improves. Less changes, quicker processing, and noticeably quicker delivery are all observed in IPD initiatives. The primary goal of IPD is to address a number of significant flaws in traditional project delivery techniques, including uncertain productivity levels, poor time and budget management, inadequate information in specifications and drawings, and high levels of material waste (Nguyen & Akhavian, 2019:2). The age of digitalisation enables integrated collaboration to a substantial extent. The transparency and communication advantages of partnering and integrated project delivery translate back to vertical integration, which forms a critical part 4IR and potentially poses significant benefits to EPC project delivery.

2.3.3 Integrated supply chains

The typical method of contracting the work from top to bottom through numerous layers to the EPC contractor, subcontractors, and their sub suppliers in a contractual hierarchy result in transaction expenses that account for 40% of the project costs (Wagner, 2020:2249). The supply chain will be flattened via relation contracting as opposed to roll-up contracts, which will result in a network instead of a contracting hierarchy (Wagner, 2020:2249). The integration of the supply chain into the plant design can be improved through the use of standardization and modularization. Many components are over-specified, and by removing these over-specifications, costs can be reduced. Platform solutions that are scalable and agile, like those used in automotive design, allow uniformity without removing important variations (Wagner, 2020:2249).

Dallasega *et al.* (2018:206) argued that to enhance the efficiency of a construction supply chain careful focus should be given to proximity theory. A key factor influencing knowledge transfer, innovation, and inter-organizational cooperation, according to proximity research, is the distance between two or more entities (Amin & Wilkinson, 1999:122). Dallasega *et al.* (2018:217) introduced the use of 4IR technology to address supply chain proximity with the concepts displayed in Figure 2-7 below.

Figure 2-7: 4IR technology applications to supply chain proximity



Source: Dallasega *et al.* (2018:217)

Dallasega *et al.* (2018:222) concluded that 4IR concepts has a noteworthy influence on technological, organisational, geographical, and cognitive dimensions of proximity which has the potential to integrate the construction supply chain significantly.

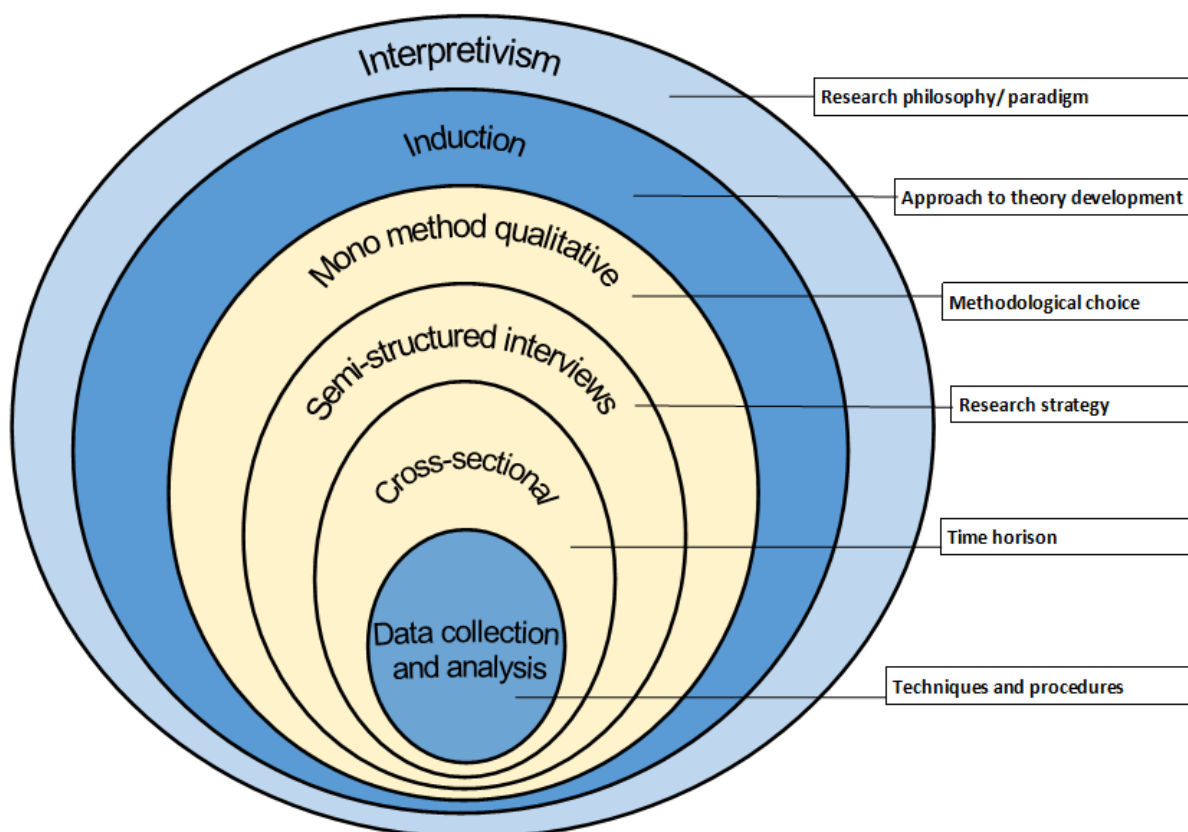
CHAPTER 3 RESEARCH METHODOLOGY

3.1 Empirical study

Empiricism denotes that knowledge gained through experience and the senses can be accepted (Bryman *et al.*, 2015:xxi). Academic research in business and management focuses on questions pertaining to the fields relevant to business and management and has a social science orientation (Bryman *et al.*, 2015:xxi). The study will consist of primary data analysed to develop a theoretical framework of Industry 4.0 technology and its application within the execution of EPC projects.

Saunders, Lewis and Thornhill (2019:130) propose the research onion model as a framework for designing business and management research. The framework in Figure 3-1 below is adapted from the research onion model as a summary of the research design of this study:

Figure 3-1: The research onion model derived for this study



Source: Adapted from Saunders *et al.* (2019:130)

The research design, as summarised in Figure 3-1, will be introduced in the sub-sections to follow.

3.1.1 Research paradigm (Figure 3-1, Layer 1)

The research paradigm articulates a set of beliefs regarding and guides behaviours related to the ontology, epistemology, and methodology guiding the research and the methods employed (King, 2021:121). The research paradigm chosen for this study is interpretivism. The interpretive view emphasises that humans create meanings, separating them from physical phenomena (Saunders *et al.*, 2019:148). Social scientists and natural scientists approach their subject matter in fundamentally different ways. Interpretivism begins from the assumption that people and their institutions comprise the subject matter of the social sciences (Bryman *et al.*, 2015:148).

That is why this study is subjective of nature, and the author aimed to understand the value and risk perception of strategic role players within a specific industry when implementing a theoretical technology framework in EPC practice. The purpose of the interpretive research is to create new, richer understandings of the value perception within the boundaries of the study theme.

3.1.2 Research approach (Figure 3-1, Layer 2)

The inductive approach involves working exclusively from the participant experiences that drive the analysis entirely. According to Thomas (2006:238), the inductive research approach utilises detailed readings of raw data to derive concepts and themes. The process involves sifting through the data line-by-line and assigning codes to each paragraph or segment as concepts emerge (Bradley *et al.*, 2007:1759; Curry *et al.*, 2009:1444) relevant to the research questions (Thomas, 2006:238).

Inductive research is chosen for the study due to its connection to humanities and its emphasis on the importance of subjective interpretations. The study collected data and analysed the data to observe trends. A theory was then formulated based on the result of the analysis.

3.1.3 Methodological choice (Figure 3-1, layer 3)

A qualitative study has a humanistic focus (Gephart, 2004:455), which means it aims to understand the worldviews of participants rather than the concrete realities of objects.

Referring to the clear subjective and socially constructed phenomenon being studied; a mono method qualitative methodology is followed in this study. Qualitative research frequently takes an inductive approach to theory construction, using naturalistic and emergent research methods to develop a theory or provide a richer theoretical perspective than existing (Saunders *et al.*, 2019:179). Quantitative research consists primarily of non-numerical data such as words, pictures and actions (Bryman *et al.*, 2015:41). The author aimed to engage with strategic and management

stakeholders within the relevant industry and aim to collect thick data to observe perceptions and trends.

3.1.4 Research strategy (Figure 3-1, layer 4)

Researchers conduct research interviews by asking concise and unambiguous questions about the interviewee and listening attentively to them (Saunders *et al.*, 2019:434). Generally, qualitative interviews tend to be less structured, and the initial research ideas tend to be more general (Bryman *et al.*, 2015:224). The advantages of semi-structured interviews include their flexibility in addressing specific dimensions of the research question while also providing room for participants to provide new meanings to the topic of the study (Galletta, 2012:2).

Owing to the nature of the intended study, a semi-structured interview was the primary data source for this study. The interview aimed to discuss structured constructs and give the interviewee room to bring new conceptualisations into the data set. Semi-structured interviews will also allow the researcher to probe further responses on a previous answer of the interviewee.

3.1.5 Time horizon (Figure 3-1, layer 5)

A cross-sectional research design consists of data collected from more than one source at a single point in time (Bryman *et al.*, 2015:106). The referred time can be a determined timeframe of days, weeks, or months wherein a single data set is collected. This study will be conducted using a single data capture source, which will be a semi-structured interview. The research design will hence be cross-sectional in nature.

3.1.6 Study population and sampling (Figure 3-1, layer 6)

The study population will consist of strategic management stakeholders within the EPC industry in South Africa. The stakeholders will include:

1. Directors within operational and project management areas of responsibility
2. Executive managers of operational and project management departments
3. Group leaders of operational and engineering groups
4. Project managers above senior level
5. Engineering managers above senior level

The inclusions of this study will be as follows:

1. Only participants working in the EPC industry within the borders of South Africa. International participants will be allowed only if they are actively working for clients in South Africa.

2. Only participants that are direct strategic management stakeholders (functional members and decision-makers)
3. Only participants with active involvement in the petrochemical industry in South Africa

The exclusions of this study consisted of

1. Personnel in support services such as human resource management and information technology departments.
2. EPC consultants that are not actively serving clients with a majority income derived from the petrochemical industry

The sample frame consists of respondents, directly and indirectly, accessible to the researcher. The data saturation point determined the sample size. Saunders *et al.* (2019:315) states that data saturation is reached when there are few new discoveries or themes derived from the additional data collected.

3.1.7 Designing the measuring instrument (Figure 3-1, layer 6)

Qualitative studies are designed to explore and interpret the opinions of participants. The sample participants were interviewed in semi-structured format to gain the primary data needed to make recommendations by identifying related themes and factors. The questions were open-ended to ensure that responses were unique and covered unknown factors. Each interview started with an introduction to the study. All the relevant factors were mentioned for the participant to gain the necessary background. It was made clear that participation in the study is entirely voluntary, and the participant can, at any time, decide not to be part of the study anymore. Each participant signed an informed consent form stating that they understand the terms and what they need to do. A sample of the informed consent form can be found in Annexure A. The typical questions for the semi-structured interview can be found in Annexure B.

3.1.8 Collection of data (Figure 3-1, layer 6)

The data collection will be through semi-structured interviews. The interviews were conducted virtually using Microsoft Teams. All interviews were recorded to ensure that no data is missed. During the interview, the researcher made notes and the transcription function of Microsoft Teams was used to transform the interview to text. The notes and Microsoft Teams transcription was combined and confirmed with the sound recording to reach the final data set for each respondent.

3.1.9 Statistical analysis (Figure 3-1, layer 6)

The researcher is interested to understand specific themes, constructs or models that become evident through the data. A thematic analysis will therefore be used. The essential purpose of this approach is to find themes or patterns that occur in a given data set (Saunders *et al.*, 2019:651). Once the qualitative data was collected, the data was be transcribed into text with the transcription functionality of Microsoft Teams. The researcher combined the transcribed data with any relevant notes taken during the interview. The interviews were recorded to ensure where the Microsoft Teams transcription functionality did not accurately capture the data, it can be confirmed at a later stage. The participants were asked permission to record and transcribe the interview. After reading and editing the draft transcript, the data can be analysed while considering pauses, repetitions, and emphasis (Kruger, 2018:37). The researcher analysed the notes by identifying:

1. The words the respondents use during the interview, terms they use to describe their situation, and keywords in context help explain what they are talking about
2. Unfamiliar words or unfamiliar usages of words to identify new themes in different datasets
3. The contrast in answers between datasets
4. Common conceptualisations between the different datasets

3.1.10 Reliability and validity

Bryman *et al.* (2015:44-45) describes the trustworthiness of data as made up out of four criteria. This includes:

1. *Credibility*: The researcher supplies the participants with the findings of the research. The participants then ensure that the researcher has correctly understood their social world. Semi-structured interviews will allow the researcher to clarify concepts, probe meanings and explore responses from various angles. This concept can also be referred to as respondent validation. The participants will be asked to validate the data analysis findings to ensure that no misinterpretation is present in the analysis.
2. *Transferability*: To provide readers with the possibility of transferability of results and findings to other contexts. The fundamental constructs of this study will be relevant to any business and can be transferred to other studies.
3. *Dependability*: The research will be audited to establish the merit of research in terms of trustworthiness. Every phase of the research process should be kept on record.
4. *Confirmability*: The researcher's confirmability will be confirmed when the first three criteria above are met. It confirms that the findings are derived from actual data collected during

semi-structured interviews and that no personal values, conflict of interest or external environments influenced the study.

CHAPTER 4 DATA ANALYSIS

4.1 INTRODUCTION

The participants were recruited through convenience sampling based on their current roles within EPC projects, their experience within the different management functions of EPC projects and their willingness to partake in the study. Chapter 4 will contain the data analysis of the data gathered through the five semi-structured interviews and a discussion of the findings after each Section.

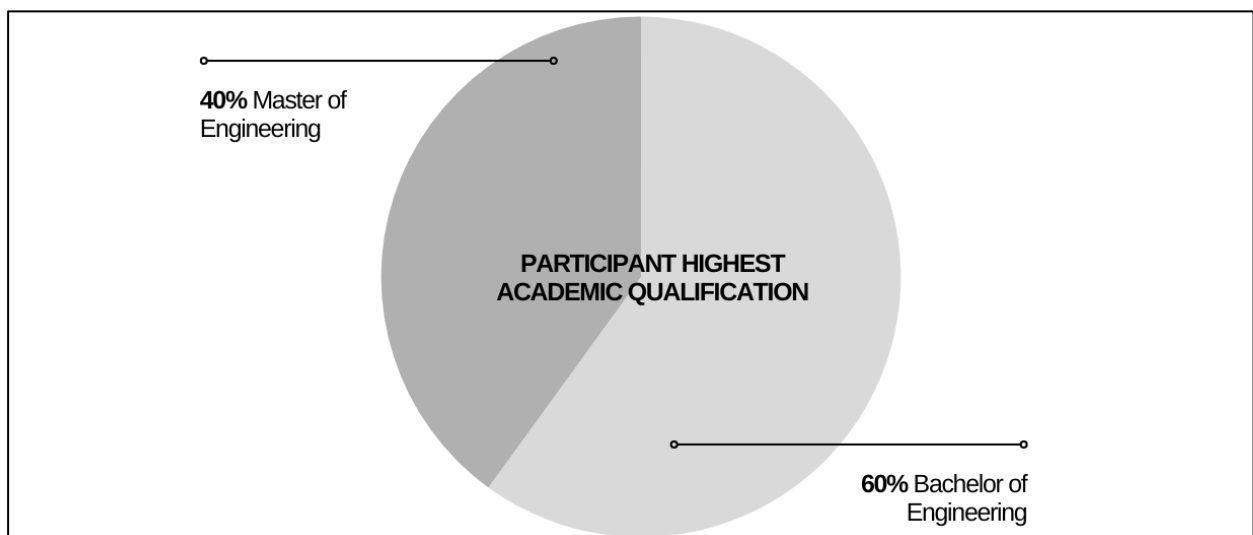
4.2 DEMOGRAPHIC DESCRIPTION

The range of the demographic population will be indicated by reflecting upon selected information that was captured during the interviews with the participants.

4.2.1 Highest academic qualification of participants

The target population discussed in Section 3.1.6 generally consists of tertiary-qualified engineering professionals in project management and engineering management roles. The full sample of this study has Bachelor of Engineering degrees, with one participant obtaining a Master of Engineering as displayed in Figure 4-1.

Figure 4-1: Highest academic qualifications of participants

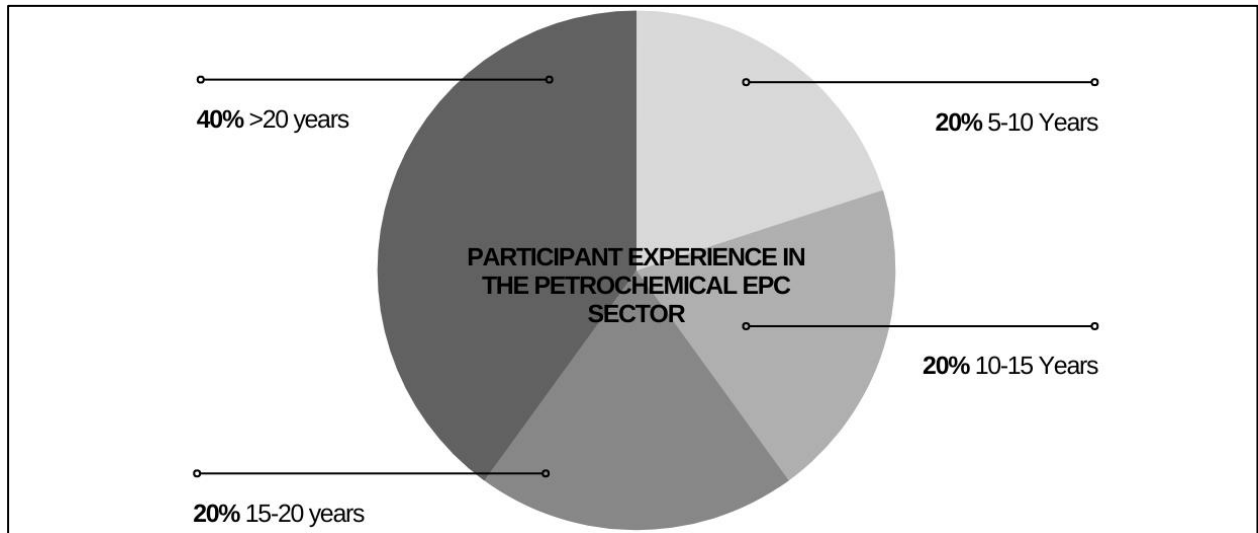


4.2.2 Years of experience in the South African petrochemical EPC sector

The target population discussed in Section 3.1.6 generally reach senior and principal roles in the petrochemical EPC sector later in their career due to the high level of complexity and

accountability in these positions. The participants are considered experienced role players in the South African petrochemical EPC sector, with an average of 19.4 years of experience in the industry. Figure 4-2 graphically displays the distribution of experience among the participants.

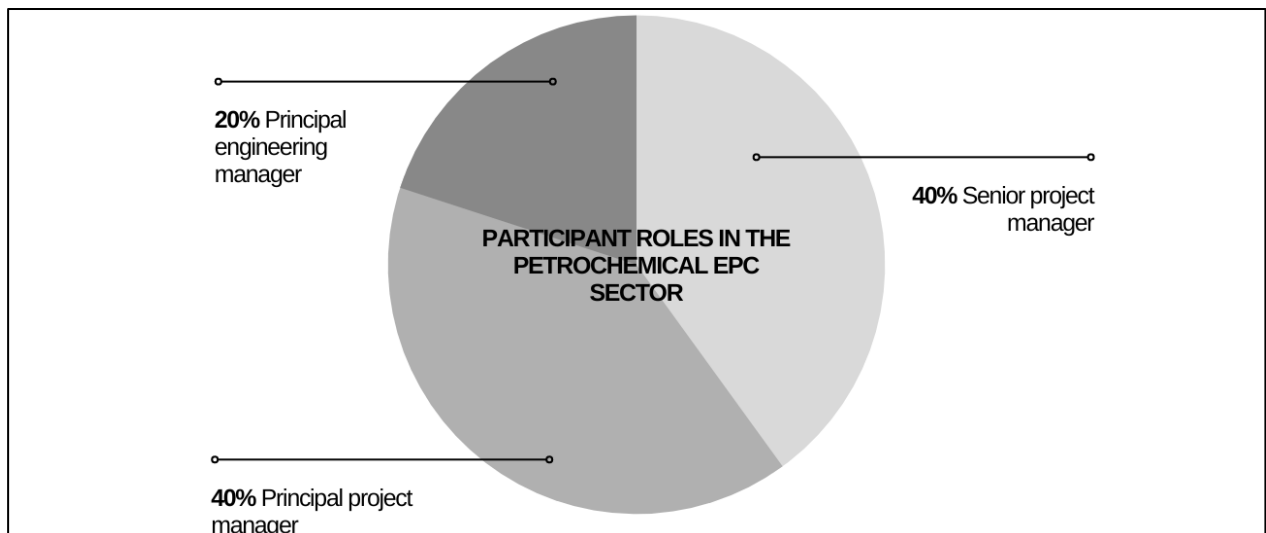
Figure 4-2: Participants' experience in the petrochemical EPC sector



4.2.3 Roles of participants in the South African petrochemical EPC sector

The participants fulfil roles demarcated in Section 3.1.6. The distribution of the current roles of the participants is graphically displayed in Figure 4-3 below:

Figure 4-3: Participants' roles in the petrochemical EPC sector



4.3 THE CURRENT CHALLENGES FACED IN SOUTH AFRICAN PETROCHEMICAL EPC PROJECTS

4.3.1 Introduction

The semi-structured questions aimed to investigate the challenges faced, the extent of technology implementation and the perceived hurdles of technology implementation in the various phases of petrochemical EPC projects in South Africa. The transcribed data were analysed for key themes and statuses in the South African context of petrochemical EPC projects, and the results will be displayed in this Section.

4.3.2 Challenges faced during the engineering design phase

Table 4-1 below displays the themes of challenges participants noted in the engineering design phase:

Table 4-1: Challenges faced in the engineering phase

Participant	Code	Themes identified
P001	EP1	Interface management and communication among engineering disciplines
	EP2	Unclear project scope definition and project objectives
	EP3	High turnover of engineers on projects
P002	EP1	Interface management and communication among engineering disciplines
	EP3	High turnover of engineers on projects
P003	EP2	Unclear project scope definition and project objectives
	EP1	Interface management and communication among engineering disciplines
P004	EP2	Unclear project scope definition and project objectives
	EP1	Interface management and communication among engineering disciplines
P005	EP1	Interface management and communication among engineering disciplines
	EP2	Unclear project scope definition and project objectives
	EP4	Delays in multi-discipline engineering design

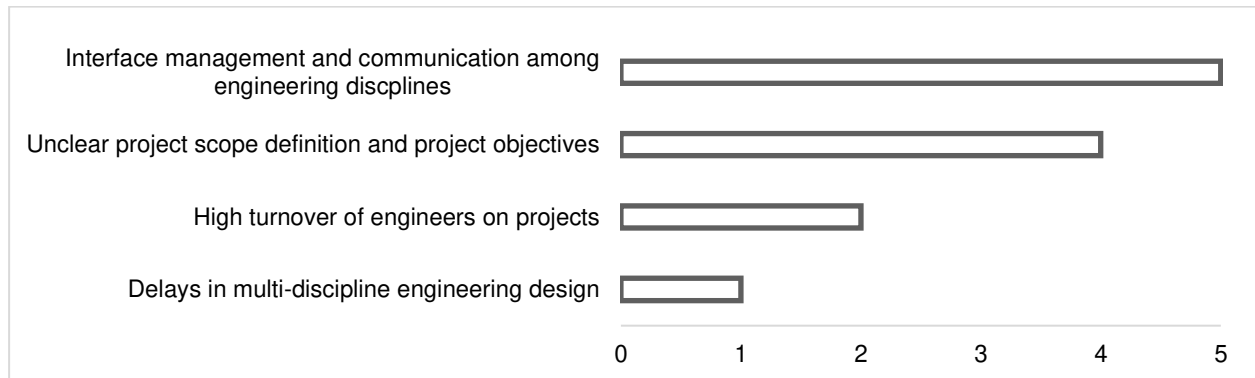
Table 4-2 below displays the frequency of the identified recurring themes within the sample group with a percentage of how many of the respondents found the theme as a challenge:

Table 4-2: Frequency statistics of challenges faced in the engineering phase

Theme	Code	Frequency	Percentage
Interface management and communication among engineering disciplines	EP1	5	100%
Unclear project scope definition and project objectives	EP2	4	80%
High turnover of engineers on projects	EP3	2	40%
Delays in multi-discipline engineering design	EP4	1	20%

A graphic representation of the recurring themes of challenges in the engineering phase is displayed in Figure 4-4 below:

Figure 4-4: Frequency statistics of challenges faced in the engineering phase



4.3.3 Challenges faced during the procurement phase

Table 4-3 below displays the challenges participants noted in the procurement phase:

Table 4-3: Challenges faced in the procurement phase

Participant	Code	Themes identified
P001	PP1	Interface management between designer and supplier
	PP2	Long lead times of material necessitates ordering of material required before detail design is completed
	PP3	Unreliable suppliers
P002	PP1	Interface management between designer and supplier
	PP4	Design errors and emissions
P003	PP1	Interface management between designer and supplier
	PP5	Changes in project scope
	PP4	Design errors and emissions
P004	PP1	Interface management between designer and supplier
P005	PP1	Interface management between designer and supplier
	PP2	Long lead times of material necessitates ordering of material required before detail design is completed

Table 4-4 below displays the frequency of the identified recurring themes within the sample group with a percentage of how many of the respondents found the theme as a challenge:

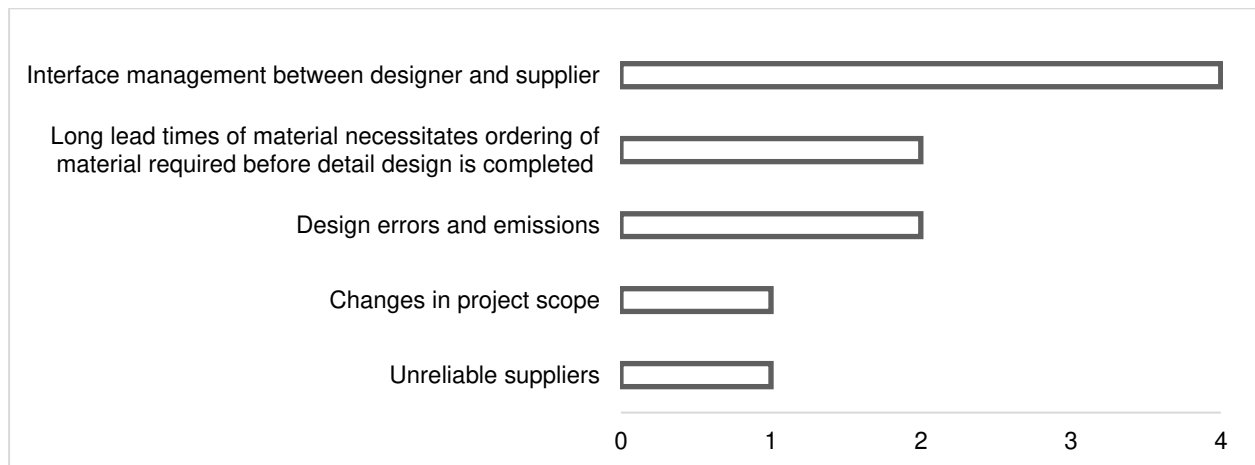
Table 4-4: Frequency statistics of challenges faced in the procurement phase

Theme	Code	Frequency	Percentage
Interface management between designer and supplier	PP1	5	100%
Design errors and emissions	PP4	2	40%

Theme	Code	Frequency	Percentage
Long lead times of material necessitates ordering of material required before detail design is completed	PP2	2	40%
Unreliable suppliers	PP3	1	20%
Changes in project scope	PP5	1	20%

A graphic representation of the recurring themes of challenges in the procurement phase is displayed in Figure 4-5 below:

Figure 4-5: Frequency statistics of challenges faced in the procurement phase



4.3.4 Challenges faced during the construction phase

Table 4-5 below displays the challenges participants noted in the construction phase:

Table 4-5: Challenges faced in the construction phase

Participant	Code	Themes identified
P001	CP1	Lack of skilled labour
	CP2	Interface management and communication
	CP3	Poor planning and scheduling
P002	CP2	Interface management and communication
	CP3	Poor planning and scheduling
	CP1	Lack of skilled labour
P003	CP1	Lack of skilled labour
	CP4	Rework
	CP5	Changes in project scope
	CP2	Interface management and communication
P004	CP2	Interface management and communication
P005	CP1	Lack of skilled labour
	CP6	Poor labour productivity
	CP2	Interface management and communication

Participant	Code	Themes identified
	CP4	Rework

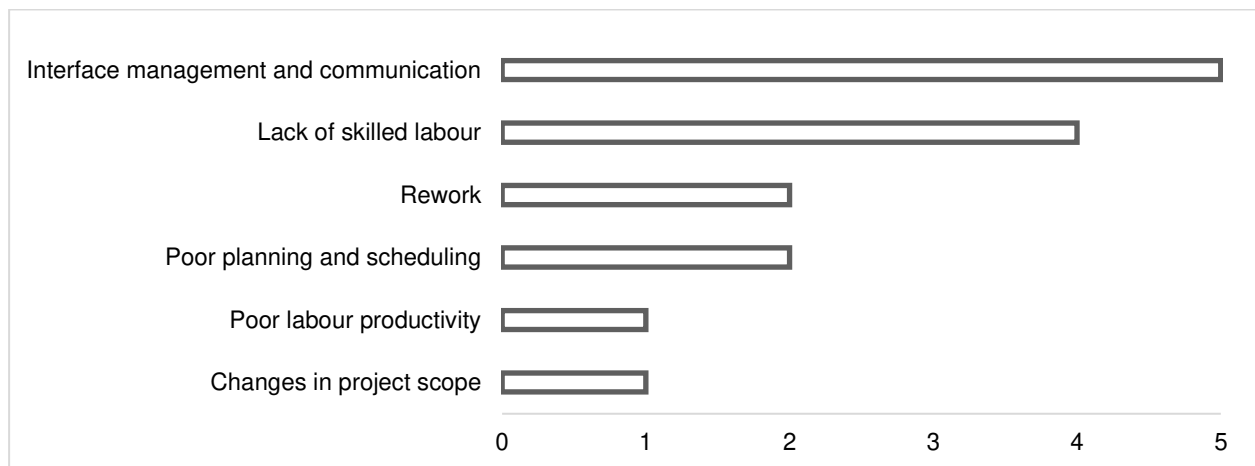
Table 4-6 below displays the frequency of the identified recurring themes within the sample group with a percentage of how many of the respondents found the theme as a challenge:

Table 4-6: Frequency statistics of challenges faced in the construction phase

Theme	Code	Frequency	Percentage
Interface management and communication	CP2	5	100%
Lack of skilled labour	CP1	4	80%
Poor planning and scheduling	CP3	2	40%
Rework	CP4	2	40%
Changes in project scope	CP5	1	20%
Poor labour productivity	CP6	1	20%

A graphic representation of the recurring themes of challenges in the construction phase is displayed in Figure 4-6 below:

Figure 4-6: Frequency statistics of challenges faced in the construction phase



4.3.5 Validation of Table 2-1 in the South African context

Table 2-1 contains a summary of repetitive problems that have cost and schedule impact in each phase of engineering and construction projects worldwide. Each of the themes of these repetitive problems was described to the participants, and they were requested to acknowledge whether these problems exist in the South African petrochemical EPC sector. All the participants acknowledged that the nine problems exist in the South African petrochemical EPC sector. The content of Table 2-1 is deemed validated in the South African petrochemical EPC context.

4.3.6 Discussion of findings

4.3.6.1 Engineering phase

The two most prominent themes arising in the engineering phase are interface management and the lack of clear project scope and objectives, which largely contribute to each other. *P003* noted that scope changes often occur due to unclear scope definitions in the early stages of projects. Maherry (2012:29) similarly found that the design team may not be in alignment because of inadequate project objectives, which could lead to changes in the design. *P003* further noted that the resulting changes complicate communication and interface management between the engineering disciplines. This is confirmed by Long (2022:1), which described each process unit as an assembly line, where the output of the previous unit becomes the input for the next unit. As a result, a change to the operation or equipment of one process can affect the design of its successors. *P002* noted that the communication of these changes often leads to emission by one of the engineering disciplines. *P005* pointed out that this is often an occurrence on the interfaces between civil designs and mechanical and piping designs and then between instrumentation designs and mechanical or piping designs: *"We have various instances of problems on the interfacing between disciplines, and it is not complicated... Especially between instrumentation and mechanical, it's lack of communicating the information regarding the sizing of control valves, for example and subsequently valves do not fit in the construction phase"*. *P001* and *P002* further noted the high turnover of engineers on projects, which additionally introduced an information transfer interface between the resigning engineer and the replacement engineer. This is especially true in South Africa, where professionals are emigrating rapidly, where 30% of the South African critical skills shortage list directly impacts the EPC sector (Department of Home Affairs, 2022).

4.3.6.2 Procurement phase

Interface management between the designers and suppliers is rated as the most significant challenge noted by all participants. *P004* stated that the problem does not only involve the transfer of technical information, but also the commercial accountability aspect of the supplier's offering that is required to ensure the project schedule and cost objectives are met. *P005* stated that due to the manual and unstandardised process involved in the compilation of bills of material, a lot of manhours are spent on the verification process of bills of material and even after verification, it is still prone to errors. *P002* further noted that due to the high levels of requirements bound to materials procured for petrochemical equipment, the information flow between the engineers and sales representatives, that is often not equipped with the required technical knowledge, often leads to miscommunication and materials that do not conform to the requirements subsequently

delivered. A further factor of supplier interface management noted by *P001* and *P004* was the expediting of material that frequently gets neglected. This results in suppliers often being unreliable in adhering to the agreed lead times. *P001* and *P005* referred to the parallel model of engineering and procurement where schedule pressure induces the need for procurement orders to be placed before the detail engineering design has been completed due to the long lead time of the material. The bill of material is not accurate at this design stage and is often influenced by design changes, errors, and emissions.

4.3.6.3 Construction phase

Interface management and communication are rated as the most significant challenge noted by all participants. Interface management during the construction phase of petrochemical EPC projects consists of the Engineering Contractor managing a vertical interface with the owner on the one end and the various construction contractors on the other. *P002* mentioned that if the owner representatives do not understand the project's scope, it will lead to delays as no physical construction can commence until work permits are issued. *P005* similarly noted that in a typical shift, the productive hour of the workforce is significantly reduced due to delays of work permits and the safety conditions of the permits that get issued. *P005* argued that once all the permit conditions have been addressed, four hours of each shift are lost. *P001* noted that the interface between the engineering contractor and the various construction contractors is often challenging because the construction contractors only have knowledge about their own scope and delays often occur when simultaneous operations are not efficiently sequenced. *P004* similarly noted that the interfacing of different construction contractors working in the same area is challenging from a safety and productivity perspective. The example noted is when overhead rigging is in progress, no labour is allowed to work under the suspended load, and with heavy lifts, delays of multiple shifts are often not planned for. *P001* and *P002* described similar interface delays due to poor planning and scheduling that led to ineffective construction activity sequencing. As noted by four participants, the lack of skilled labour is a significant challenge in the South African petrochemical EPC sector. Due to the strict regulations on pressure equipment, quality artisans are required to ensure that activities like the welding of pressure equipment conform to quality standards. *P003* noted that weld repair rates are often the result of the lack of skills in artisans and that rework due to substandard craftsmanship poses a significant threat to construction schedules. *P005* added that construction contractors are constrained in the appointment of labour due to socio-economic and political factors, which further contributes to the challenge of obtaining the required skilled artisans.

4.4 CURRENT STATUS OF DIGITALISATION WITHIN THE PARTICIPANTS' EPC ENVIRONMENTS

4.4.1 Information flow and communication systems

Throughout the semi-structured interviews, probing questions was asked to determine the level of digitalisation and automation of information flow within the participants' project functions. The following rating system (Table 4-7) is applied to analyse the level of digitalisation and information flow:

Table 4-7: Rating system of digitalised information flow

Rating	Description
Digitalised information flow	Formal digitalised information flows introduced between all project functions
Highly digitalised information flow	Formal digitalised information flows introduced between more project functions than not.
Semi-digitalised information flow	Formal digitalised information flows introduced between some of the project functions
Limited digitalised information flow	Limited formal digitalised information flows introduced between project functions
Manual information flow	Information flows reliant on manual communication

Table 4-8 below displays the level of digitalised information flows described by participants:

Table 4-8: Ratings of digitalised information flow

Participant	Rating of digitalised information flow
P001	Manual information flow
P002	Limited digitalised information flow
P003	Limited digitalised information flow
P004	Limited digitalised information flow
P005	Manual information flow

Table 4-9 below displays the frequency of the identified ratings within the sample group:

Table 4-9: Frequency statistics of identified digitalised information flow ratings

Rating	Frequency
Limited digitalised information flow	3
Manual information flow	2

A graphic representation of the identified ratings is displayed in Figure 4-7 (P.65):

Figure 4-7: Frequency statistics of identified digitalised information flow ratings



4.4.2 Supply chain and procurement automation

When asking the participants questions pertaining to procurement in the semi-structured interviews, probing questions was asked to determine the level of digitalisation and automation of procurement activities within the participants' project functions. The following rating system (Table 4-10) is applied to analyse the level of digitalisation and information flow:

Table 4-10: Rating system of digitalised procurement

Rating	Description
Digitalised procurement	Formal digitalised procurement and expediting introduced in all project disciplines
Highly digitalised procurement	Formal digitalised procurement and expediting introduced in more project disciplines than not.
Semi-digitalised procurement	Formal digitalised procurement and expediting introduced in some of the project disciplines
Limited digitalised procurement	Limited formal digitalised procurement and expediting introduced in project disciplines
Manual procurement	Procurement and expediting reliant on manual communication

Table 4-11 below displays the level of digitalised procurement described by participants:

Table 4-11: Ratings of digitalised procurement

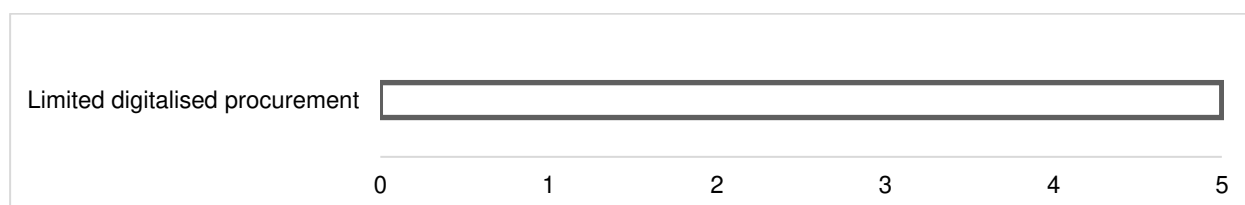
Participant	Rating of digitalised information flow
P001	Limited digitalised procurement
P002	Limited digitalised procurement
P003	Limited digitalised procurement
P004	Limited digitalised procurement
P005	Limited digitalised procurement

Table 4-12 (P.66) displays the frequency of the identified ratings within the sample group:

Table 4-12: Frequency statistics of identified digitalised procurement ratings

Rating	Frequency
Limited digitalised procurement	5

A graphic representation of the identified ratings is displayed in Figure 4-8 below:

Figure 4-8: Frequency statistics of identified digitalised procurement ratings

4.4.3 Data capturing and analytical usage of captured data

The participants were asked to what extent data is captured within their project functions and then analysed to identify trends and opportunities. The following rating system (Table 4-13) is applied to analyse the level of data capturing and analytics:

Table 4-13: Rating system of data capturing and analytics

Rating	Description
High data capturing and analytics	Standardised and formal data capturing systems with applied analytics to identify trends and opportunities
High data capturing; no analytics	Standardised and formal data capturing systems, but the data is not analysed to identify trends and opportunities
Limited data capturing and analytics	Limited standardised and formal data capturing systems with some applied analytics to identify trends and opportunities
Limited data capturing; no analytics	Limited standardised and formal data capturing systems and the data is not analysed to identify trends and opportunities
No data capturing	No standardised or formal data capturing

Table 4-14 below displays the level of digitalised procurement described by participants:

Table 4-14: Ratings of digitalised information flow

Participant	Rating of digitalised information flow
P001	Limited data capturing; no analytics
P002	Limited data capturing; no analytics
P003	Limited data capturing; no analytics
P004	Limited data capturing; no analytics
P005	No data capturing

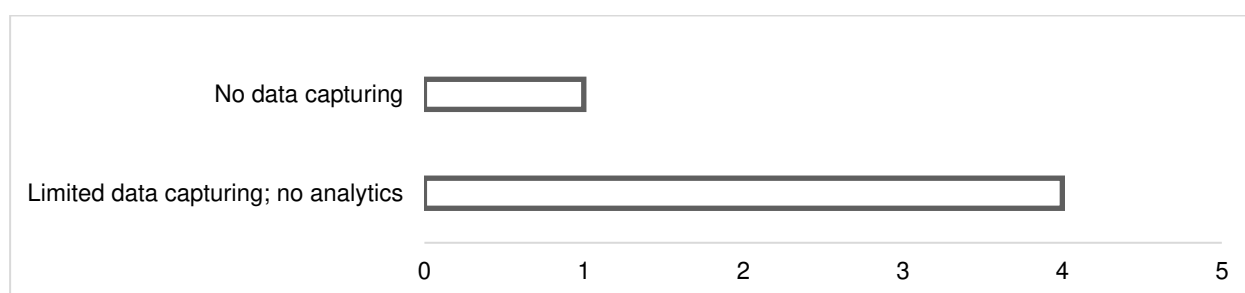
Table 4-15 below displays the frequency of the identified ratings within the sample group:

Table 4-15: Frequency statistics of identified data capturing ratings

Rating	Frequency
Limited data capturing; no analytics	4
No data capturing	1

A graphic representation of the identified ratings is displayed in Figure 4-9 below:

Figure 4-9: Frequency statistics of identified data capturing ratings



4.4.4 Discussion of findings

The data on the current status of digitalisation within the South African petrochemical EPC sector clearly shows sign of the delayed adoption of digitalisation. Boston Consulting Group. (2016:14-15) argued that the delayed adoption of digitalisation and the lack of innovation in the construction industry is a major contributor to the low productivity figures evident in the sector.

4.4.4.1 Information flow

The information flow within the participants' organisations is at a very early stage of digitalisation. All participants noted that only financial processes and approvals are formally digitalised. *P001* indicated that the flow of information other than financial approvals is still a manual process wherein project managers and engineering managers act as the distribution channel for communication between the different project functions. *P004* confirmed this and noted that the manual flow of information makes interface management throughout the project very difficult. *P005* noted that even standard information flow functions like document control are not automated. All participants acknowledged the need for digitalisation in the flow of information in all phases of their projects and confirmed the potential benefit thereof.

4.4.4.2 Procurement

Similar to the findings of Section 4.4.4.1, all participants noted that only the financial processes and approvals are formally digitalised in the procurement phase of projects. *P004* stated that the full function of procurement is rarely executed because continuous expediting and tracking of material is omitted in digital and manual form. *P004* further notes that without digitalisation within the procurement system, the latter-mentioned omission results in only buying taking place on projects, not procurement, as procurement includes full awareness from the bidding phase to the delivery of the items. *P005* noted that even though design software packages include functionality to fully digitalise the flow of procurement data, designers revert to the manual take-off of the bill of materials. This is often due to designers not trusting the software to transfer procurement information accurately.

4.4.4.3 Data capturing and analytics

Although the participants noted that some data gets captured throughout the project's lifecycle, it is only used for tracking and reporting and is not used for analytics and insights. *P004* noted that a lack of commitment from all disciplines to capture data in a standardised and common database makes analysing the data difficult. *P001* pointed out that the insights gained for improving project functions rely on the personal experience of the project management and planning stakeholders. Most planning estimations are not based on a foundation of data collected in previous projects but on the duration and cost perceptions of similar activities executed by the individuals responsible for planning. *P002* noted that due to the lack of data capturing during previous projects, the transfer of lessons learned knowledge is merely a meeting with a PowerPoint presentation that seldom add value when the challenges recur. *P002* noted: *"If we could from the past have captured a lot of information and data, we would be able to resolve a lot of constraints and issues with the current reality much more efficiently and effectively rather than to reinvent the wheel every time that we address the problem"*. *P005* noted that even if the data is available, it is not analysed in any way.

4.5 PERCEIVED BARRIERS OF TECHNOLOGICAL IMPLEMENTATION

P004 notes that technological implementation initiatives often need to be driven upwards into the organisation's leadership by those that have an aptitude to innovate. *P004* notes that this creates a bi-directional flow of innovation, which makes implementation initiatives difficult. The flow of innovation should be one-directional from the strategical leaders of organisations downwards into the organisation to ensure that the required commitment is received on all levels of the organisation. *P005*, similar to the findings of Boston Consulting Group. (2016:14-15) noted that

the benefits of innovation are only visible in the long term, but the capital expenditure is present. Therefore, the leadership in organisations is often unwilling to have significant expenditure on research and development. It was further noted that due to the South African petrochemical EPC sector being very fluctuating, organisations find it difficult to invest in innovation due to the lack of secure and steady income. *P005* further noted that innovation and technology require a definite skill set, understanding and aptitude for technology, which is a challenge in South Africa as there is already a big shortage of technical knowledge in its most basic form. *P005* noted that "...the younger workforce that is more accustomed to working with technology tends to emigrate as soon as they have the technical knowledge to add value to the sector". This is confirmed by a survey conducted by the South African Ichikowitz Family Foundation wherein the researchers found that more than half of young people between the ages of 18-24 years consider emigrating to other countries in the next three years (Businesstech, 2022). Liu *et al.* (2015:163) further confirmed the high cost of the implementation of software packages, the high cost of training personnel in the application, and the lack of skilled professionals to execute innovation ventures.

Confirming the findings of Oesterreich and Teuteberg (2016:123) and Boston Consulting Group. (2016:14-15), *P002* noted that the South African petrochemical EPC sector is renowned for having a robust, inflexible culture and highly resistant to change. This resistance to change can be argued to be influenced by the ageing workforce (Boston Consulting Group., 2016:14-15) in the sector that is not accustomed to and often does not trust high levels of technological implementation on projects. *P002* further noted that the error-prone nature of design software that is not utilised with the required technical knowledge leads to project stakeholders not trusting these software packages' functionality. *P005*, as discussed in Section 4.4.4.2, noted that stakeholders do not trust the procurement output of these software packages.

According to Hochscheid and Halin (2018:258) adoption consist out of five stages (Figure 4-10):

Figure 4-10: Five stages of adoption



Source: Adapted from Hochscheid and Halin (2018:258)

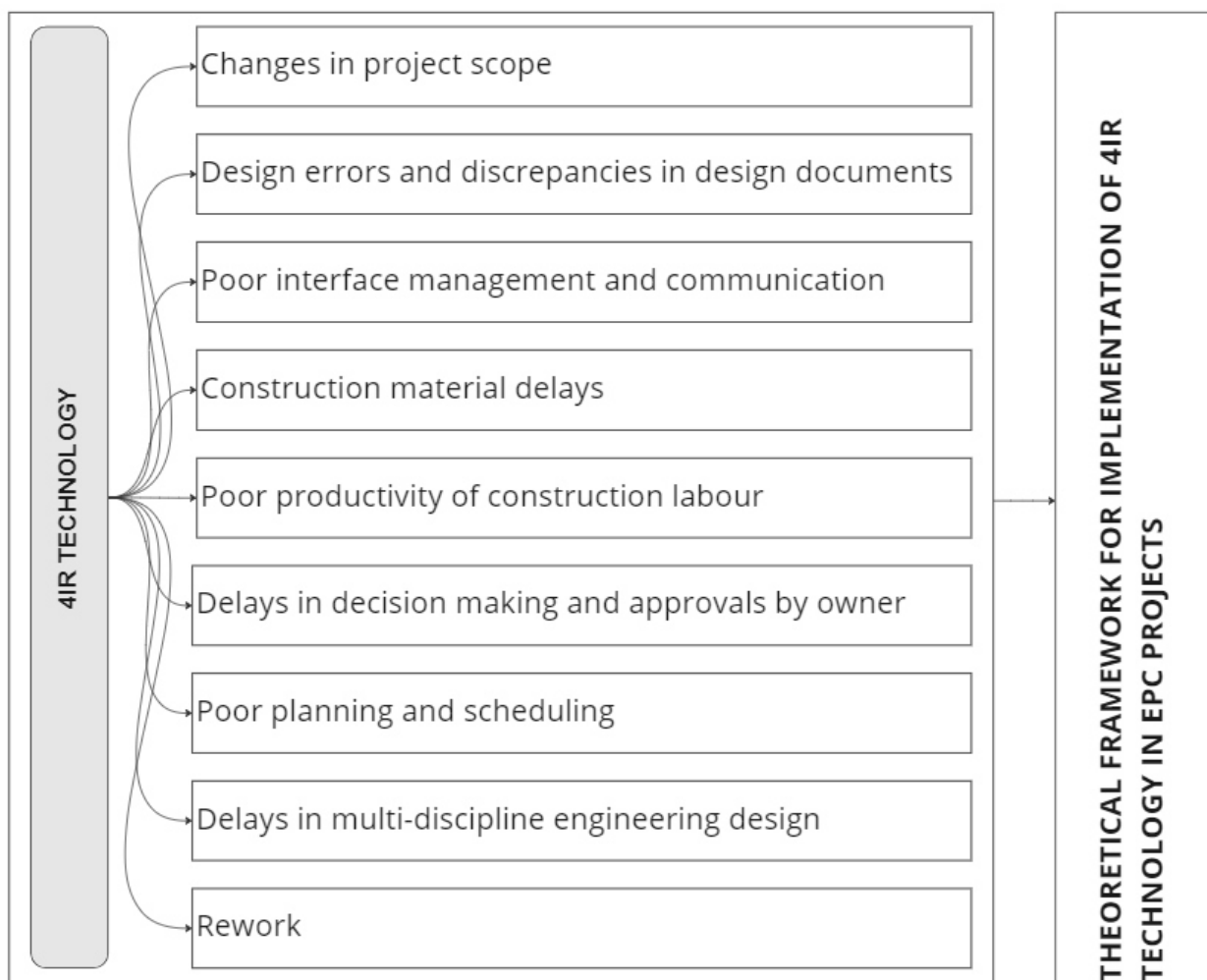
Without a flexible culture and trust in technology, the stage of decision in Figure 4-10 will not be reached, and subsequently, neither will adoption and implementation.

CHAPTER 5 THEORETICAL FRAMEWORK

5.1 INTRODUCTION

The main aim of this study was to identify opportunities to leverage technological advancements initiated by the fourth industrial revolution to address challenges associated with EPC projects within the petrochemical sector in South Africa. This chapter will close out the study by discussing the challenges identified in the empirical investigation and building a technological framework to address these challenges using secondary data. The identified challenges originated from global secondary data and were validated with primary data collection. The themes identified in Section 4.3 did not add to the secondary dataset, as displayed in Table 2-1. The participants individually validated each theme in Table 2-1. The themes that the 4IR framework will aim to address are displayed in Figure 5-1 below:

Figure 5-1: Framework methodology



5.2 IMPLEMENTING 4IR TECHNOLOGY TO ADDRESS IDENTIFIED CHALLENGES

5.2.1 Changes in project scope

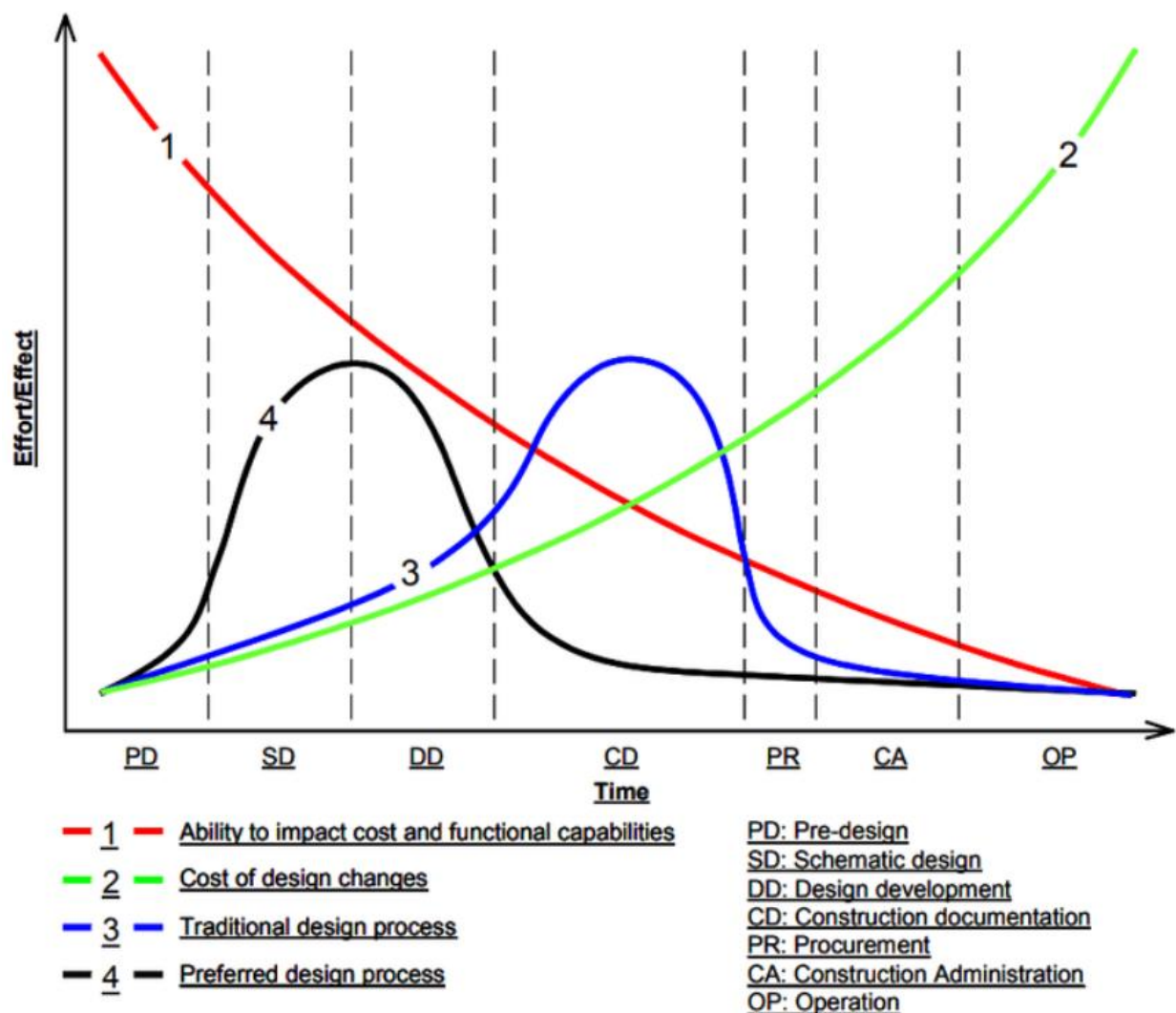
Table 5-1 below displays the opportunities identified in literature to address the influencing factors of changes in project scope.

Table 5-1: 4IR opportunities for addressing changes in project scope

Causation	4IR opportunities
Inadequate project objectives	Increased accuracy in project objectives and earlier identification of emitted requirements by partnering, IPD, BIM and AR/VR.
Errors and omission in design	Increased accuracy in project objective delivery and earlier identification of emitted requirements by partnering, IPD, BIM and AR/VR.
Financial challenges	Blockchain contracting strategies and accurate project feasibility estimations by using Big data analytics
Equipment vendor related design changes	Increased accuracy in equipment design requirements and earlier identification of equipment change impacts by IPD, BIM and AR/VR.
Inadequate details on drawings	Increased information sharing by IPD, BIM and AR/VR.

The Integrated Project Delivery (IPD) strategy involves making design decisions sooner in a project's lifecycle. IPD aims to bring together the information, methods, organizational frameworks, and business practices of various stakeholders in a collaborative process Talebi (2014:5). For the purpose of this study, IPD is seen as a form of vertical integration and will be used as an umbrella term for project management through collaboration. The MacLeamy Curve in Figure 5-3 (P72) demonstrates that the design choices made earlier in the project are more cost-effective since, at this point, there is the greatest chance to impact favourable outcomes and the least amount of money is needed to make modifications.

Figure 5-2: The Macleamy curve



Source: Adapted from American Institute of Architects (2019:12)

The design team can assess the effectiveness of the design and find mistakes before the production phase, thanks to digital representations of the infrastructure. BIM also gathers and analyses designs from all organizations collaboratively. By identifying, verifying, and correcting geometrical design errors between various construction components and installation systems, these two competencies pertain to performing quality control and assuring constructability Lee *et al.* (2018:354-368). As a result, coordination between various organizations and design disciplines is improved, errors and interface conflicts are discovered early in the design phase, and the construction process is sped up. At the same time, expenses are decreased, the likelihood of legal issues is decreased, and the construction period is reduced (Talebi, 2014:6).

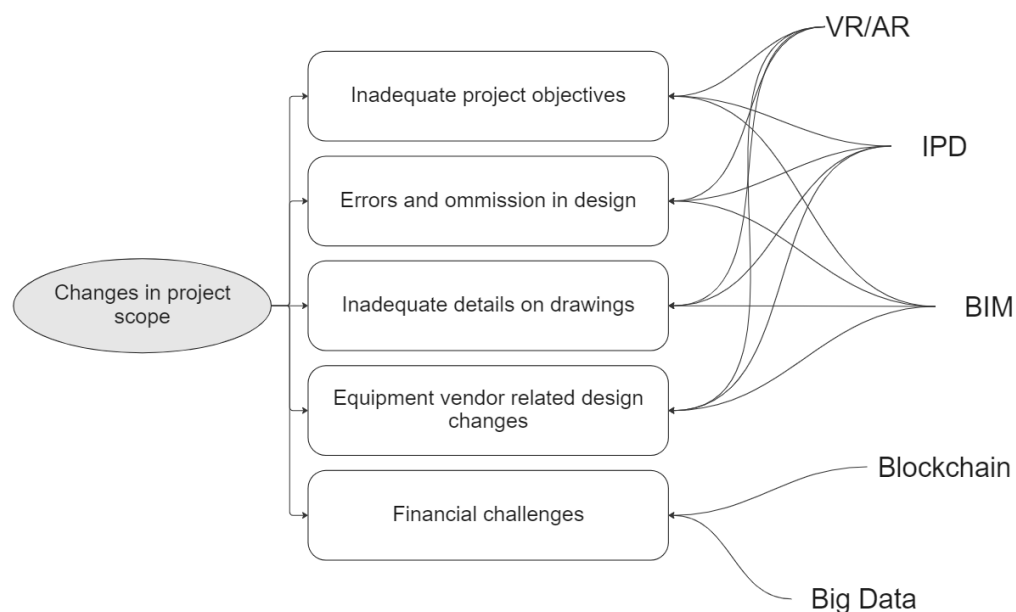
Evidence supports the effectiveness of VR technology in project schedule control, site layout optimization, and construction project safety training (Fu & Liu, 2018; Li *et al.*, 2018; Muhammad

et al., 2019). Additionally, VR technologies can create settings for improved stakeholder collaboration (Sutcliffe *et al.*, 2019), enable a better understanding of complex designs (Romano *et al.*, 2019), represent building geometry to help users understand a project and make a better design decision (Alizadehsalehi *et al.*, 2019), and support collaborative decision-making (Bille *et al.*, 2014).

There is a clear trend in the study data that design changes are a challenge and will remain a reality for petrochemical EPC projects in South Africa. However, the impact of the changes can be reduced the earlier it is made in the project lifecycle. By utilizing BIM, VR and AR visualization, collaboration, information transfer and communication can be significantly enhanced to increase accuracy in decision-making and reduce the need for changes.

Figure 5-3 below graphically displays the findings of Table 5-1.

Figure 5-3: 4IR opportunities for addressing changes in project scope



5.2.2 Design errors and discrepancies in design documents

Table 5-2 below displays the opportunities identified in literature to address the influencing factors of design errors with 4IR technology.

Table 5-2: 4IR opportunities for addressing design errors

Causation	4IR opportunities
Loss of biorhythm and adverse behaviour	Automating design activities by BIM implementation.

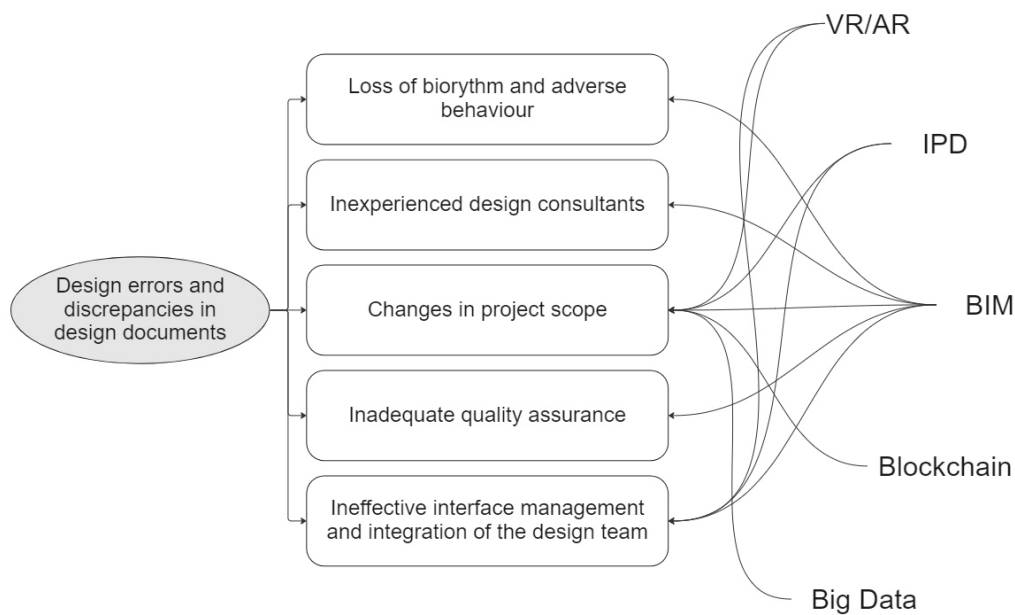
Causation	4IR opportunities
Inexperienced design consultants	Automating design verification modules in BIM models and increase the effect of knowledge sharing by IPD.
Changes in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
Inadequate quality assurance	Automating design verification modules in BIM models.
Ineffective interface management and integration of the design team	Live communication and design charrets enabled by BIM and VR/AR.

Al Hattab and Hamzeh (2015:69) emphasised the importance of a proactive strategy in design error prevention in opposition to the current reactive approaches that are inadequate in preventing the incidence of design errors. The research focussed on using BIM technology to enhance the exchange of information, which creates social cohesion with more collaboration within and between teams. The use of several defence mechanisms, including continuous and real-time communication, clash detection, automated code checking, design charrettes, and continuous learning, contributed to decreasing design errors. The automated function encapsulated in the BIM software can significantly increase design accuracy while reducing the required cognitive effort by resources that will relieve both workload and schedule pressure.

Fu and Liu (2018:430) found that by enhancing designers' perception and comprehension of both the virtual components and the actual surroundings, VR and AR are powerful design mediums that help designers comprehend concepts of designs in a better way and prevent the development of bad design ideas.

Figure 5-4 (P.75) graphically displays the findings of Table 5-2.

Figure 5-4: 4IR opportunities for addressing design errors



5.2.3 Poor interface management and communication

Interface management and communication are not viewed by literature as a lone-standing construct but as the root cause for a significant amount of the repetitive problems discussed in Section 2.2.3 and Section 4.2. Interface management has much potential as a managerial tactic since it makes inter-organisational collaboration and communication more accessible and lowers possible risks, particularly in EPC projects (Shen *et al.*, 2018:10).

Table 5-3 below displays the opportunities identified in literature to address the influencing factors of interface management with 4IR technology.

Table 5-3: 4IR opportunities for addressing poor interface management and communication

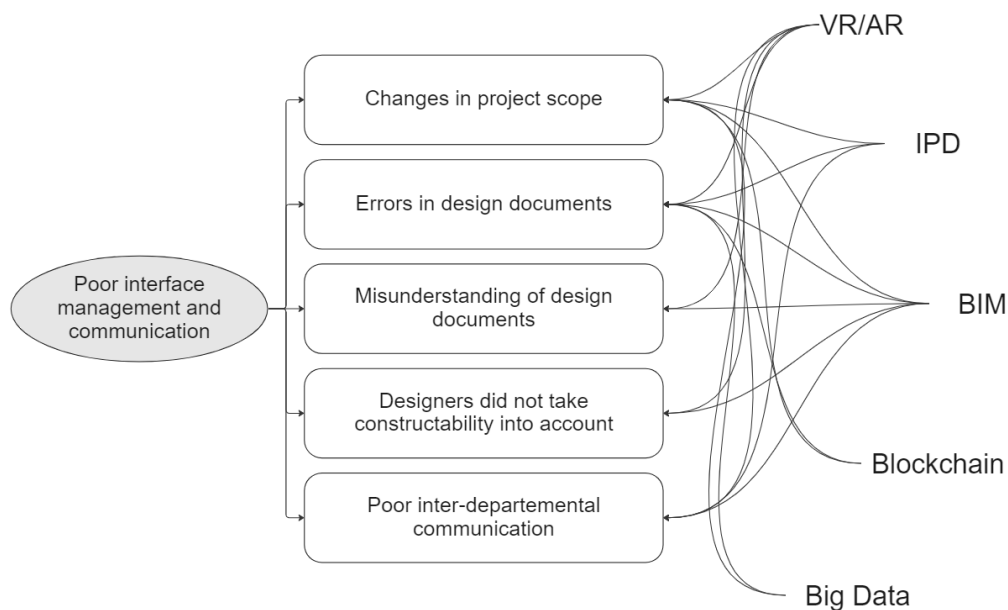
Causation	4IR opportunities
Changes in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
Misunderstanding of design documents	Virtual construction planning and constructability clarifications using BIM and AR/VR.
Errors in design documents	4IR opportunities to address errors in design documents was discussed in Section 5.2.2.
Designers did not take constructability into account	Virtual construction planning and constructability clarifications using BIM and AR/VR.

Causation	4IR opportunities
Poor inter-departmental communication	Live communication and design charrets enabled by BIM and VR/AR. The various technologies that encompass IPD can address can enhance communication channels to and from management stakeholders.

Interface management was found to be influenced by the prevailing Section 4.3.1 and Section 4.3.2, and therefore the technology relevant to the latter mentioned is relevant to interface management. The incorporation of interface management into BIM can be seen as a solid strategy for enhancing project monitoring and control to allow for real-time decision-making (Hmidah *et al.*, 2022:14). Combining interface management and BIM can help managers better understand how to manage the complexity, uncertainty, and risk associated with organisational structure, coordination, collaboration, and communication. This is especially true from the standpoint of deterministic project management (Hmidah *et al.*, 2022:14). The opportunity that 4IR brought along is accelerated communication. As information sharing and communication forms an integral part of interface management, the digitalisation of business communication systems in general and the easy access to data have the potential to impact the management of interfaces significantly. VR/AR was previously proven to be successfully implemented for establishing clear understanding, communication and enhancing decision-making (Fu & Liu, 2018:430).

Figure 5-5 below graphically displays the findings of Table 5-3.

Figure 5-5: 4IR opportunities for addressing poor interface management and communication



5.2.4 Construction material delays

Table 5-4 below displays the opportunities identified in literature to address the influencing factors of construction material delays with 4IR technology.

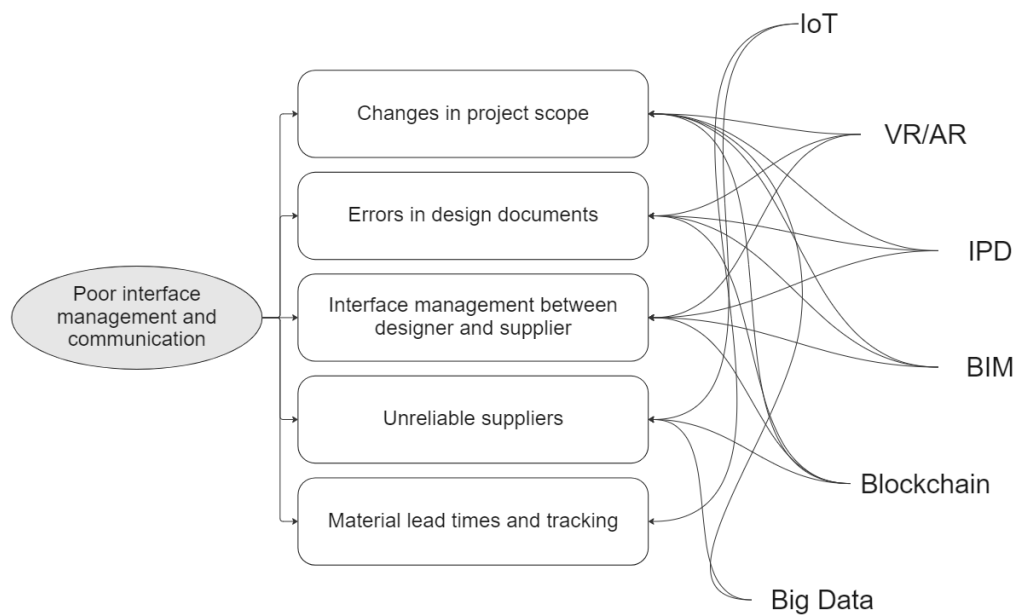
Table 5-4: 4IR opportunities for addressing construction material delays

Causation	4IR opportunities
Changes in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
Errors in design documents	4IR opportunities to address errors in design documents was discussed in Section 5.2.2.
Interface management between designer and supplier	4IR opportunities to address interface management was discussed in Section 5.2.3.
Unreliable suppliers	Integration of supply chain flows through Blockchain solutions. Big Data analytics and IoT tracking on supplier performance and material availability.
Material lead times and tracking	Big Data analytics and IoT tracking on supplier performance and material availability.

Information technology has always been and will continue to be a crucial enabler for efficient supply chain management. Information technology is crucial in assisting supply chains in overcoming the obstacles posed by a constantly changing environment and a wide range of hazards at all levels. Due to its capability of internal integration of multiple operations and, more critically, external integration with suppliers and consumers, IT has significantly changed the character and structure of supply chains. This has been accomplished by strengthening data acquisition, transmission, and communication, which has enabled efficient decision-making and improved supply chain performance (Ben-Daya *et al.*, 2019:4219). By enabling human-to-things communication and autonomous coordination among "things" while they are being held in a facility or being transferred between various supply chain entities, IoT raises the bar for supply chain communications. To address diverse SCM difficulties, IoT offers new levels of supply chain visibility, agility, and adaptability (Ben-Daya *et al.*, 2019:4220). The creation of a blockchain solution that integrates the material and financial flows within the logistics and supply chains for the construction industry has the potential to significantly improve all aspects of the production of a construction project, foster trust, transparency, and traceability in transactions, improve the quality management of deliverables, facilitate stakeholder collaboration, and generate both monetary and qualitative value (Kifokeris & Koch, 2019:337).

Figure 5-6 (P.77) graphically displays the findings of Table 5-4.

Figure 5-6: 4IR opportunities for addressing construction material delays



5.2.5 Poor productivity of construction labour

Table 5-5 below displays the opportunities identified in literature to address the influencing factors of poor productivity of construction labour with 4IR technology.

Table 5-5: 4IR opportunities for addressing poor productivity of construction labour

Causation	4IR opportunities
Poor labour supervision, management, and planning	The use of autonomous things and hyperconnectivity to access live productivity data to enable proactive supervision focus. BIM and AR/VR visual aids can assist supervision to understand and communicate activities better which can result in better productivity results.
Shortage of materials	4IR opportunities to address shortages of construction materials was discussed in Section 5.2.4.
Communication or coordination problems and misunderstanding	Virtual construction planning and constructability clarifications using BIM and AR/VR. Smart devices and IoT has the potential to enhance site activity coordination and planning.
Design change and design errors	4IR opportunities to address design changes and design errors was discussed in Section 5.2.1 and Section 5.2.2.
Shortage of skilled labour	Big Data analytics and IoT tracking on supplier performance and material availability. The use of robotics for task execution. The use of VR/AR for training.

The results of prevailing research found that technology adoption has a significant impact on increasing levels of productivity in construction projects (Azman *et al.*, 2019:83). It's critical to recognise technology as a fundamental aspect affecting productivity in construction projects given

the growing usage of technology in projects as well as current developments in robotics, drones, automation, virtual reality, and remote sensing (Hamza *et al.*, 2022:422).

Robotics has been used to produce construction projects since 1980, and since then, the number of these automated projects has increased. Robots stand out for their exceptional accuracy, speed, and efficiency in a range of jobs and their enhanced productivity when used in automated systems (Aly *et al.*, 2016:3; 2017:314). Robotics has adapted to the construction sector to provide solutions to issues, from planning routes for material transportation to automated systems carrying out construction site duties (Lundeen *et al.*, 2019:25).

Big data poses the opportunity to utilise the variety of information gathered from constructed infrastructure and facilities to better understand the needs, issues, and benefits, which improves organisational capacities in the planning and execution of construction work (Akinade *et al.*, 2018:380).

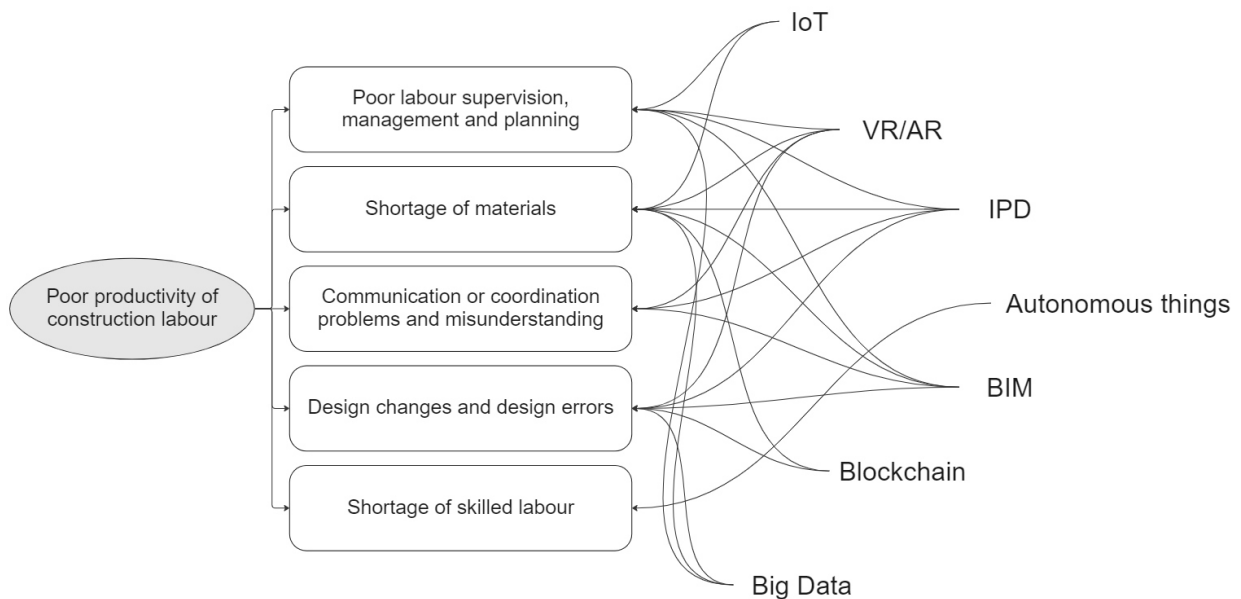
Kuenzel *et al.* (2016:25) introduced SmartSite, which brings together interconnected value chains that interact and are each already profitable on their own. The domains of construction machinery, site environment, networked work site, and construction process monitoring all contribute to these value chains. SmartSite links these value chains together to streamline the entire construction process. Kuenzel *et al.* (2016:25) noted that machinery manufacturers could offer direct access to technically sound control systems since they can supply sensor-, quality-, and process data along the complete process chain for construction equipment and plants. It is technically possible to send data between individual machines, between environments and machines, and between machines and construction process control. Real-time analysis of collected data, particularly data related to building quality, is possible. Every machine and plant along the full value chain is represented in the data that was gathered. Real-time data collection and communication is possible for environmental data like weather conditions and forecasts and process data like job progress.

Bucchiarone *et al.* (2019:40) similarly proposed an innovative construction platform wherein information is gathered and disseminated by intelligent hardware nodes spread around the construction site using the local radio network. The system is connected to a cloud platform via a wired or mobile connection using IoT gateways. Project managers can use the web-based user application to analyse the data remotely in real-time. This will enable swift decision-making regarding site coordination and labour management to counteract unproductive activities.

The opportunities to use BIM technology for information transfer, planning, training, and coordination have been discussed in Section 2.3.1.2 and the prevailing discussions of 4IR opportunities.

Figure 5-7 below graphically displays the findings of Table 5-5.

Figure 5-7: 4IR opportunities for addressing poor productivity of construction labour



5.2.6 Delays in decision making and approvals by the owner

Table 5-6 below displays the opportunities identified in literature to address the influencing factors of delays in decision making and approvals by the owner with 4IR technology.

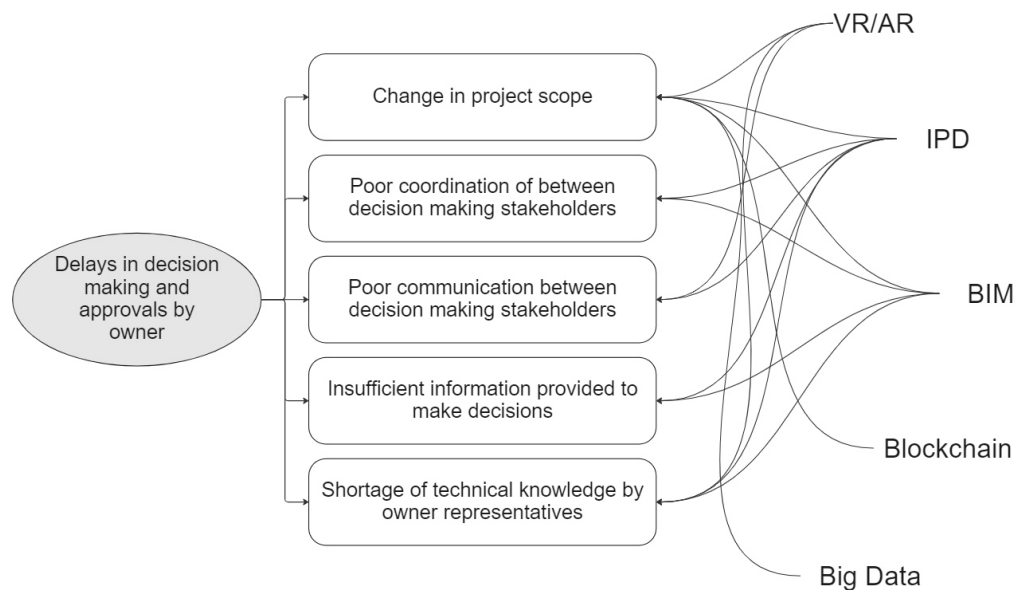
Table 5-6: 4IR opportunities for addressing delays in decision making and approvals

Code	Causation	4IR opportunities
F01	Change in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
F02	Poor coordination of between decision making stakeholders	Enhanced collaboration through IPD and BIM.
F03	Poor communication between decision making stakeholders	Live communication and design charrets enabled by BIM and VR/AR. The various technologies that encompass IPD can address can enhance communication channels to and from management stakeholders.
F04	Insufficient information provided to make decisions	IPD and access to a BIM shared data repository can enhance the flow and accessibility of information needed by decision makers.
F05	Shortage of technical knowledge by owner representatives	Enhanced knowledge sharing through AR/VR, BIM and IPD.

IPD is distinguished by early participation of all participants, close cooperation between them, and the combination of each participant's individual contribution to the development and decision-making process, always with the aim of optimizing the entire project as opposed to seeking the self-interest of their respective organisations (Ma *et al.*, 2018:290). To fully consider the number of requirements, limitations, and aspects of the final design solution, IPD from the conceptual design stages is essential. The IPD team offers a method that is focused on finding solutions (Jones, 2014:530). Jones (2014:530) coined the "Big Room" which poses significant design improvement opportunities in a collaborative virtual design environment. The "Big Room" concept can be utilized to streamline the process by having the client and all other important project partners work together in the same "room" to establish the project's sustainability and cost objectives. Assisted by responsive decision-analysis support tools, the final design will have a high degree of confidence that it will accomplish its goals in terms of sustainability, cost and time to build, and material and component efficiency which in turn makes decision making faster (Jones, 2014:530). This technique results in a collaborative, integrated, and transparent construction process by utilizing the BIM model and IPD together. Back to the main model goes all communication (Jones, 2014:530). The model is used by the entire project team as a common, rich database where all data is organized, handled, and maintained. As a result, less redundant data is generated while still allowing all participants to use the data that already exists in the model. A common, visual model to externalize and share project challenges is helpful in this regard (Jones, 2014:530). A virtual object is created even before construction begins using 3D BIM models in conjunction with schedule data (4D) and cost estimation data (5D). Design and construction are a collaborative, integrated process that takes both design and construction into account. As a result, it acts as a shared knowledge repository for data about a facility and provides a solid foundation for decisions made throughout the project's existence (Jones, 2014:530).

Figure 5-8 (P.82) graphically displays the findings of Table 5-6.

Figure 5-8: 4IR opportunities for addressing delays in decision making and approvals



5.2.7 Poor planning and scheduling

Table 5-7 below displays the opportunities identified in literature to address the influencing factors of poor planning and scheduling with 4IR technology.

Table 5-7: 4IR opportunities for addressing poor planning and scheduling

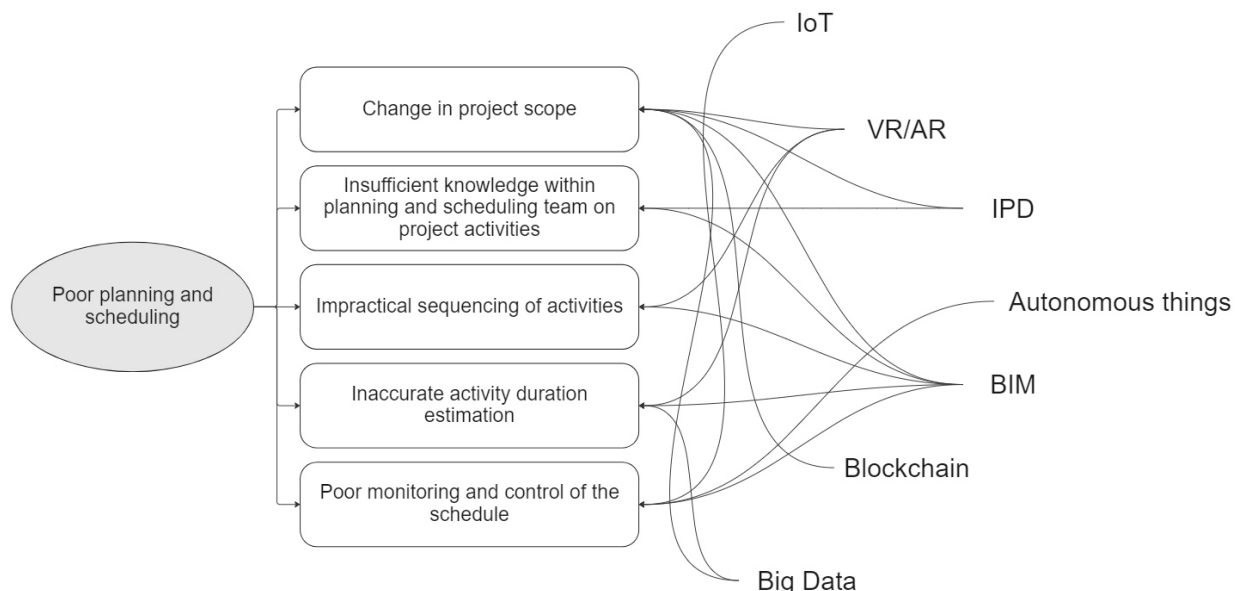
Code	Causation	4IR opportunities
G01	Change in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
G02	Insufficient knowledge within planning and scheduling team on project activities	IPD and access to a BIM shared data repository can enhance the flow and accessibility of information needed by the planning team to understand the project activities.
G03	Impractical sequencing of activities	Virtual construction planning and constructability clarifications using BIM and AR/VR.
G04	Inaccurate activity duration estimation	Virtual construction planning and constructability clarifications using BIM and AR/VR. Predictive analytics through Big data.
G05	Poor monitoring and control of the schedule	Smart devices and IoT has the potential to enhance site activity coordination and planning by enriching the data modelled in BIM.

Heigermoser *et al.* (2019:248) introduced a BIM-based construction planning tool that was found to eliminate wastage, enhance productivity, increase planning reliability, enable planning visualisation, and promote learning and improvements. The planning tool was enhanced by using virtualisation technology. Li and Liu (2019:410) introduced the concept of using drones to monitor, progress and inspect construction progress which can significantly improve the ability of the project team to monitor and control the project objectives. Kim *et al.* (2013:75) proposed a method

of construction monitoring with a 4D BIM application and 3D data. The procedure is broken down into three phases: matching the as-built data to the BIM, updating the as-built status, and aligning the as-built data with the as-planned model. Measurement of construction progress is based on the utilization of 3D as-built data acquired on the construction site using remote sensing technology and as-planned data from the BIM. The BIM comprises many sorts of information on the default or user-defined structural component attributes. The as-planned model is created using the as-planned schedule and geometric data from the BIM. This allows users to identify discrepancies earlier and plan its rectification.

Figure 5-9 below graphically displays the findings of Table 5-7.

Figure 5-9: 4IR opportunities for addressing poor planning and scheduling



5.2.8 Delays in multi-discipline engineering design

Table 5-8 below displays the opportunities identified in literature to address the influencing factors of delays in multi-discipline engineering design with 4IR technology.

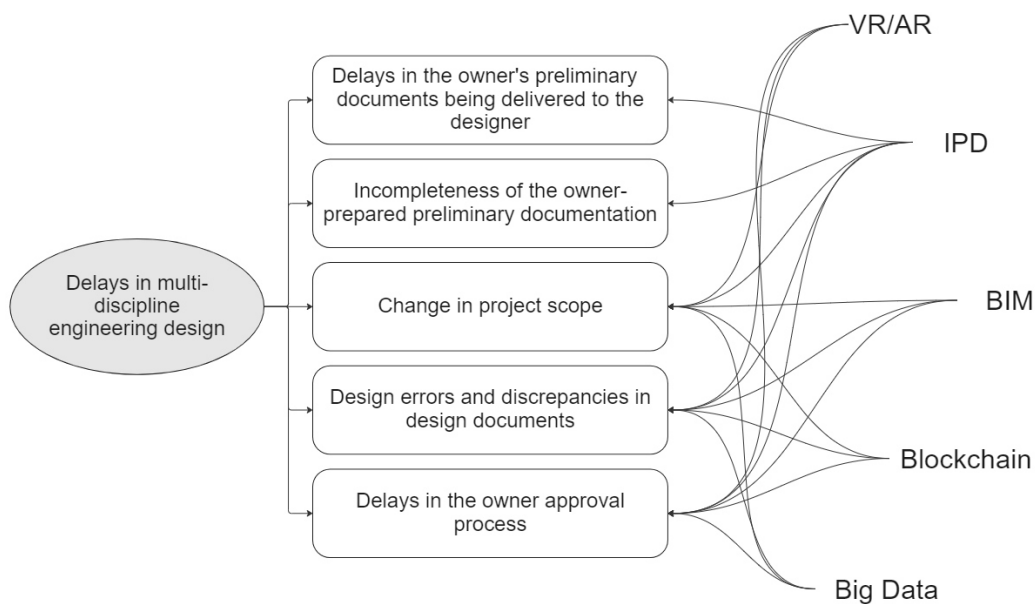
Table 5-8: 4IR opportunities for addressing delays in multi-discipline engineering design

Code	Causation	4IR opportunities
H01	Delays in the owner's preliminary documents being delivered to the designer	Onboarding the EPC contractor in the feasibility phase in an IPD approach can ensure access to the information before detail design commence.
H02	Incompleteness of the owner-prepared preliminary documentation	Onboarding the EPC contractor in the feasibility phase in an IPD approach can ensure access to the information before detail design commence.

H03	Change in project scope	4IR opportunities to address changes in project scope was discussed in Section 5.2.1.
H04	Design errors and discrepancies in design documents	4IR opportunities to address errors in design documents was discussed in Section 5.2.2.
H05	Delays in the owner approval process	4IR opportunities to address delays in owner approval was discussed in Section 5.2.6.

Figure 5-10 below graphically displays the findings of Table 5-8.

Figure 5-10: 4IR opportunities for addressing delays in multi-discipline engineering design



5.2.9 Rework

Table 5-9 below displays the opportunities identified in literature to address the influencing factors of rework with 4IR technology.

Table 5-9: 4IR opportunities for addressing rework

Code	Causation	4IR opportunities
I01	Design changes and design errors	4IR opportunities to address design changes and design errors was discussed in Section 5.2.1 and Section 5.2.2.
I02	Design interface management	4IR opportunities to address interface management was discussed in Section 5.2.3.
I03	Construction interface management	4IR opportunities to address interface management was discussed in Section 5.2.3.
I04	Construction and quality defects	The use of autonomous things to do inspections. The use of BIM to register identified defects.

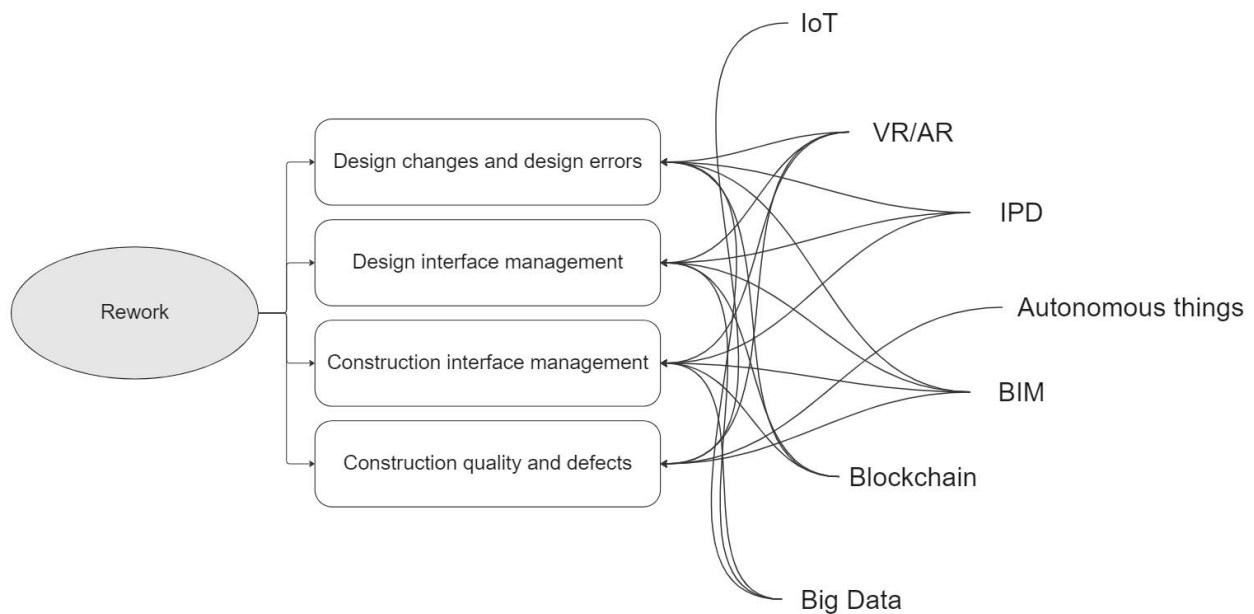
Chen and Luo (2014:65) introduced a 4D BIM-based application for project quality management in the construction phase which can benefit projects in the factors displayed in Table 5-10:

Table 5-10: Opportunities for a 4D BIM-based application for project quality management

Factor	Description
Consistency in information	Ensures there is consistency in the information from the design to the building stage. BIM is a parametric modelling initiative that offers tabular views of components and distinctive interactions with their parts, including name, type, characteristics, relationships, and metadata (Redmond <i>et al.</i> , 2012:175). Instead of manually analysing individual drawings and change orders, the substantial data for each construction product can be utilized as the foundation for an automatic assessment of the significance of differences between the design and as-built circumstances (Chen & Luo, 2014:65).
Process control consistency during construction	The BIM program allows for continuous, real-time viewing of the percentage of completion for each activity in the construction schedule (Kim <i>et al.</i> , 2013:75). As a result, quality inspections can be planned immediately after an activity is finished and before the start of the next, keeping the quality inspection process on schedule and consistent with the construction process (Chen & Luo, 2014:65).
Collaboration between participants	Construction projects that employ BIM technology have the potential to be improved since everyone on the team will be able to communicate more accurately and efficiently than when utilizing conventional methods (Qiu, 2011:282).
BIM integration with other advanced technologies	BIM, IoT and AR have been successfully integrated in applications of quality defect management and remote inspections (Dave <i>et al.</i> , 2018; Park <i>et al.</i> , 2013:61)

Figure 5-11 (P.86) graphically displays the findings of Table 5-9.

Figure 5-11: 4IR opportunities for addressing rework



5.3 4IR TECHNOLOGIES AND THEIR POTENTIAL VALUE

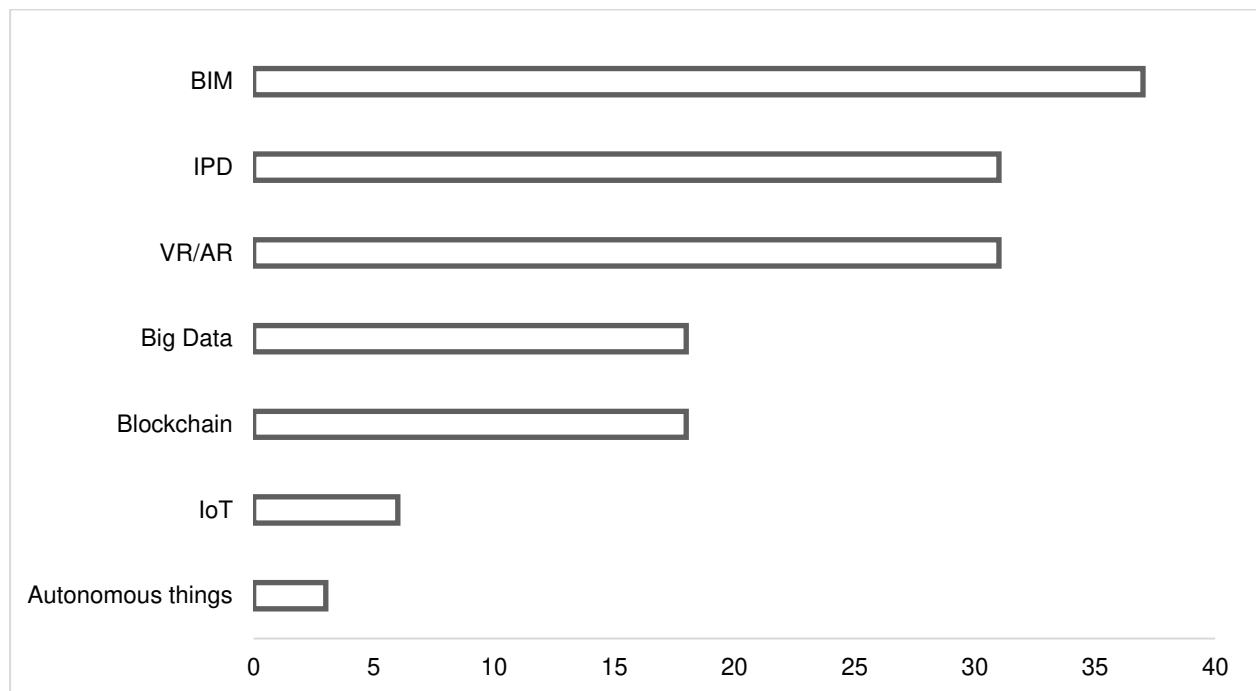
The potential of addressing the factors influencing the challenges that lead to cost and schedule overruns with 4IR was described in Section 5.2. To understand what the 4IR technologies are that has the biggest potential benefit for the South African petrochemical EPC sector, the 4IR technologies are ranked in Table 5-11 below according to the frequency of identified potential use to address challenges:

Table 5-11: Potential benefit ratings of 4IR technologies

4IR technology	Frequency
BIM	37
IPD	31
VR/AR	31
Big Data	18
Blockchain	18
IoT	6
Autonomous things	3

Figure 5-12 (P.87) graphically displays the findings of Table 5-10.

Figure 5-12: 4IR opportunities for addressing rework



The results show that BIM has the most significant potential impact on addressing the challenges associated with EPC projects. It is closely followed by IPD and VR/AR. The Big Data, Blockchain, IoT and autonomous things concepts are in the initial stages of implementation worldwide. The availability of literature addressing their benefits is noted to impact this finding. BIM, on the other hand, is a well-established concept and is used in various industries worldwide.

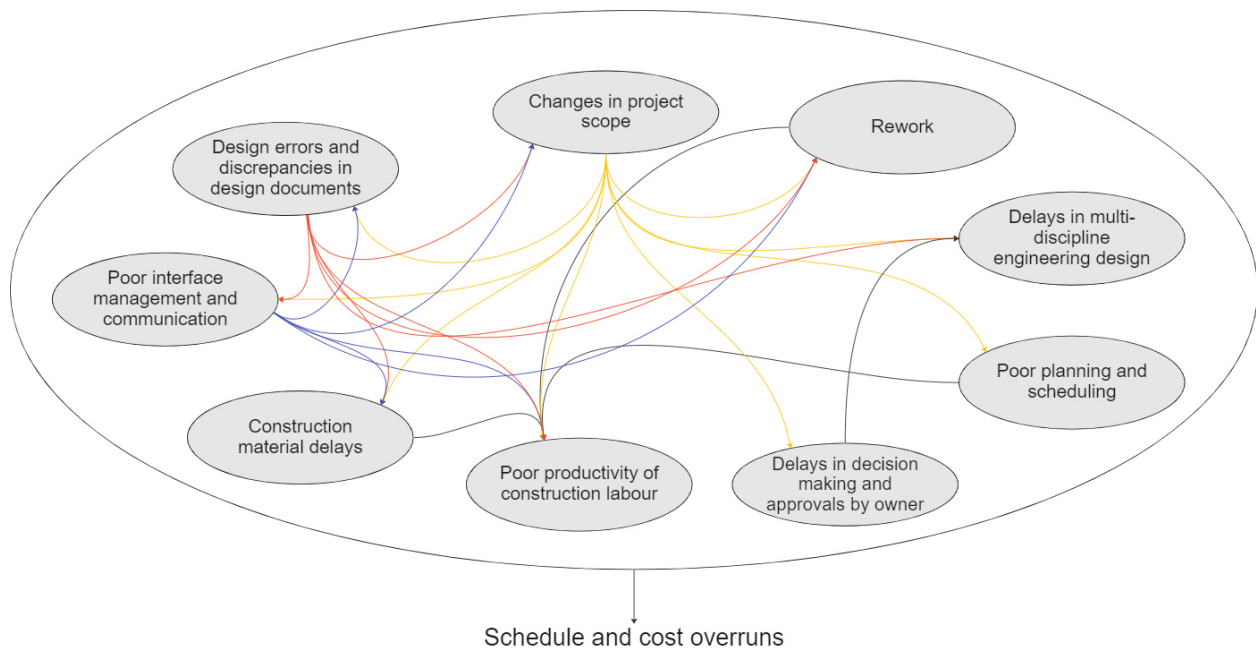
In some cases, standardised regulatory guidance documents have been published by local governments with the aim of standardising the BIM implementation process. When designing and constructing infrastructure in the petrochemical industry, a significant amount of human and material resources are involved, which leads to considerable amounts of complex interfaces. BIM is deemed to assist in managing these interfaces. It is noted that interface management was the biggest challenge the participants faced in all the phases of their EPC projects. This adds to the argument that BIM has the most considerable potential benefit towards addressing interface management in EPC projects.

5.4 IDENTIFIED CONNECTIONS BETWEEN THE PROBLEMS FACED AND THEIR FACTORS OF INFLUENCE

A finding that was not deemed a primary or secondary objective of this study yet deemed significant is how interrelated the identified challenges are and how they have significant, influential connections. This arguably promotes the relevance of Koeleman *et al.* (2019:2) finding

that the aim of digitalisation should be to address the root cause of challenges rather than implementing systems merely on their benefits. Figure 5-13 below displays the paths of influential connections between the identified challenges:

Figure 5-13: Influential connections between the identified challenges



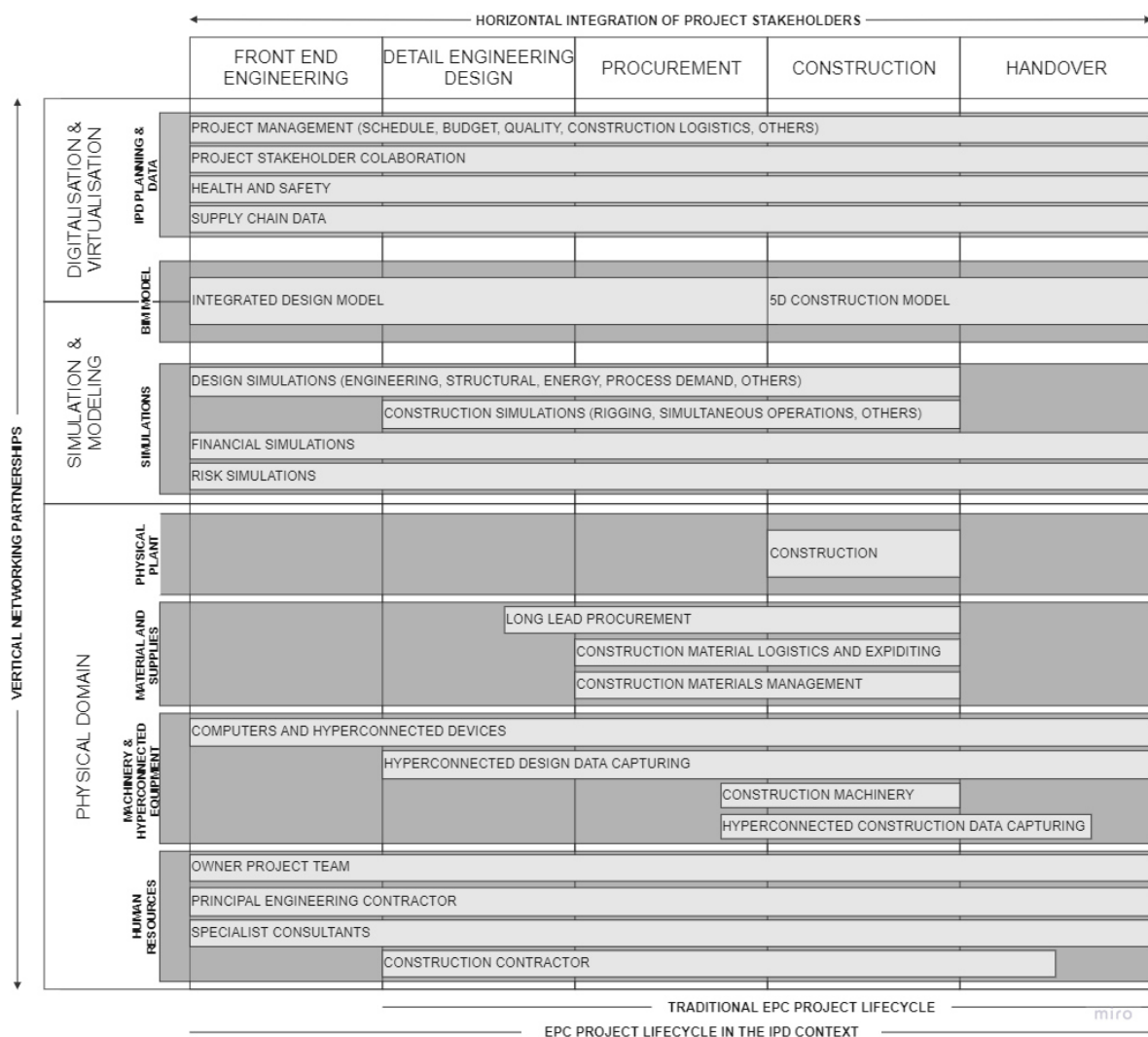
From Figure 5-13, it is evident that three themes, also the most common themes in literature, have a considerable influence on the other identified themes. Changes in project scope, for example, influence all the other challenge themes. This proves the high importance of front-end engineering design to ensure that the project scope is correctly captured, and the work breakdown structure is frozen. *P002* noted: “We don’t get to a point where we allow sufficient time to properly scope work and do the front-end engineering design to the required standard”. Hansen and Schroeder (2016:3) similarly blamed inadequate scope definition before project execution for this high degree of scope expansion. By minimising this one factor, namely changes in project scope, the other eight challenges will be partially resolved as changes in project scope significantly impact them. The finding, therefore, leads to the argument that addressing the challenges faced in the EPC sector should start with addressing the challenges with the most influential connections to other challenges.

5.5 INTRODUCTION OF A THEORETICAL FRAMEWORK OF 4IR TECHNOLOGY IMPLEMENTATION

The proposed theoretical framework is based on enhanced information flow and interface management through stakeholders’ integration and early involvement. The traditional EPC

transactional contracting strategies are designed to shift project risk from the owner to the contractor, as well as from the contractor to consultants and construction contractors. The proposed framework aims to promote IPD as a paradigm shift as it entails risk sharing rather than risk transfer, taking project stakeholder collaboration and integration to a more efficient level (Barutha, 2018:3). The framework, therefore, focuses on horizontal integration of project phases and vertical networking of project functions and the technology that can potentially be of benefit to this approach. Figure 5-14 below displays the proposed 4IR enabled EPC project framework:

Figure 5-14: Proposed 4IR enabled EPC framework



5.5.1 Horizontal integration of project stakeholders

The framework aims to involve key project stakeholders earlier than what is usually the case in traditional EPC contracting strategies. The owner team, principal engineering contractor team and specialist consultants are involved from the beginning of the front-end engineering design phase, where collaborative scope development aims to achieve enhanced accuracy and mutual

understanding of the project scope and objectives and subsequent scope freezing before the detailed design phase is started. The key stakeholders of the construction contractors that will be responsible for the physical execution are then involved from the beginning of the detail design phase. Although no physical activities will be executed, the construction contractor is given a chance to be familiarised with the project scope and objectives much earlier. This can enhance early planning activities, and valuable input on the constructability of the design can be received from specialist execution individuals. Similarly, the framework aims to keep engineering professionals, designers, and specialist consultants part of the construction execution team to ensure timely technical support when required. A study by (Barutha, 2018:12) statistically supported the concept of early involvement and enhanced collaboration and integration by finding that it has a direct positive correlation to project performance while significantly minimising project outcome uncertainty.

5.5.2 Vertical networking partnerships

The framework further aims to create collaborative vertical networking and shared risk partnerships among project stakeholders and project functions. Vertical networking is a concept developed at the beginning of the 1980s, where externalisation and outsourcing generalisation changed the landscape of international industries (Baudry & Chassagnon, 2012:288). The traditional EPC contracting strategies utilise vertical networking but are based on a risk transfer strategy (Barutha, 2018:3). By introducing partnering to vertical networking, the underlying idea is to establish contractual relationships based on agreements that reward parties for achieving their shared objectives so that all parties are motivated to work toward the same common goals while sharing risks and pains, as well as opportunities and gains (Ritsche *et al.*, 2019:23). While typical EPC contracts frequently involve claims and blame games, these collaborative models call for the development of trust and transparency (Ritsche *et al.*, 2019:23). By enhancing integration with the 4IR technology discussed in Section 5.2, live physical, virtual, and digitalised communication forms the basis of transparent information transfer and availability between the various interfaces in the project lifecycle. The enhanced communication aims to promote clear and shared objectives.

5.5.3 Segment integration

The physical domain receives input from human resources, machinery, material, and tools operated by professionals. The interconnected physical environment collects and sends real-time data to the BIM 5D model to enable real-time updates and data-based adjustments, whereafter, the data is stored in the digitalisation and virtualisation segment for storage to subsequently use in project management, safety, and supply chain analytics. The framework further allows for this

flow to be bi-directional. The information in the digitalisation, virtualisation, and simulation segments can feed data from the top down to enable indications to control actions such as the sequencing of activities. The framework is based on each of the identified technologies in Section 5.2, feeding live information into the BIM model to generate a virtual of progress in the project phase.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The final Chapter of the study aims to give insight into the findings derived from the previous Chapters to achieve the research objectives described in Chapter 1. Based on the findings, the researcher will share practical implications and recommendations. The limitations found in the data analysis will be listed, and themes will be suggested that are deemed eligible for future research.

6.2 EVALUATION OF STUDY OBJECTIVES

6.2.1 Primary objective

The primary objective of this study was to derive a theoretical framework for leveraging Industry 4.0 technology to address challenges in South African petrochemical EPC projects by using primary and secondary data. This framework was composed and presented in Section 5.5. The framework could give EPC project management professionals insight into the broad spectrum of opportunities within 4IR technology to assist in integrating project execution functions to enable project execution teams to operate with increased collaboration, efficiency, and transparency. This framework can guide EPC project management professionals to utilise strategic technology implementation to mitigate the risk of the most prominent challenges in EPC project environments.

6.2.2 Secondary objectives

The secondary objectives of this study were achieved as described below:

- A literature review was conducted to determine the most recurring themes of challenges in construction and engineering projects. Through semi-structured interviews, the recurring themes in the secondary data were validated in the South African petrochemical EPC sector. Causation research, as presented in Section 2.2.3, was further conducted on each of these themes, which gave insight into the factors contributing to these themes.
- The current state of digitalisation in the South African petrochemical EPC sector was determined by asking participants of semi-structured interviews a series of questions pertaining to digitalisation. The findings are presented in Section 4.4.4.

- The study aimed to identify the South African petrochemical EPC context of barriers to technology implementation through a series of questions in semi-structured interviews. The findings are presented in Section 4.5.
- Methods of enhancing collaboration between EPC project stakeholders are recommended in Section 5.5.

6.3 MANAGERIAL IMPLICATIONS OF THE STUDY

The study gives guidance to several aspects contributing to the low performance of EPC projects. The traditional EPC project execution strategy creates a large set of complicated interfaces that requires accurate information transfer, which induces pressure on project managers and engineering managers in the EPC sector to manage these interfaces efficiently. This study found that the underlying root cause of the majority of the challenges faced by the South African petrochemical EPC sector is the lack of accuracy in managing a large number of interfaces throughout the EPC project functions. The findings promote two opportunities for more effective interface management:

- Increased collaboration between project stakeholders through partnering and IPD
- Enhanced communication and information transfer by leveraging 4IR technology

The current culture of EPC contracting, where clear boundaries between the owner, EPC contractor and sub-contractors are visible, is counterproductive in terms of stakeholder collaboration and often results in disputes. The opportunity to leverage technology to assist with the flow of information can enhance collaboration between project stakeholders. Still, it would not be able to address the cultural aspects of project teamwork. The author notes, therefore, that even though the findings show enormous potential within 4IR technology, a parallel cultural shift is required within project stakeholders to create an EPC environment that is characterised by trust and transparency.

The opportunities displayed in this study will require an EPC sector that promotes innovation. Significant barriers must be overcome before the opportunities discussed in this study can be implemented. Managers within EPC contractor organisations should aim to breach these barriers and create environments where employees have the freedom to innovate while giving guidance on addressing the areas of most significant concern rather than implementing impressive cutting-edge technology that creates more challenges than adds value.

Once a cultural shift in the attitude, trust and awareness of technological implementation is established, clear innovation strategies that consist of thorough research and planning should be

established. This study shows that out of all the 4IR technologies identified, BIM poses the most significant opportunity to add value. It is proposed that BIM strategies be developed in close collaboration with the owners of petrochemical plants in South Africa to achieve standardisation in implementing BIM throughout the South African EPC sector. Although this study only focussed on the application of BIM in the EPC lifecycle context, BIM further has the potential to add value to owner operations past the typical EPC lifecycle.

The author argues that the identified challenges, no matter how complex, are fundamentally the result of poor communication and that technology can enhance this skill within people. Still, the skill cannot be acquired through technology. The communication of technical information by engineers and technical consultants of various disciplines is a challenge that was found to exist within the EPC industry. Organisations should aim to train and upskill engineers and technical personnel in the communication of technical information. Further, tertiary institutions should focus on placing bigger emphasis through academic modules on the efficient communication of technical information throughout the academic career of engineers. Effective and standardised communication among technical resources can alleviate many factors that lead to cost and schedule overruns in EPC projects.

The closing argument arising from the findings is that design engineers should be actively involved throughout the EPC lifecycle to promote the collaboration culture between engineers and construction executing professionals. Involvement and experience in construction activities are critically important to promote the design of infrastructure that is efficiently constructible.

6.4 OVERALL STUDY LIMITATIONS

The interpretivist qualitative data gathered was retrieved from a small sample of the population and will not fully represent the population. The time constraints of this study make more extensive samples impractical, and hence the research will not be deemed representative of the entire population. It should be emphasized that a convenience sample strategy was utilised because of the time restrictions of this investigation. It should further be noted that the framework is idealistic and theoretical and the commercial, contractual and governance aspects of implementing such a framework was excluded from this study. The study did not include the in-depth investigation to the technical barriers on implementation of each of the identified technologies but was rather aimed to uncover the potential thereof.

6.5 OPPORTUNITIES FOR FUTURE RESEARCH

Further research in the South African context of project governance, commercial management and contractual management of collaborative project execution strategies and the barriers thereof will be required to understand the practicality of the implementation of such a strategy. A BIM focussed study on the South African context is proposed to further the body of knowledge towards the standardised implementation of BIM throughout industries. The finding of this study confirms that BIM forms the foundation of any of the other technologies and further research in all forms of BIM implementation is promoted.

6.6 CONCLUSION

The study reached its primary objective by proposing a framework for leveraging 4IR technologies in the South African petrochemical EPC industry. The study further reached its secondary objectives by exploring the causation of challenges faced by the South African petrochemical EPC industry, by finding that the South African petrochemical EPC industry has limited digitalisation adoption to date, finding that similar barriers of technology adoption exist in the South African EPC industry and the global EPC industry and lastly proposing methods of enhanced collaboration among project stakeholders. Charles Darwin famously said: "It is neither the strongest, nor the most intelligent of a species that survives, but the one that is most adaptable to changes". The South African petrochemical EPC industry is changing, and EPC contractors needs to answer the call to reduce the capital expenditure of petrochemical plants. This study concludes that changes in culture and the innovative application of 4IR technologies can be the tools that help EPC contractors to answer that call.

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ANNEXURE A

October 2022

DEAR PARTICIPANT

INFORMED CONSENT LETTER TO INTERVIEW PARTICIPANTS

You are being invited to take part in a research study that forms part of a Master of Business Administration (MBA) degree. Please take some time to read the information presented here, which will explain the details of this study. Please ask the researcher or person explaining the research to you any questions about any part of this study that you do not fully understand. It is very important that you are fully satisfied that you clearly understand what this research is about and how you might be involved. Also, your participation is entirely voluntary, and you are free to say no to participate. If you say no, this will not affect you negatively in any way whatsoever. You are also free to withdraw from the study at any point, even if you do agree to take part now.

This study has been approved by the NWU Economic and Management Sciences Research Ethics Committee (EMS-REC) and will be conducted according to the ethical guidelines and principles of the North-West University and other international ethical guidelines applicable to this study.

Title of the project: *Identifying opportunities for leveraging industry 4.0 technology in petrochemical engineering, procurement, and construction projects in South Africa*

Institution: NWU Business School

Ethics Reference Number: NWU-00654-22-S4

Names and contact details of project staff

	Supervisor	Researcher
Title, name & surname	Prof MJ Grobler	Mr RJ van Rooyen
Full Names	Leenta Grobler	Roan van Rooyen
Function in Project	Principle Investigator	Researcher
Telephone	082 878 5894	083 843 5268

What is this research study about?

Mr Roan van Rooyen is conducting research for his MBA degree at the NWU Business School to explore the extent to which Industry 4.0 technologies can be used in typical EPC (Engineering, Procurement and Construction) projects in the petrochemical industry. Primary data will be collected to determine current challenges faced in executing EPC projects in the petrochemical industry in South Africa. Apart from the current challenges experienced within petrochemical EPC projects, probing questions will also be asked to determine the opportunities for and barriers to the implementation of technology to improve project management capabilities within this sector. Secondary research data will then be used to derive a theoretical model for leveraging industry 4.0 technologies in the petrochemical industry to address these challenges.



Why have been invited to participate?

You have been invited to participate in this research study because you fall into at least one of the following categories:

- Directors within operational and project management areas of responsibility.
- Executive managers of operational and project management departments.
- Project managers and project engineers above senior level.
- Engineering managers above senior level.
- Your voluntary willingness to participate in this research study.

What will be expected of you?

You will be expected to:

- Participate in a 45 – 60min semi-structured interview with the researcher at a suitable time and private area without interruptions that is convenient for both parties via an online platform. This will be scheduled by the researcher once approved by the NWU ethics committee.
- Respond to the questions in an open and honest manner.
- Inform the supervisor should you feel or experience any form of discomfort or distress during the research process and inform the supervisor if you at time feel the need to terminate your involvement in the research process.

Will you gain anything from taking part in this research?

This research study intends to give you a voice to reveal, explain and reflect on the challenges faced within your sector. No monetary reward shall be made available for participation in the study. You will however be furnished with a two-page communique on the outcomes of the study that you can utilise to consider how Industry 4.0 technologies can be applied within your company and/or organisation if you so wish.

Are there risks involved in you taking part in this research and what will be done to prevent them?

Participation in this study does not create any physical risk to you as the study does not involve any physical activities or experiments. We, however, have identified certain ethical principles that shall be always maintained to prevent any damages to you. The focus of these principals will be to protect your dignity and keep all records provided private and confidential.

How will we protect your confidentiality and who will see your findings?

You will be assigned a unique participant ID. Our interview will be recorded and saved with reference to the ID, but data collected shall be regarded as confidential and will not be shared with any 3rd party that is not directly involved in the research process. Personal details of participants and their direct input to the research study shall not be made public. All records of the research shall be kept for a retention period and destroyed in an appropriate means. The findings of the study will be made public however will not contain any raw data that might incriminate certain individuals.

What will happen with the findings or samples?

The findings concluded in the study will be for academic purposes and will only be utilised to add to the current body of available knowledge.

How will you know about the results of this research?

Participants in the study, should they require, will be made aware of the results of the research, through a two-page communique, by means of electronic mail. The electronic final version of the dissertation will also be made available if requested.

Will you be paid to take part in this study and are there any costs for you?

Participation in this study will not yield monetary value to you. There is no cost envisaged to you except the time that you spend to participate in this study. This study will be funded by the researcher.



Is there anything else that you should know or do?

You may contact the supervisor, Prof Leenta Grobler, on at 082 878 5894 if you have any further questions or have any problems. You will receive a copy of this information and consent form for your own purposes.

DECLARATION

Declaration by participant

By signing below, I (P001) agree to take part in the research study titled: *Identifying opportunities for leveraging industry 4.0 technology in petrochemical engineering, procurement, and construction projects in South Africa*

I declare that:

I have read this information/it was explained to me by a trusted person in a language with which I am fluent and comfortable in. The research was clearly explained to me. I have had a chance to ask questions to both the person getting the consent from me, as well as the researcher and all my questions have been answered. I understand that taking part in this study is voluntary and I have not been pressurised to take part. I may choose to leave the study at any time and will not be handled in a negative way if I do so. I may be asked to leave the study before it has finished, if the researcher feels it is in the best interest, or if I do not follow the study plan, as agreed to.

Signed at: _____

On: _____

Signature of participant

Signature of witness

Declaration by researcher

I Roan van Rooyen declare that:

- I explained the information in this document to (P001)
- I did/did not use an interpreter
- I encouraged them to ask questions and took adequate time to answer them or I was available should they want to ask any further questions.
- I am satisfied that they adequately understand all aspects of the research, as described above.
- I am satisfied that they had time to discuss it with others if they wished to do so.

Signed at: Cape Town On: 2022-10-10

Signature of researcher

Signature of supervisor







ANNEXURE B

1. Tell me more about your role and experience in the EPC industry?
2. When you think about the recent projects you were a part of, what are the biggest problems, challenges?
 - a. Probe: What is the first term that comes into mind when you think of project challenges?
3. Which of these challenges can be addressed by recent technology advancements?
4. To what extent are the various EPC functions within your current or recent projects' value chain automated?
 - a. Probe: Does the current flow of information within your EPC value chain enable you to effectively manage change and make you agile enough to adapt to change?
 - b. Probe: Is there benefit in having live communication between the various links in your EPC value chain?
5. To what extent do your current project systems allow you to analyse real-time data from outside your organisation to forecast possible demand and supply fluctuations?
6. What were the biggest challenges you faced during the engineering design phase of your current or recent EPC projects?
7. Do you often find communication and change management challenges between different engineering disciplines involved in the engineering design phase of a project?
 - a. Probe: How do you manage the interface between engineering disciplines?
 - b. Probe: Is there a possibility that interface management can be improved by using digital simulation and virtualisation technology?
8. What are the biggest challenges you face in the procurement phase of EPC projects?
 - a. Probe: To what extent can supply chain automation and digitalisation assist in addressing these challenges?
 - b. Probe: To what extent have you addressed supply chain challenges with digital technology to date?
9. What are the biggest challenges faced during the project construction phase?
 - a. Probe: To what extent can technology assist in addressing these challenges?
 - b. Probe: Have you recently introduced innovative technology on your construction sites? What are the perceived benefits of this technology?
10. To what extent is data captured during your current EPC project lifecycle?
 - a. Probe: How is this data captured?
 - b. Probe: How is this data analysed to identify opportunities for improving execution strategies?

- c. Probe: How does this data enable knowledge transfer between resources in your organisation?

As a final question confirmation from the respondents was requested on the challenges identified in Table **2-1**.