BIM AS A TOOL FOR QUANTIFYING THE IMPACT OF CHANGE ON LABOUR PRODUCTIVITY

Craig Peter Goldswain

Thesis presented in fulfilment of the requirements for the degree of
Master of Civil Engineering
in the Faculty of Engineering at Stellenbosch University
Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: December 2016
Abstract

South Africa, when compared to the rest of the world has been relatively slow in implementing BIM technologies. This study aims to find a new way in which BIM may address problems in construction associated with project change. By analysing Variation Orders (V.O.s) and the associated delay and disruption events, it was found that there exists an unforeseen impact of change on labour productivity. Although some contractors are aware of the reduced productivity associated with changes in construction, it is difficult to prove and, furthermore, difficult to quantify.

This study analyses existing literature that suggests methods for quantifying the impact of change on labour productivity. However, the current methods are flawed. Most of the methods are used upon completion of a project to resolve the financial differences caused by multiple change orders. The reliability of each model is determined by the reliability of source data used. Furthermore, this data will depend on the scope of work, types of work observed (trades) as well as the data analyses technique used (Sanders and Nagata 2003). A study by others suggests a method of using both a discrete and cumulative analyses to predict the impact of change. This method, by others was used as the basis for a proposed BIM plug-in which directs contractors to existing studies and quantification methods for factors influencing productivity. However, it is unreasonable to expect that a contractor would have heard of, or have access to these studies.

The BIM solution is used to integrate the current methods into a supplementary BIM program, or plug-in, that may allow a contractor to easily access the necessary information to predict the impact of change on labour productivity for their relevant project. The BIM process developed is implemented in a case study where the change impact is quantified and compared to original contractor estimates. It was found that for three changes that occurred during the case study, there was an unforeseen impact on cost and time. The proposed method calculated that labour costs increased by 6% and there was a four day delay due to the cumulative impact of change.

Subsequently, the case study and developed model was validated by consultation with industry professionals for criticism and recommendations as to how the BIM plug-in should be developed. The participants in the validation process agreed that it is a tool that they would use once the
challenges have been corrected. The model was criticised for the platform in which it was presented (Revit). It was recommended that the plug-in be developed as a quantity surveying tool to be used through Navisworks. Nevertheless, the participants identified the plug-in as a useful management tool to visually communicate changes and its effect amongst project parties. It was also recognised as an objective means to quantifying the impact of change on labour productivity.

BIM can be used to manage the unforeseen impacts of multiple variation orders and quantify the time and cost impacts of variation orders on productivity.
Opsomming

Suid-Afrika het Bou Inligtingsmodelle (BIM) relatief stadig ge-implementeer in vergelyking met die res van die wêreld. Die oogmerk van hierdie studie was 'n nuwe wyse waarop BIM die probleme met veranderinge in konstruksie kan oplos. Deur die ontleding van wysigingsopdragte (V.O.s) en die gepaardgaande vertragings en ontwrigtings is gevind dat daar 'n onbeplande impak van verandering op arbeidsproduktiwiteit is. Alhoewel sommige kontrakteurs bewus is van die verband tussen veranderinge in konstruksieen en die verminderde produktiwiteit, is dit moeilik om te bewys en nog moeiliker om te kwantifiseer.

Hierdie studie analiseer bestaande literatuur wat metodes vir die kwantifisering van die impak van verandering op arbeidsproduktiwiteit voorstel. Die huidige metodes is egter gebrekkig. Die meeste metodes word gebruik by die voltooing van 'n projek om die finansiële verskille veroorsaak deur verandering op te los. Die betroubaarheid van elke model word bepaal deur die betroubaarheid van die bron data gebruik. Verder sal hierdie inligting afhang van die omvang van die werk, tipes werk waargeneem (ambagte) asook die data ontleed tegniek gebruik (Sanders and Nagata 2003). ’n Studie deur ander navorsers dui op 'n metode deur die gebruik van diskrete en kumulatiewe ontledings om die impak van verandering te voorspel. Hul metode is gebruik as die basis vir 'n voorgestelde BIM toepasting vir kontrakteurs om bestaande studies en kwantifisering metodes te gebruik om produksiwiteitsfaktore aan te pas. Dit is egter onredelik om te verwag dat 'n kontrakteur bekend sou wees van, of toegang sal hê, tot hierdie studies.

Die BIM benadering word in hierdie studie gebruik om die bestaande metodes in 'n aanvullende BIM program, of toepassing, te integreer. Dit kan 'n kontrakteur toelaat om maklik toegang tot die nodige inligting te verkry om die impak van verandering op arbeidsproduktiwiteit vir 'n projek te voorspel. Die ontwikkelde BIM proses word toegepas in 'n gevallestudie waar die impak van verandering gebekwantifiseer word en vergelyk word met die oorspronklike beplanning. Dit is gevind dat daar 'n onbeplande impak op koste en tyde is vir drie veranderinge wat tydens die gevallestudie plaasgevind het. Die voorgestelde metode bereken dat arbeidskoste met 6% styg en dat daar 'n vier dae vertraging is as gevolg van die kummulatiewe impak van veranderinge. Daarna is persone in die konstruksie bedryf genader vir kritiek en vir aanbevelings ten opsigte van hoe die BIM toepassing ontwikkel kan word.
Die deelnemers van die verifikasie proses het bevestig dat dit ’n instrument is wat hulle sou gebruik wanneer die veranderinge aangebring is. Die model is gekritiseer vir die platform waarop dit aangebied is (Revit). Daar is aanbeveel dat die toepassing ontwikkel word as ’n bourekenkunde hulpmiddel deur die gebruik van Navisworks. Nogtans het die deelnemers die toepassing as ’n bestuurshulpmiddel bevestig. Daar is ook erkenning gegee dat dit gebruik kan word om die arbeidsproduktiwiteit te kwantifiseer.

BIM kan dus gebruik word om die onbeplande gevolg van projekveranderinge te bestuur en te kwantifiseer deur die tyd en koste impak op produktiwiteit te kwantifiseer.
Acknowledgements

The author wishes to acknowledge the following people and institutions for their various contributions towards the completion of this work:

- My family, Godfrey, Anthea and Toni: for putting up with me and encouraging me throughout my life. I could never begin to say how grateful I am.

- Wayne Smart: for your supply of knowledge and information to this research. Your help led to the success of this project.

- Research Participants: Thank you for contributing to this research by taking the time to share your experiences and knowledge.

- Chis Jurgens: for always attending the weekly meetings, helping me define my topic and come up with new ideas to solve the problems I faced.

- Jan Wium: As my supervisor you possibly faced a challenge greater than my own. Thank you for your continuous comments and feedback that helped give me direction and motivation. Thank you for taking the extra time to ensure I reached my goals.
# Table of Contents

## Abstract

## Opsomming

## Acknowledgements

## List of Acronyms

## List of Figures

## List of Tables

## List of Algorithms

## Research Overview

1.1 Background .................................................... 1

1.2 Research Question ........................................... 2

1.3 Research Aims and Objectives ............................... 2

1.3.1 Aims .......................................................... 2

1.3.2 Objectives .................................................... 3

1.4 Scope and Limitations of the Study ......................... 3

1.5 Research Design ............................................. 3

1.6 Research Methodology ...................................... 4

1.7 Thesis Outline ............................................... 4

viii
# Table of Contents

## 2 Understanding BIM

2.1 Introduction ......................................................... 6
2.2 Definitions .......................................................... 6
2.3 BIM Software and Supplementary Programs ........................ 7
2.4 The Role of BIM in the Construction Industry ...................... 8
   2.4.1 Benefits of Implementing BIM for Change in Construction .... 8
   2.4.2 Risks of Applying BIM ........................................... 11
2.5 Chapter Summary .................................................... 13

## 3 The Cumulative Impact of Change

3.1 Introduction .......................................................... 16
3.2 The History of Cumulative Impact .................................. 17
3.3 Defining the Cumulative Impact of Change ........................ 17
3.4 Construction Contracts and Change ................................ 18
   3.4.1 Types of Change According to Contracts .................... 18
   3.4.2 Valuation of a V.O.............................................. 19
3.5 Characteristics of Cumulative Impact ............................. 20
3.6 Analysis of the Loss of Labour Productivity ...................... 21
   3.6.1 Defining Labour Productivity .................................. 22
3.7 Changes in the South African Construction Industry .............. 23
   3.7.1 Human Factors .................................................. 23
   3.7.2 Difficult Working Conditions ................................... 24
   3.7.3 Organisational Constraints ..................................... 25
   3.7.4 Summary of Factors Affecting Labour Productivity ........... 26
   3.7.5 Systematic Overview of the Cumulative Impact of Change .... 27
   3.7.6 Section Summary ............................................... 34
3.8 Global Understanding of the Cumulative Impact of Change ....... 35
   3.8.1 Project and Contract Factors ................................. 37
   3.8.2 Location and Environmental Factors ........................... 37
# Table of Contents

3.8.3 Project Team Factors ........................................... 38  
3.8.4 Managerial Actions and Decisions During Project Execution ..................... 38  
3.8.5 Disruption Events ........................................ 39  
3.8.6 Human/Workers’ Reaction ........................................ 39  
3.8.7 External Factors ........................................ 40  
3.8.8 Section Summary ........................................ 40  
3.9 Chapter Summary ........................................ 42  

4 Quantifying the Cumulative Impact of Change ........................................ 43  
4.1 Introduction ........................................ 43  
4.2 Limitations to Current Quantification Methods ........................................ 43  
  4.2.1 Existing Methods for Quantifying Change Impact ........................................ 44  
4.3 Quantification Methodology ........................................ 45  
  4.3.1 General Process ........................................ 46  
4.4 BIM Use and Software Interaction ........................................ 50  
  4.4.1 The Process Using Revit ........................................ 50  
  4.4.2 The Role of Navisworks ........................................ 52  
4.5 Chapter Summary ........................................ 55  

5 BIM as a Solution for Change Management ........................................ 56  
5.1 Introduction ........................................ 56  
5.2 Case Study to Demonstrate BIM Quantification Method ........................................ 56  
  5.2.1 Project Description ........................................ 57  
  5.2.2 Description of Changes to the Project ........................................ 58  
5.3 Quantifying the Changes ........................................ 61  
  5.3.1 House Width Change Quantification ........................................ 64  
  5.3.2 Slab Dimension Quantification ........................................ 72  
  5.3.3 Roof Height Change Quantification ........................................ 82  
5.4 Summary of the Changes ........................................ 88
6 Validation

6.1 Introduction ................................................. 90
6.2 Validation Objectives ...................................... 90
6.3 Methodology .................................................. 91
6.4 Question Response ......................................... 91
   6.4.1 In your experience, is labour productivity considered when quoting changes? 92
   6.4.2 Were you previously aware of the Cumulative Impact of Change or the indirect impacts of changes? ......................... 92
   6.4.3 Following the presentation, do you see value in quantifying the indirect and cumulative impact of changes? ......................... 93
   6.4.4 Do you use BIM on your projects? ...................... 93
   6.4.5 Would you consider using the proposed BIM plug-in? ............... 94
   6.4.6 List all criticism you may have for the proposed method of quantifying change impact ........................................... 94
   6.4.7 List any positive aspects you may have from the presentation ................. 95
   6.4.8 List any recommendations you may have for the proposed method of quantifying change impact ........................................... 96
6.5 Chapter Summary .............................................. 97

7 Conclusion ......................................................... 98

7.1 Introduction .................................................. 98
7.2 Results from the Investigation .......................... 98
7.3 Conclusion ...................................................... 101

8 Recommendations ................................................ 103

8.1 Study Selection ................................................ 103
8.2 Validity of Data ............................................... 103
8.3 Further Development ....................................... 104

References ........................................................... 105
Table of Contents

A NEC Compensation Events
   A.1 Introduction ................................................................................................. 113
   A.2 Procedure for Compensation Events ............................................................ 114
      A.2.1 Notification .............................................................................................. 114
      A.2.2 Quotation ............................................................................................... 115
      A.2.3 Assessment ............................................................................................... 115

B Productivity Factors from Quantification Studies .............................................. 117
   B.1 Overtime Studies ............................................................................................ 117
      B.1.1 Kossoris (1947) ...................................................................................... 117
      B.1.2 O’Connor (1969) ................................................................................... 118
      B.1.3 Howerton (1969) ................................................................................... 119
      B.1.4 Smith (1975) ......................................................................................... 120
      B.1.5 NECA (1962, 1969, 1989) .................................................................... 121
      B.1.6 The US Army Corps of Engineers (1979) .............................................. 123
      B.1.7 Blough (1973) ....................................................................................... 124
      B.1.8 Bromberg (1988) .................................................................................. 125
      B.1.9 Haneko and Henry (1991) ...................................................................... 126
      B.1.10 Mechanical Contractors Association of America (1994) ................. 127
      B.1.11 Hanna and Sullivan (2004) .................................................................. 128
      B.1.12 Hanna, Chang, Lackney and Sullivan (2005) ....................................... 130
   B.2 Congestion Studies ....................................................................................... 131
      B.2.1 The US Army Corps of Engineers (1979) .............................................. 131
      B.2.2 Kappaz (1977) ...................................................................................... 131
      B.2.3 Smith (1987) ....................................................................................... 132

C Bill of Quantities ............................................................................................... 134

D Case Study Floor Plans and Elevations ............................................................ 139
List of Acronyms

AEC  Architecture, Engineering and Construction.
AGC  Associated General Contractors of America.
AIA  American Institute of Architects.
BIM  Building Information Modelling.
BOQ  Bill of Quantities.
CAD  Computer Aided Drafting
C.O.  Change Order.
CORPS  The US Army Corps of Engineers
DBB  Design Bid Build.
DD  Design Development.
E&O  Errors and Omissions.
E.O.T  Extension of Time
FIDIC  International Federation of Consulting Engineers.
GCC  General Conditions of Contracts.
GFL  Ground Floor
IFC  Industry Foundation Classes.
IP  Intellectual Property.
IPD  Integrated Project Delivery.
JBCC  Joint Buildings Contract Committee.
List of Acronyms

**JOC** Job Order Contract.

**LOD** Level of Development.

**MCAA** Mechanical Contractors Association of America.

**NEC** New Engineering Contract.

**PI** Professional Indemnity.

**P&G** Preliminary and General.

**RFC** Request for Clarification.

**RFI** Request for Information.

**ROI** Return on Investment.

**SOW** Scope of Works.

**V.O.** Variation Order.
# List of Figures

<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Ability to Influence Costs on a Project</td>
<td>10</td>
</tr>
<tr>
<td>3.1</td>
<td>Visual Representation of the Cumulative Impact</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>The Delta Approach</td>
<td>21</td>
</tr>
<tr>
<td>3.3</td>
<td>Estimated Productivity versus Measured Productivity</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Labour Productivity Delay and Disruption Events</td>
<td>27</td>
</tr>
<tr>
<td>3.5</td>
<td>Phase 1: Process 1</td>
<td>29</td>
</tr>
<tr>
<td>3.6</td>
<td>Phase 1: Process 2</td>
<td>29</td>
</tr>
<tr>
<td>3.7</td>
<td>Process 1 Revised</td>
<td>30</td>
</tr>
<tr>
<td>3.8</td>
<td>Process 2 Revised</td>
<td>30</td>
</tr>
<tr>
<td>3.9</td>
<td>Project Controls</td>
<td>32</td>
</tr>
<tr>
<td>3.10</td>
<td>Cause and Effect Matrix</td>
<td>33</td>
</tr>
<tr>
<td>3.11</td>
<td>Project System Consisting of Productivity Factors</td>
<td>36</td>
</tr>
<tr>
<td>3.12</td>
<td>Expanded Disruption Cycle Model</td>
<td>41</td>
</tr>
<tr>
<td>4.1</td>
<td>Decision Making Process</td>
<td>47</td>
</tr>
<tr>
<td>4.2</td>
<td>Study and Method Map</td>
<td>49</td>
</tr>
<tr>
<td>5.1</td>
<td>3D View of Residential House</td>
<td>57</td>
</tr>
<tr>
<td>5.2</td>
<td>Plan View of Change to House Width</td>
<td>58</td>
</tr>
<tr>
<td>5.3</td>
<td>Plan View of Change to Floor Slab</td>
<td>60</td>
</tr>
<tr>
<td>5.4</td>
<td>Elevation of Roof Height Change</td>
<td>61</td>
</tr>
<tr>
<td>5.5</td>
<td>Initial Project Gantt Chart</td>
<td>63</td>
</tr>
</tbody>
</table>
List of Figures

5.6 Schedule Shift for House Width Change Acceleration 69
5.7 Width Change Outcome 71
5.8 Slab Width Learning Curve 75
5.9 Overmanning Studies' Results 77
5.10 Slab Dimension Outcome 81
5.11 Shift Work Efficiency Loss 84
5.12 Bromberg Study Results 85
5.13 Slab Dimension Outcome 87

B.1 Kossoris 1947 118
B.2 O'Connor 1969 118
B.3 Howerton 1969 119
B.4 Smith 1969 120
B.5 Association 1962 121
B.6 Association 1969 122
B.7 Association 1989 123
B.8 Corps 1979 124
B.9 Blough 1973 125
B.10 Bromberg 1988 126
B.11 Haneiko and Henry 1991 127
B.12 MCAA 1994 128
B.13 Hanna and Sullivan 2004 129
B.14 Hanna, Chang, Lackney, and Sullivan 2005 130
B.15 Corps 1979 131
B.16 Kappaz 1977 132
B.17 Smith 1987 133

C.1 Earthworks 135
C.2 Concrete 136
C.3 Masonry 137
List of Figures

C.4 Roof Coverings ......................................................... 138
D.1 Original House Elevation ........................................... 140
D.2 Final House Elevation ............................................. 141
D.3 Original House Floor Plan ......................................... 142
D.4 Final House Floor Plan ............................................. 143
D.5 Section Through House Smart ...................................... 144
List of Tables

2.1 BIM Authoring Tools .................................................. 7
2.2 BIM Construction Management and Scheduling Tools ............. 8
2.3 BIM Benefits to Project Participants .................................. 9
2.4 LOD Definitions ........................................................ 14
3.1 Literature Sources ...................................................... 28
3.2 Literature used for Productivity Factor Categories .................. 36
5.1 Initial Project Costs .................................................... 62
5.2 Overtime Studies ....................................................... 66
5.3 Overtime Studies ....................................................... 67
5.4 Loss of Productivity Due to Overtime ................................ 68
5.5 Width Change Cost Summary ........................................ 68
5.6 Overtime and Standard Hours Worked ................................ 70
5.7 Overmanning Studies .................................................. 76
5.8 Slab Dimension Change Cost Summary: Activity 1 ............... 78
5.9 Congestion Studies ..................................................... 79
5.10 Slab Dimension Change Cost Summary: Activity 2 .............. 80
5.11 Roof Height Change Summary: Activity 1 ........................ 84
5.12 Joinery Fitting Overtime Costs ...................................... 85
5.13 Roof Change Summary ............................................... 86
5.14 Unforeseen Losses in Case Study .................................... 88
<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Contractor Response: Question 2 Results</td>
<td>92</td>
</tr>
<tr>
<td>6.2</td>
<td>Contractor Response: Question 3 Results</td>
<td>93</td>
</tr>
<tr>
<td>6.3</td>
<td>Contractor Response: Question 4 Results</td>
<td>94</td>
</tr>
<tr>
<td>6.4</td>
<td>Contractor Response: Question 5 Results</td>
<td>94</td>
</tr>
<tr>
<td>6.5</td>
<td>Contractor Response: Question 6 Results</td>
<td>95</td>
</tr>
<tr>
<td>6.6</td>
<td>Contractor Response: Question 7 Results</td>
<td>96</td>
</tr>
<tr>
<td>6.7</td>
<td>Contractor Response: Question 8 Results</td>
<td>96</td>
</tr>
</tbody>
</table>
List of Algorithms

3.1 Relative Productivity of A ................................................................. 23
4.1 Revit Data Handling ................................................................. 51
4.2 Naviswork Data Handling ................................................................. 54
5.1 Calculating the Productivity Loss due to Shift Work ......................... 83
CHAPTER 1

Research Overview

1.1 Background

Building Information Modelling (BIM) is becoming more popular within the construction industry and is marketed for its ability to intelligently model buildings and other structures. While a relatively large number of leading companies across the world have taken steps to implement BIM technologies, companies in South Africa have been slower at picking up the trend. (Tabesh 2014).

Information sharing is an important part of the construction industry for all parties involved from the design phase to construction and project closeout phases. BIM has the potential to benefit all parties, however, as stated previously, South African companies have not implemented BIM to the same extent as European or American companies. It is therefore necessary to determine whether there is a use for BIM in South Africa, and what support BIM could bring to South African companies.

Variations to the original scope of work (SOW) was identified as an area whereby South African companies may benefit from implementing BIM. Varying the SOW has a great time and cost impact on a project (Williams 1997). Generally, South African contractors understand and are able to quantify the direct impact of Variation Orders (V.Os), however there is an unforeseen secondary impact of V.Os that is not as well recognized or managed (Neff and Wium 2014). V.Os may cause delays and disrupt work on a project. These delays and disruptions may occur as a direct result of a single V.O. or as a cumulative effect of multiple V.Os.

The cumulative impact, or synergistic effect of multiple V.Os is difficult to determine, quantify, and may often only be realised once a project has been completed. This could severely influence contractors not being able to request additional time or payment on a project. Different project parties may also have varying motives towards quantifying the impact of a change. For example:
1.2. Research Question

Clients may wish to pay as little as possible, regardless if he/she was the cause of the change to the project. The engineer may also wish to avoid any penalties or the damage to his/her reputation resulting from the V.O. even if it was directly linked to their actions/inactions. The contractor, however, may view changes to the project as an opportunity to make a profit. The contractor would then inflate the cost of a change to cover other losses or if the project was priced low due to competition in the market.

Therefore, the main aim of this research is to propose and validate a possible manner in which BIM can be used to address the unknown factors of the cumulative impact of V.Os as well as a standard method for quantifying the cumulative impact of change.

1.2 Research Question

BIM is a powerful tool that has not yet made a significant impact in the South African construction industry. South African contractors lack the knowledge and resources to predict the cumulative impact of V.Os. The research questions are thus:

- Is it possible to use BIM to manage the unforeseen impacts of multiple V.Os?
- Can BIM be practically applied to this problem to quantifiably measure the cumulative impact of change?

Understanding a BIM process would assist contractors with claims and will reduce the losses in time and cost due to the issuance of multiple V.Os.

1.3 Research Aims and Objectives

1.3.1 Aims

This research aims to identify causes and trigger events of the cumulative impact of change so that a relationship may be developed to better predict the cumulative impact. This will be done for the South African construction industry, although the results will be universal.

Furthermore, the South African construction industry has not fully adapted to the use of BIM. Some contractors have not identified the need for the software. It is therefore the aim of this research to identify the capability of BIM in managing the cumulative impact of change. To more easily understand the cumulative impact of change, BIM will be used to predict and visualise unforeseen impacts of multiple V.Os.
1.3.2 Objectives

The following are objectives to achieve the aims of the research:

- **Present the definition** of the cumulative impact of change
- **Investigate** different delay and disruption events triggered by the cumulative impact of change
- **Investigate** factors affecting labour productivity
- **Find** a quantification methodology for the cumulative impact of change
- **Propose** a possible BIM solution to managing the cumulative impact of change
  - Identify the advantages and disadvantages of BIM
  - Propose a possible solution in which BIM may predict secondary impacts of change
- **Validate** the solution by consulting with construction industry professionals

1.4 Scope and Limitations of the Study

To achieve the aims and objectives of this study it is necessary to define the scope and to set research limitations.

Although this study is focused on the cumulative impact of change, it will not be an investigation into this topic. Information from existing literature will be presented to create an understanding of the topic.

BIM software and the manipulation of BIM software will be investigated, however this will not include the computer programming of a new BIM plug-in. The study will focus on the conceptual illustration of impact relationships and the logic behind implementing these processes with BIM. Autodesk Revit will be used for the study as it has been made available by Stellenbosch University.

1.5 Research Design

Existing literature will be reviewed to better understand the topics involved in this research. This research will make use of existing qualitative and quantitative data collected from other researchers in the form of surveys, interviews and case studies. In order to develop a solution to the problem, the study will be methodological whilst utilizing secondary data analyses.
1.6 Research Methodology

Therefore, the design blueprint will be an inductive approach as follows:

1. Analyse existing literature
2. Develop relationships between productivity factors
3. Propose a possible solution
4. Validate solution

1.6 Research Methodology

As it has been identified that BIM may field a possible solution to the problem of unforeseeable delay and disruption events caused by change management, a literature review of BIM and BIM software will be performed. This study will identify and develop an understanding of BIM and the potential for a change management plug-in possible.

In order to identify what cumulative impact is, this research will first seek to identify factors causing the secondary impact of change so that the cumulative impact of change may be defined.

Following the definition of the cumulative impact of change, existing data and the results of empirical research will be analysed to develop impact relationships between delay and disruption events. Understanding the knock-on effect of a change will enable the proposal of a recommended solution. No further surveys will be conducted as information will be collected from previous studies.

Subsequently, the developed BIM approach for quantifying the impact of change on labour productivity will be demonstrated. The methods used to quantify changes will be applied to a case study so that a real life application is performed. The case study will aid in explaining the process of quantifying the impacts as well as to enable the validation of the model.

Finally, once a solution has been found, the study will use a consultation or interview approach to gather information from industry professionals. The interviews will determine whether or not the proposed solution is valid and whether the solution would be beneficial to the construction industry. This will allow recommendations to be made with regards to change management for contractors in the construction industry, as well as potential uses of BIM.

1.7 Thesis Outline

Chapter 1 – Introduction
1.7. Thesis Outline

The inaugural chapter provides the reader with a background for the proposed research. The problem statement and research aims and objectives are defined in this chapter with a brief summary of other chapters included in the report.

Chapter 2 – Understanding BIM

The first chapter in the literature study will provide the reader with a fundamental understanding of BIM as well as the advantages, disadvantages and capabilities of BIM software.

Chapter 3 – The Cumulative Impact of Change

Chapter 3 will identify what cumulative impact of change is. It will firstly be necessary to identify the current state of understanding amongst contractors. Additionally, factors causing the cumulative impact of change will be identified in this chapter so that the cumulative impact of change may be defined. This entails an in-depth review of factors affecting productivity so that a systematic overview of labour productivity may be given.

Chapter 4 – Quantifying the Cumulative Impact of Change

This chapter will investigate delay and disruption events caused by multiple V.Os and will attempt to identify relationships between events. Once relationships have been identified, it will be possible to propose a method for quantifying the cumulative impact of change.

Chapter 5 – BIM as a Solution to Change Management

A case study will be used to demonstrate the proposed BIM solution. This chapter will display the outcomes from a simulation whereby change is quantified using BIM.

Chapter 6 – Validation

Chapter 6 presents the results of consultations and interviews with industry professionals, with regards to the validity and viability of the proposed solution.

Chapter 7 – Conclusion

The ability of BIM as a tool to manage the cumulative impact of change is concluded. This chapter will state whether the aims and objectives of the study were met.

Chapter 8 – Recommendations

Recommendations are given for the implementation of the proposed solution as well as future improvements and requirements of the solution.
CHAPTER 2

Understanding BIM

2.1 Introduction

Although BIM (Building Information Modelling) was first developed as a design tool, BIM software is increasingly becoming favoured by contractors (McGraw-Hill 2008). This chapter will identifies BIM is and how it may be used to combat issues associated with the cumulative impact of change. Understanding the advantages and disadvantages of BIM will demonstrate how BIM may be used to solve the research question of this thesis. This will be a fundamental step in progressing to more advanced BIM applications.

BIM software often works in conjunction with other programs, such as Microsoft Project and Navisworks. These programs will also be discussed to aid in defining and implementing the quantification process of Chapter 4.

2.2 Definitions

The McGraw Hill report (2008) defines BIM as “the process of creating and using digital models for design, construction and/or operation of projects”. This view on BIM is somewhat simplified as this definition focuses on the technical features of BIM as opposed to the intelligence and information-storing capabilities of a BIM tool (Barlish and Sullivan 2012).

BIM, as defined by Woo, Wilsmann, and Kang (2010), is “an intelligent 3D virtual building model that can be constructed digitally by containing all aspects of the building information into an intelligent format that can be used to develop optimised building solutions with reduced risk and increased value before committing to a design proposal”.

Although many different definitions of BIM exist, it is difficult to include all features of BIM in a single title and it is therefore necessary to gather knowledge from different sources. BIM
may be viewed as an activity (building information modelling) as opposed to an object (building information model). The activity of BIM progresses throughout the lifecycle of a project, from design until operation and decommission, continually updating and adding information such as time, cost and quality (4D, 5D and 6D) with tools such as Navisworks. (Eastman, Teicholz, and Sacks 2011).

2.3 BIM Software and Supplementary Programs

This section identifies a variety of software tools available that enable BIM use on a project. Certain software packages specialise in architectural, structural, MEP (Mechanical Electrical Plumbing), and/or site work modelling (Hergunsel 2011). Table 2.1 lists some of the many software packages with each manufacturer and primary function.

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Manufacturer</th>
<th>Primary Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadpipe HVAC</td>
<td>AEC Design Group</td>
<td>3D HVAC Modeling</td>
</tr>
<tr>
<td>AutoCAD Architecture</td>
<td>Autodesk</td>
<td>3D Architectural Modeling</td>
</tr>
<tr>
<td>Revit BIM Suite</td>
<td>Autodesk</td>
<td>3D Architectural Modeling, Structural Modeling, Detailed MEP Modeling</td>
</tr>
<tr>
<td>AutoCAD MEP</td>
<td>Autodesk</td>
<td>3D MEP Modeling</td>
</tr>
<tr>
<td>AutoCAD Civil 3D</td>
<td>Autodesk</td>
<td>Site Development</td>
</tr>
<tr>
<td>Cadpipe Commercial Pipe</td>
<td>AEC Design Group</td>
<td>3D Pipe Modeling</td>
</tr>
<tr>
<td>Dprofiler</td>
<td>Beck Technology</td>
<td>3D Concept Modeling and time cost estimating</td>
</tr>
<tr>
<td>Bentley BIM Suite</td>
<td>Bentley Systems</td>
<td>3D Architectural, Structural, Mechanical, Electrical, and Generative Components Modeling</td>
</tr>
<tr>
<td>Fastrak</td>
<td>CSC (UK)</td>
<td>3D Structural Modeling</td>
</tr>
<tr>
<td>SDS/2</td>
<td>Design Data</td>
<td>3D Detailed Structural Modeling</td>
</tr>
<tr>
<td>ArchiCAD</td>
<td>Graphisoft</td>
<td>3D Architectural Modeling</td>
</tr>
<tr>
<td>HydraCAD</td>
<td>Hydratec</td>
<td>3D Fire Sprinkler Design and Modeling</td>
</tr>
<tr>
<td>Tekla Structures</td>
<td>Tekla</td>
<td>3D Detailed Structural Modeling</td>
</tr>
</tbody>
</table>

A few of the software packages listed in Table 2.1 are also capable of cost estimation and scheduling. Additionally, construction management and scheduling tools are available that work in conjunction with BIM software (see Table 2.2).

Although many platforms have been created for BIM use, this study is limited to the Autodesk software packages, namely: the Revit Suite and Navisworks. Where Revit is used for 3D modelling, scheduling and providing quantity estimates, Naviswork is used for clash detection and sequencing of projects (Hergunsel 2011). Autodesk Navisworks has a function called Timeliner. This function can link Microsoft Project and Primavera project planner files to various BIM
2.4 The Role of BIM in the Construction Industry

Table 2.2: BIM Construction Management and Scheduling Tools (Reinhardt 2009)

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Manufacturer</th>
<th>BIM Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navisworks Manage</td>
<td>Autodesk</td>
<td>Clash Detection and Scheduling</td>
</tr>
<tr>
<td>Project Wise</td>
<td>Bentley</td>
<td>Clash Detection and Scheduling</td>
</tr>
<tr>
<td>Digital Project Designer</td>
<td>Gehry Technologies</td>
<td>Model Coordination</td>
</tr>
<tr>
<td>Synchro</td>
<td>Synchro Ltd</td>
<td>Planning and Scheduling</td>
</tr>
<tr>
<td>Tekla Structures</td>
<td>Tekla</td>
<td>Structure-centric Model, Schedule driven</td>
</tr>
<tr>
<td>Vico Office</td>
<td>Vico Software</td>
<td>Coordination, Scheduling, Estimating</td>
</tr>
</tbody>
</table>

platforms (i.e. Revit, etc.).

Autodesk Revit and Navisworks will be used to predict the direct and cumulative impact of change through the visualisation of components, clash detection, sequencing and resource and material scheduling.

2.4 The Role of BIM in the Construction Industry

BIM enables both the owner of a project and the contractor to save considerably on costs, as BIM progressively reduces error and enhances the performance of the project team (Dawood, Scott, Sriprasert, and Mallasi 2005). BIM also has the capability of linking cost and time to elements and processes in a project. Having the connection of time and cost on a project enables the planner of the project to accurately and practically identify issues affecting the work and to maintain control over the project (Dawood, Scott, Sriprasert, and Mallasi 2005).

Table 2.3 summarizes a few of the uses for BIM with the respective project participant. However, this report will predominantly focus on aspects of BIM related to the cumulative impact of change.

BIM has a broad range of services available to the construction industry. BIM may be used in visualisation, creating fabrication drawings, to reviews codes of best practise, cost estimating, construction sequencing, conflict/interference/collision detection, forensic analysis and facilities management (Azhar 2011).

2.4.1 Benefits of Implementing BIM for Change in Construction

According to Azhar (2011), Gilligan and Kunz (2007) and McGraw-Hill (2008) the top drivers for the implementation of BIM are:

1. improved coordination
2. increased productivity
2.4. The Role of BIM in the Construction Industry

<table>
<thead>
<tr>
<th>Project Participant</th>
<th>Potential Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>Quality information about facilities, planning and budgeting to make decisions</td>
</tr>
<tr>
<td>Planner</td>
<td>Information about existing physical site and program needs</td>
</tr>
<tr>
<td>Appraiser</td>
<td>Information about the facility to support valuation</td>
</tr>
<tr>
<td>Designers</td>
<td>Planning and site information</td>
</tr>
<tr>
<td>Engineers</td>
<td>Electronic model from which to import into design and analysis software</td>
</tr>
<tr>
<td>Quantity Surveyor</td>
<td>Accurately obtain quantities and share comparables</td>
</tr>
<tr>
<td>Contracts and Legal</td>
<td>Accurate legal descriptions and able to defend or on which to base litigation</td>
</tr>
<tr>
<td>Contractors</td>
<td>Intelligent objects for bidding, ordering, and a place to store gained information</td>
</tr>
<tr>
<td>Sub-Contractors</td>
<td>Clear communication and same support for contractors</td>
</tr>
<tr>
<td>Code Officials</td>
<td>Faster and more accurately code checking software</td>
</tr>
<tr>
<td>Facility Management</td>
<td>Provides product, warranty and maintenance information</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Identify, track, budget, and schedule; repair, replacement, maintenance needs</td>
</tr>
<tr>
<td>Restoration</td>
<td>Identify, track, budget, and schedule capital reinvestment requirements</td>
</tr>
<tr>
<td>Simulation</td>
<td>Electronically build facility and eliminate conflicts, simulate growth needs</td>
</tr>
<tr>
<td>Environmental</td>
<td>Improved information for environmental impact analysis</td>
</tr>
<tr>
<td>Plant Operations</td>
<td>3D visualization of processes</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Energy analysis including energy and condition analyses concurrently</td>
</tr>
<tr>
<td>Space and Security</td>
<td>Intelligent objects in 3D provide better understanding of usage, flow, security issues</td>
</tr>
<tr>
<td>Risk Management</td>
<td>Better understanding of potential risks and how to avoid or minimize</td>
</tr>
</tbody>
</table>

3. improved communication

4. improved quality control

A study found that participants indicated that BIM led to better document development and an increase in productivity due to better engagement from project staff (Gilligan and Kunz [2007]). With BIM, information is shared more effectively and with faster processes (Azhar [2011]). Having updated and accurate drawings, which may be extracted from a model at any time, is achievable with BIM (Sacks [2004]). This allows for a more productive design with decreased labour requirements. Design constructability may improve labour productivity factors such as reducing concurrent operations, reduced errors and omissions (E&O), optimum crew size,
2.4. The Role of BIM in the Construction Industry

working in confined spaces etc. (Intergraph 2012). BIM manages change in an iterative process so that any change to a part of the database will be reflected in all other parts (Autodesk 2002). The Aquarium Hotel Garden Inn in Atlanta, Georgia, implemented BIM for design coordination and clash detection (Azhar 2011). The implementation of BIM cost the project $90,000, however, the software managed to identify 590 clashes before construction began which lead to a net saving of $200,392 (Azhar 2011). An early identification of clashes may enable the contractor to reduce costs as fewer variation orders (V.Os) will be necessary (Staub-French and Khanzode 2007; Yan and Damian 2008). Eastman, Teicholz, and Sacks (2011) identified that there is a much greater ability to influence the costs earlier on in a project. Later changes to a project are also more expensive (Cholakis and Trebas 2013). This is displayed in Figure 2.1 where a traditional procurement process (Design-Bid-Build (DBB)) is compared to a Job Order Contract (JOC) and an Integrated Project Delivery (IPD). Therefore, being able to predict clashes and prevent V.Os will aid in reducing delays and disruption due to the reduced cumulative impact of change.

Another project, a higher education facility, used BIM for planning and value analysis. BIM was used to identify different options for the construction and aesthetics of the project. The
BIM software streamlined the process and led to a saving of $1\,995\,000 (16.6\% of project cost) at the predesign stage. Although this may be done using traditional drawings, the use of BIM technology aided in making a well-informed, quick and definitive decisions (Azhar 2011). A simulated model in the conceptual phase of a project may be used as an evaluation tool that allows an owner to comprehend if the project will be feasible given the time and budget (Eastman, Teicholz, and Sacks 2011).

A questionnaire survey performed in 2008 by McGraw-Hill Construction identified current and future trends in the role BIM plays in the architecture, engineering and construction (AEC) industry. From a sample consisting of 39 clients, 82 architects, 101 engineers, and 80 contractors in the United States, 79\% of BIM users experienced improved project outcomes, such as fewer requests for information (RFI) (McGraw-Hill 2008).

Tabesh (2014) reported that BIM has the capability of enhancing change management on a project. Processing change orders (C.Os) or V.Os is a time consuming procedure. In addition to this, V.Os have an influence on a project that may only become known at a later stage (Barlish and Sullivan 2012). Being able to simulate and integrate all components of a project, BIM will not only speed up the change management process, but also has the potential to identify conflict and effects caused by the changes that would have only been noticed later (Eastman, Teicholz, and Sacks 2011). This is a core component of current BIM use as 3D and 4D clash detection has been identified as the main use of BIM in AEC companies (Azhar 2011). Similarly, in other surveys it was found that visualisation, clash detection, building design and as-built models are the top ranked benefits of applying BIM (Becerik-Gerber and Rice 2010).

However, despite the many advantages of implementing BIM within a project, there also exist certain risks which prevent some organisations from utilising BIM.

### 2.4.2 Risks of Applying BIM

The risks of applying BIM to a project will be categorised in terms of the human factors, compatibility, legal concerns and the value of cost versus quality.

#### 2.4.2.1 Human Factors

A human component is required to implement software based technology in the form of the user. BIM needs willingness from the project team as the successful implementation of the software relies on collaboration between project parties (Tabesh 2014). The training required to use BIM technologies is one of the obstacles companies face when implementing BIM (Yan and Damian 2008).
A similar factor that challenges the implementation of BIM is the need for the information to be accessible to all team members. This is a challenge as it may require a shift in the organisational culture and infrastructure of a company (Eastman, Teicholz, and Sacks 2011). A lack of specialist BIM managers within an organisation or team adds to the difficulty in implementing a BIM approach (Johnson and Gunderson 2009; Kashiwagi, Kashiwagi, Kashiwagi, and Sullivan 2012; Ku and Taiebat 2011; Mayo, Giel, and Issa 2012). The cultural change within the organisation may provide further challenges which stem from a lack of motivation, and need for a return on investment (ROI), from the owners and investors (Birkeland 2009; Brewer and Gajendram 2011; Makanae, Yabuki, and Kashiyama 2010; Denzer and Hedges 2008).

The need to be profitable is an argument against the implementation of BIM (Wix 1997). Wix (1997) argues that being profitable is the most important objective of a business and, therefore, companies need proof that the investment in BIM will have a significant return on investment (ROI). However, more recent studies have been able to provide proof that BIM offers a significant initial ROI, between 300 and 500% (McGraw-Hill 2008). Nevertheless, there is resistance to change and new technology in the AEC industry as traditional, proven methods are still used despite the benefits of BIM (Tabesh 2014).

### 2.4.2.2 Compatibility

There exists a wide range of BIM tools. This has led to a challenge when implementing BIM on a project when project participants may use different BIM software. The different software tools have differing data formats which are incompatible with one another. However, with the development of the Industry Foundation Classes (IFC) standards, a mechanism for interoperability between software formats has been created. (Eastman, Teicholz, and Sacks 2011; Johnson and Gunderson 2009).

### 2.4.2.3 Legal Concerns

One of the legal concerns regarding BIM is the copyright of databases when sharing a model (Briggs and Brumpton 2001; Christensen, McNamara, and O’Shea 2007; Johnson and Gunderson 2009). Intellectual Property (IP) and Professional Indemnity (PI) insurance are areas of concern due to the uncertainties involved with sharing a BIM model (Eadie, Browne, Odeyinka, McKeown, and McNiff 2013). BIM implementation requires collaboration which could result in the sharing of IP amongst project participants.

Another legal concern with regards to implementing BIM revolves around the ownership of the model. Specifically, the question: who owns the multiple design, fabrication, analysis and construction datasets (Eastman, Teicholz, and Sacks 2011)? Furthermore, it leads to the question:
who is responsible for paying for the design, fabrication, analysis and construction datasets? However, professional groups, such as the AIA (American Institute of Architects) and the AGC (Associated General Contractors of America), are developing guidelines to contractually address the use of BIM on a project (Eastman, Teicholz, and Sacks 2011).

2.4.2.4 Value of Cost versus Quality

Barlish and Sullivan (2012) identified that the value of BIM is related to the project size, the nature of communication amongst teams, the proficiency of team members and other external factors. Hergunsel (2011) similarly defines the cost of implementing BIM as a function of project complexity and the Level of Development (LOD) of the model.

The LOD refers to how complete the model is (Autodesk 2008). The LOD may vary from 100 to 500 for different stages of design (See Table 2.4). Methods exist to control the LOD of drawings. However, the LOD system does not measure the quality of the drawing and therefore cannot assess the effect of the drawing on constructability or time and cost savings (Luth, Schorer, and Turkan 2013). This implies that although costs may be significant to achieve a certain LOD BIM model, the model may still not provide quality data.

Consequently, the cost of providing trained resources is one of the most pivotal challenges when implementing BIM on construction projects (Crotty 2011). This is to ensure the quality of the BIM model. Furthermore, the benefits of BIM may not be immediately achievable and take time to be discerned. (Azhar, Carlton, Olsen, and Ahmad 2011; Eadie, Browne, Odeyinka, McKeown, and McNiff 2013; Sebastian 2010; Yan and Damian 2008).

2.5 Chapter Summary

BIM offers a holistic approach to management in the construction industry. By implementing BIM on a project, from conception to operation and finally decommission, a contractor or project team may reap considerable benefits including, but not limited to, the following:

1. Reduce error in design/early detection of design error
2. Increase performance of the project team
3. Accurately identify time/cost issues affecting work
4. Maintain control of the project schedule
5. Improved coordination
Table 2.4: Level of Development Definitions (BIMForum 2015)

<table>
<thead>
<tr>
<th>Level of Development</th>
<th>Potential Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOD 100</td>
<td>The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.</td>
</tr>
<tr>
<td>LOD 200</td>
<td>The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.</td>
</tr>
<tr>
<td>LOD 300</td>
<td>The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.</td>
</tr>
<tr>
<td>LOD 350</td>
<td>The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.</td>
</tr>
<tr>
<td>LOD 400</td>
<td>The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.</td>
</tr>
<tr>
<td>LOD 500</td>
<td>The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.</td>
</tr>
</tbody>
</table>

6. Increased productivity in coordination and design for constructability

7. Improved communication

8. Improved quality control

9. Fewer changes necessary during construction

10. Improved decision making

Nevertheless, there are uncertainties regarding the value of BIM. Human factors, compatibility issues, legal concerns and the value of costs versus quality were identified as inhibitors to the implementation of BIM. However, with recent studies proving the value of implementing BIM, the development of Industry Foundation Classes, and professional groups proposing guidelines for BIM implementation, many of these risks may be mitigated. Additionally, it is evident that
the many advantageous aspects of BIM allow for a predictive means to assess the cumulative impact of change. This will be the potential tool this study aims to identify.

BIM software, such as Autodesk Revit, allows for additional programs (plug-in/add-ins) to run through the BIM software. It is through a BIM plug-in that the process of quantifying the cumulative impact of change will be explained.
CHAPTER 3

The Cumulative Impact of Change

3.1 Introduction

This thesis seeks to identify a manner in which a contractor may predict and quantify the cumulative impact of change. It is therefore an essential component of the study to understand and clearly define the cumulative impact of change.

Many construction projects inherently have variations to the original scope of work (SOW). During the design or planning phase of a project some uncertainty exists. When a variation order (V.O.) is issued, the direct impact on cost and time is generally well understood, however, V.Os have a secondary impact that is not as well recognized (Neff and Wium 2014).

This chapter will define secondary impact and its link to cumulative impact. Several definitions for the cumulative impact of change exist. Understanding the definitions of the cumulative impact of change will create a background from which to develop the possible impact relationships between productivity factors. Different approaches to understanding the cumulative impact of change will be discussed with the associated factors that will contribute to productivity losses when changes are made during construction.

The literature used for the study was obtained from a combination of sources. The content of the literature includes, but is not limited to, research that was performed from direct observation, as well as research literature analysing contract claims, research from contractors, and research about the cumulative impact of change. This was to achieve an understanding that could represent the construction industry as close as possible. Published academic journals are peer reviewed which makes them the best form of data, however, there are a limited number of sources available. Therefore, other types of literature were included such as academic books, reports, unpublished theses and conference proceedings.
3.2 The History of Cumulative Impact

In 1942, the United States Supreme Court denied the existence of the cumulative impact of change (Jones 2001). In a case for claims due to the cumulative impact of change orders the court ruled that “an equitable adjustment was appropriate for work changed by the plan... but an adjustment was not appropriate for the increased cost of completing the unchanged work” (United States v. Rice 1942). This implies that the court only recognised the direct impacts of change and not the secondary or cumulative impacts. This decision by the court lead to the case being referred to as the Rice doctrine (Jones 2001). Therefore, in all subsequent cases the same ruling would be applied (Meintjes-van der Walt 2008). This prevented contractors claiming for expenses incurred as a result of the cumulative impact of change orders until the abolishment of the Rice doctrine in 1967 (Jones 2001). Subsequently, the increased number of claims following the abolishment of the Rice doctrine has led to more sophisticated definitions of the cumulative impact of change (Neff 2014).

3.3 Defining the Cumulative Impact of Change

The cumulative impact of change is a disruption in work that occurs between multiple V.Os and the standard work (unchanged work). Direct disruption is defined as the direct influence that a change in work has on the unchanged work on a project. Therefore, the cumulative impact is the synergistic disruption of multiple changes. (Ibbs 2008).

Hanna, Camlic, Peterson, and Lee (2006), Ibbs (2005) and Jones (2001), have also performed research on the cumulative impact of change by analysing statements acquired from boards of contract appeals and various court cases. The definitions from these sources of the cumulative impact of change are summarised as: disruption events resulting in the loss of productivity and an increase in project cost on unchanged work because of the synergistic effect of multiple V.Os.

At this point it is necessary to mention the difference between the secondary impact and the cumulative impact of change. This research views the secondary impact as the indirect impact of a single change, whereas, the cumulative impact of change refers to the synergistic effect of multiple changes. V.Os do not necessarily cause a direct change in productivity on a project. The changes made through issuing V.Os result in an indirect loss of productivity (secondary impact), commonly known as delay and disruption events. Furthermore, these delay and disruption events occur because of all of the V.Os issued on a project. The delay caused by a single V.O may be planned for, however the unforeseen cumulative impact occurs as a result of the synergy of multiple V.Os.

An initial step is needed to analyse the conditions of contracts so that it can be determined who
is responsible for the delays, disruptions and other effects of the cumulative impact of change. The contractor can then claim for the appropriate losses.

This will establish whether the contract will allow for the existence of the cumulative impact of change and whether the contractor will be able to make a claim against such losses. The primary value of a method to quantify the cumulative impact of change lies in being able to manage change on construction more effectively. However, if the contract does not allow for claims against the cumulative impact of change, the value of creating a method for quantifying the cumulative impact of change will not be as significant.

3.4 Construction Contracts and Change

This section analyses the General Condition of Contract for Construction Works (GCC) (SAICE 2010), the Joint Building Contracts Committee Principal Building Agreement (JBCC) (JBCC 2007) and the New Engineering Contract (NEC3) (NEC3 2005).

All three contract documents allow for change to occur. Clause 16.3.1 of the GCC states: “If, at any time... the engineer shall require any variation... that may be necessary or appropriate, he shall have power to order the contractor to do... so”. Similarly the JBCC, under clause 17.1, states: ”The principal agent may issue contract instructions [V.Os] to the contractor”. The NEC refers to change as compensation events (CE). The NEC3 Engineering and Construction Contract also identifies that “the Project Manager may give instruction to the Contractor which changes the Works Information or a Key Date”. (JBCC 2007; NEC3 2005; SAICE 2010).

Although the information from the contracts has the appearance of an omnipotent engineer/principal agent/project manager in terms of changes on a project, there are restrictions in terms of the type of changes that may be made (Schwartzkopf 2004).

3.4.1 Types of Change According to Contracts

Change may be categorised as a direct change, a constructive change or a cardinal change (Schwartzkopf 2004). A direct change refers to a formal variation order (V.O.) issued by the client and are explicitly stated in the contract (Hanna and Swanson 2007). Constructive changes arise from actions or inactions of the client (Oracle-Corporation 2009). Constructive changes are not formally directed by the client and may be as a result of issues such as; untimely inspections, failure to provide material specification, and impractical design for performing the work (Oracle-Corporation 2009). The final category of changes, however, are not legal (Neff 2014). Cardinal changes are changes that result in an excessive change to the original scope of work (Hanna and Swanson 2007). Cardinal changes cause the work to be completely different.
from the representation of the works in the original contract (Schwartzkopf 2004). Contractors are not obliged to conform to these changes (Hanna and Swanson 2007).

Although directed changes are the only changes directed by V.Os, the secondary impact of change is not exclusive to constructive and cardinal changes (Neff 2014). For example, if a direct change results in constructive changes and/or cardinal changes, their impact on unchanged work is considered to be part of the cumulative impact of change. This is because the constructive or cardinal changes stemmed from the initial issue of a V.O. This is an important concept as it is the rationale of the cumulative impact of change that is quantified in the case study.

3.4.2 Valuation of a V.O.

Under the GCC and the JBCC, it is the responsibility of the engineer or principal agent to value the costs of a V.O. (clause 6.4.1 of the GCC and clauses 32.1 and 17.5 of the JBCC). Therefore, it is expected of the engineer or principle agent to have the knowledge to be able to comprehend the cumulative impact of change. Furthermore, the engineer or principal agent should include this in the valuation of the V.O. However, this may be difficult because, as previously stated, the cumulative impact of V.Os may only become known after they have been implemented. Moreover, clause 6.4.1 of the GCC and clause 32.2 of the JBCC may be interpreted as primarily focusing on the direct costs and fail to identify impacts on unchanged work (Neff 2014).

With regards to claiming for an extension of time (E.O.T.), neither the GCC nor the JBCC are limited to the impact of a single V.O. (clause 5.12 of the GCC and clause 29.2.3 of the JBCC). When V.Os result in a critical delay, the contractor may claim against the cumulative impact of change, provided the contractor can prove the delay. Therefore, it should be less difficult to be compensated for an extension of time (E.O.T.) due to the cumulative impact of change than the expense and losses incurred under the GCC and JBCC contracts.

The NEC, however, deals with change differently. There may be several ways of altering the works information for a V.O. and Clause 62.1 of the NEC enables the project manager to consider these different options. Furthermore, the clause provides that the contractor (or subcontractor in certain instances) submits quotations using methods other than that which the project manager has proposed. These are then discussed between the contractor and the project manager to ensure the proposed methods are practicable. Clause 62.2 then states “Quotations for compensation events comprise proposed changes to the Prices and any delay to the Completion Date and Key Dates assessed by the Contractor... If the programme for remaining work is altered by the compensation event, the Contractor includes the alterations to the Accepted Programme in his quotation”. This demonstrates a more collaborative approach to dealing with change. Both parties are involved in the decision process and it allows for the recognition of secondary impacts associated with V.Os. Although in difficult circumstances, the collaboration between contractor...
3.5 Characteristics of Cumulative Impact

and project manager may turn to conflict.

It can therefore be derived from the contracts that there is no limit to the number of changes, provided that they do not completely alter the original scope of works. In general, the GCC and the JBCC do not explicitly make allowance for the cumulative impact of change, nor provide guidelines as to how the cumulative impact of change should be addressed. For that reason, the case study in Chapter 5 of this research will be on the assumption that the NEC is used. This shows that the development of a method to quantify the cumulative impact of change will be valuable for the contracts discussed. Nevertheless, the challenge of quantifying the cumulative impact of change still remains.

3.5 Characteristics of Cumulative Impact

Ibbs and McEniry (2008) have identified that the contractor is for the most part, unaware of the secondary impacts of change orders. This is because it is unreasonable to expect the contractor to anticipate the cumulative impact of multiple V.Os and to predict the number and sizes of future V.Os (Ibbs and McEniry 2008). This has led researchers to believe that the cumulative impact of change will only become quantifiable once the project has been completed (Williams 1997).

Moreover, the defined cumulative impact of multiple V.Os is made unclear by the “2+2=5” effect (Williams 1997). This suggests that the synergistic effect of multiple change orders is greater than the sum of the individual inputs of the change orders. The individual impact from a V.O may at first appear to be insignificant; however, the combined impact of change may result in detrimental delays and losses in productivity to a project.

Figure 3.1 graphically illustrates the definition of the cumulative impact of change. The figure shows that the V.Os trigger disruption and delay events. The sum of these delay and disruption events cause a disruption greater than the sum of the individual parts.

![Figure 3.1: A Visual Representation of the Cumulative Impact of Change (Neff 2014)](https://scholar.sun.ac.za)
3.6. Analysis of the Loss of Labour Productivity

Figure 3.2 displays a similar representation of delays caused by the cumulative impact of change. If one is to neglect the approved V.O. hours on a project, the actual duration and estimate duration should be the same. Figure 3.2 explains what is meant by the delta approach. The delta in Figure 3.2 is a representation of the time lost on a project due to inefficiencies, underestimating the original contract, and the impact caused by the secondary impact of change.

![Diagram of Delta Approach](image)

**Figure 3.2: The Delta Approach (Hanna, Camlic, Peterson, and Lee 2006)**

Delta is defined as the difference in the actual labour hours used to complete a project and the original estimate for project completion with the approved changes. Although other factors affect the delta value, projects where the change orders were the main reason for delay and disruption can use the delta approach to measure the cumulative impact of change quantifiably. (Hanna, Camlic, Peterson, and Lee 2006).

### 3.6 Analysis of the Loss of Labour Productivity

Heretofore, this chapter has defined the cumulative impact of change. In addition to this, the knowledge obtained from literature indicates that the cumulative impact of V.Os leads to delay and disruption. These delay and disruption events affect labour productivity (Neff and Wium 2014). However, the types of delay and disruption events are yet to be identified. It is, therefore,
necessary to identify the factors that affect labour productivity, so as to understand how the delay and disruption events lead to an increased project cost and durations.

### 3.6.1 Defining Labour Productivity

Certain authors refer to productivity as being the man hours expended per week or month, however, this refers to intensity of effort and not productivity (Halligan, Demsetz, Brown, and Pace [1994]; Lee [2007]). Labour productivity may simply be defined as the units of work produced per man-hour (production rate) (Halligan, Demsetz, Brown, and Pace [1994]). This definition may also be used inversely as the number of man-hours required per unit (unit rate) (Jones [2001]; Lee [2007]). An important aspect of labour productivity is to distinguish between estimated productivity and actual productivity. Figure 3.3 graphically displays the difference between estimated and actual productivity. The estimated unit rate is dependent on the experience of the estimator and the information available at the time of the estimate (Schwartzkopf [2004]). This unit rate is often viewed as a constant, however, at the time of construction it is no longer appropriate to view the labour productivity rate as constant (Halligan, Demsetz, Brown, and Pace [1994]). This is because productivity continually varies whilst an activity is being performed. The quality of work may also have a significant impact on labour productivity. (Neff and Wium [2014]).

![Figure 3.3: Estimated Productivity versus Measured Productivity (Halligan, Demsetz, Brown, and Pace [1994])](image)

The relationship between productivity and quality is important, as a high productivity rate of work does not necessarily imply good quality (Cooper [1993]). For example, Figure 3.3 may display good productivity; however, if the quality of work is substandard it will require rework.
and need to be executed again. Therefore, this thesis will assume that the quality of the planned work is sufficient and that rework on planned work will not be required.

For a certain standard productivity, measuring productivity loss is simple. By comparing the production rate or unit rate to the standard productivity rate it is possible to determine the productivity loss or the % productivity. See Algorithm 3.1 (Lee 2007).

\textbf{Algorithm 3.1: Relative Productivity of A}

<table>
<thead>
<tr>
<th>Data</th>
<th>Productivity Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 if Production Rate then</td>
<td></td>
</tr>
<tr>
<td>2 { \begin{align*} \frac{A's \text{Production Rate}}{\text{Standard Production Rate}} &amp;= \frac{A's \text{Output/Input}}{\text{Standard Output/Input}} = \frac{A's \text{Units}}{\text{Standard Units}} \ \end{align*} }</td>
<td></td>
</tr>
<tr>
<td>3 if Unit Rate then</td>
<td></td>
</tr>
<tr>
<td>4 { \begin{align*} \frac{\text{Standard Production Rate}}{A's \text{Production Rate}} &amp;= \frac{\text{Standard Output/Input}}{A's \text{Output/Input}} = \frac{\text{Standard Labour}}{A's \text{Labour}} \ \end{align*} }</td>
<td></td>
</tr>
</tbody>
</table>

An overabundance of factors exist that contribute to labour productivity (Halligan, Demzet, Brown and Pace, 1994:47). As it is not possible to discuss each factor, common factors in the construction industry will be analysed that result in the cumulative impact of change.

Neff and Wium (2014) categorised the factors as human factors, organisation constraints, or difficult working conditions. These factors will be discussed, however, as the groups are broad and include a range of factors themselves there is an inconsistency with the naming and defining of these factors when compared to other researchers. Therefore, a study by Lee (2007) will also be analysed in terms of labour productivity and the cumulative impact of change.

3.7 Changes in the South African Construction Industry

Neff and Wium (2014) conducted research on the South African construction industry to determine the understanding amongst contractors of the cumulative impact of change\(^1\). The research then proposed guidelines of how contractors may manage the cumulative impact of change due to variation orders.

3.7.1 Human Factors


\(^1\)Referred to as the Secondary Impact of change by Neff and Wium (2014)
From the dissertation by Neff (2014), it was found that the level of productivity of a worker is dependent on three factors, namely: the ability of employee, knowledge and skills, and level of motivation (Maloney and McFillen 1983). Furthermore, it was identified that the ability of workers refers to the mental and physical capability of the employees (Maloney and McFillen 1983). As such, for the construction industry, it was concluded that employees have the ability to perform construction activities (Neff 2014). Therefore, reasons for a loss in productivity are a result of inadequate knowledge and skills and a lack of motivation.

Concerning lack of skills and knowledge, the possible delay and disruption events that could impede productivity are:

1. Procurement of inexperienced employees
2. Lack of supervision
3. Lack of training

Events that could influence an employee’s motivation and therefore productivity are:

1. Repeated interruption
2. Rework and demolition
3. Changes in team members
4. Lack of supervision
5. Or any event that impacts an employee’s progress and withholds them from completing a task

This information will be used in developing impact relationships and the quantifying the cumulative effect of the secondary impact of change (Neff 2014).

3.7.2 Difficult Working Conditions

Alternatively, working conditions may have an adverse effect on productivity (Maloney and McFillen 1983). Working conditions have a physiological effect on employees, (Neff 2014), which may lead to reduced productivity. Additionally, difficult working conditions may also effect the motivation and morale of employees (Neff and Wium 2014). Neff (2014) also identified that literature commonly highlights the following factors to be counterproductive:

1. Adverse weather conditions
2. Out of sequence work

3. Interruptions

4. Acceleration Methods

5. Learning curve

3.7.3 Organisational Constraints

Finally, organisational constraints form a category that is responsible for a loss in productivity; however, it is unlikely to be the cause of V.Os (Neff 2014). Organisational constraints relate to the ability of the contractor to perform work, specifically the contractors ability to plan and manage (Neff 2014). Although it is not necessarily the cause of V.Os, it is important to understand that not all losses in productivity are a result of external factors such as the cumulative impact of change.

A summary of organisational constraints is presented from the literature of Maloney and McFillen (1983), Halligan, Demsetz, Brown, and Pace (1994), Neff (2014), and Rivas, Borcherd, Gonzalez, and Alarcón (2010). The summary will be grouped into three categories of delay and distription events.

Material problems in the organisation:

1. Lack of on-time delivery
2. Lack of material available prior to commencement of work
3. Material location far from work site
4. Insufficient equipment to move materials

Tool and equipment problems:

1. Tools located away from work area
2. Lack of control over replacement of broken tools
3. Insufficient number of tools
4. Tools not available when required

Supervision problems:

1. Inexperience of site supervisors
3.7.4 Summary of Factors Affecting Labour Productivity

Although delay and disruption events may appear to be insignificant, small changes to work sequence, short interruptions or other influence may have a great impact on productivity. Furthermore, factors that affect labour productivity have the same effect as delay and disruption events. As organisational constraints are dependent on the contractor they are unlikely to form part of the delay and disruption events associated with V.Os.

Therefore, factors under the categories difficult working conditions and human factors may be viewed as collections of delay and disruption events that could be triggered by V.Os (See Figure 3.4). These factors inhibit work performed during construction activities by reducing coordination and communication between parties, reducing quality and reducing productivity (Gilligan and Kunz 2007).
3.7. Changes in the South African Construction Industry

Variation Orders

Delay and Disruption Events

Human Factors
- Knowledge and skill
- Low morale
- Low self esteem
- Low motivation

Difficult Working Conditions
- Adverse weather conditions
- Acceleration methods
- Working out of sequence
- Interruptions
- Learning curve

Any event impacting a labourer’s progress such as, lack of training, inexperience, changes to crew members, demolition, rework, disruption

Extreme cold or hot, heat exhaustion, hypothermia, reduced dexterity, hazards, loss of enthusiasm, weather sensitive work in bad weather, overtime, fatigue, effectiveness of supervisors, low motivation, absenteeism, rework, demolition, poor quality, shift work, accidents, poor information flow, out-of-sequence work, overcrowding, congestion, loss of momentum or job rhythm, learning curve disruption, idle time, information delays

Figure 3.4: Delay and Disruption Events that Could Be Triggered by V.Os.

3.7.5 Systematic Overview of the Cumulative Impact of Change

The previous discussion of factors affecting productivity is now synthesized using a comprehensive and systematic overview. The comprehensive and systematic overview of the cumulative impact of change aims to identify the steps followed when change occurs during construction in a logical manner. The steps refer to the mapping of delay and disruption events and when these delay and disruption events will occur during a project. This section will explain how V.Os may result in delay and disruption events, as well as how the interaction of delay and disruption events interact with each other causing losses in productivity on unchanged work. In creating a comprehensive and systematic overview of the causes and effects of V.Os, Neff and Wium [2014].
3.7. Changes in the South African Construction Industry

analysed the literature from the sources in Table 3.1

Table 3.1: Literature Sources Used for Comprehensive Overview (Neff 2014).

<table>
<thead>
<tr>
<th>n</th>
<th>Author</th>
<th>Year</th>
<th>Type</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Eden; Williams; Ackermann; Howick</td>
<td>2000</td>
<td>Journal Article</td>
<td>Authors’ Experience</td>
</tr>
<tr>
<td>2</td>
<td>Love, Holt, Shen, Li, and Irani</td>
<td>2002</td>
<td>Journal Article</td>
<td>Direct Observation</td>
</tr>
<tr>
<td>3</td>
<td>Han, Lee, and Peña-Mora</td>
<td>2011</td>
<td>Journal Article</td>
<td>Literature Review</td>
</tr>
<tr>
<td>4</td>
<td>Lal</td>
<td>2002</td>
<td>Academic Book</td>
<td>Direct Observation</td>
</tr>
<tr>
<td>5</td>
<td>Williams</td>
<td>2002</td>
<td>Academic Book</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Schwartzkopf;</td>
<td>2004</td>
<td>Academic Book</td>
<td>Court Cases</td>
</tr>
<tr>
<td>7</td>
<td>Heather</td>
<td>1989</td>
<td>Conference Proceeding</td>
<td>Case Studies</td>
</tr>
<tr>
<td>8</td>
<td>Warhoe and Giammalvo</td>
<td>2011</td>
<td>Conference Proceeding</td>
<td>Literature Review</td>
</tr>
<tr>
<td>9</td>
<td>Nelson</td>
<td>2011</td>
<td>Report</td>
<td>Construction Industry Studies</td>
</tr>
<tr>
<td>10</td>
<td>Long International Inc.</td>
<td>2011</td>
<td>Report</td>
<td>Construction Industry Studies</td>
</tr>
<tr>
<td>11</td>
<td>Ibbs; Vaughn;</td>
<td>2012</td>
<td>Report</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Leonard;</td>
<td>2012</td>
<td>Unpublished Thesis</td>
<td>Analysis of Construction Claims</td>
</tr>
</tbody>
</table>

In general, delay and disruption events triggered by V.Os form in two project phases, namely: Phase 1 and Phase 2 (Neff and Wium 2014). Phase 1 refers to the period prior to the implementation of a V.O. whilst Phase 2 refers to the delays following the issuance of a V.O.

Delay and disruption events that occur in Phase 1 (prior to the implementation of a V.O.) are dependent on the whether the engineer initiates a change or if the change arises as a result of an error or omission in the designs. Phase 2 (after the V.O. has been issued) delay and disruption events may be dissected into consecutive stages, namely: Stage 1 - Management Response, Stage 2 - Cumulative Impact, and Stage 3 - Acceleration.

The following information is structured under the two main phases and related subcategories. The references used are primarily from Table 3.1 unless stated otherwise.

3.7.5.1 Phase 1 Delay and Disruption Events

A process followed before a V.O. is implemented is illustrated in Figure 3.5. This explains that the engineer issues a V.O. with, for most construction projects, revised drawings. Subsequently, the contractor should then have the necessary information to implement the V.O. This will be referred to as Process 1.

The second process however, will arise from design deficiencies, known as errors and omissions (E&O). Therefore, following a logical sequence, the V.O. will only be issued once the E&O becomes known to the engineer. Thus, there are two extra steps in the process, which are...
3.7. Changes in the South African Construction Industry

displayed in Figure 3.5. Once the contractor identifies the E&O, there will be a request for information (RFI) or a request for clarification (RFC). Thereafter, the process will be the same as in Process 1. However, in reality the processes are not so simple. Often these processes result in additional delays that hamper productivity.

Process 1 incurs several delays which complicates the system. Similarly, Process 2 is also susceptible to delay and disruption events. However, due to the additional steps in Process 2, there are additional feedback loops which increase the risk of delay and disruption events. The following are a list of possible delay and disruption events that will have an impact on the productivity of work:

1. The timing of the V.O. (early in the project versus late in the project)
2. Late issue of drawings
3. Errors in revised drawings
4. Dilution of supervision/poor quality/rework and demolition

Therefore, Process 1 may be revised to incorporate the possible delay and disruption events (Figure 3.7). Similarly, the revised system for Process 2 is displayed in Figure 3.8.

Process 1 and Process 2 are discussed in terms of a single V.O. It is important then to consider that at different stages of a project, several V.Os may be issued. Each V.O. will then cause a repetition in the processes. Consequently, delay and disruption will be present in the project.
3.7. Changes in the South African Construction Industry

so long as V.Os are issued. Neff and Wium (2014) conducted a survey amongst South African contractors and it was found that the difficulties associated with Phase 1 are true. The contractors questioned confirmed that the administration of V.Os is time consuming, it requires considerable effort, and it interferes with other management tasks.
3.7. Changes in the South African Construction Industry

3.7.5.2 Phase 2 Delay and Disruption Events

As previously stated, Phase 2 consists of 3 stages after the V.O. has been issued. Due to the delays and disruptions of Phase 1, the progress on unchanged work is affected and the changed work is disrupted.

1. Stage 1 refers to the delay and disruption events triggered by the management response taken to control the direct impact (the impact on the changed work).
2. Stage 2 refers to the cumulative impact of the individual delay and disruption events caused by the issuance of V.Os.
3. Stage 3 refers to the delay and disruption events triggered by the acceleration methods, implemented by management, to control delays as a result of the numerous V.Os issued on the project.

The management controls in Stage 1 include stop-and-go operations, out-of-sequence work and a do nothing approach. The management control actions are seen as trigger events effecting productivity. These trigger events lead to problems such as labourers working in a rushed manner, interruptions, initiate contributory and preparation work, invalid assumptions, changing working conditions, etc. This in turn leads to a loss in productivity, as was discussed in previous sections. The combination of delay and disruption events interact (Stage 2) causing a cumulative impact (also termed a portfolio effect (Eden, Williams, Ackermann, and Howick 2000), greater than the sum of the individual delay and disruption events. Eden, Williams, Ackermann, and Howick (2000) explains, “[portfolio] effects would probably not occur if only one or two small delays and disruptions had occurred”, as opposed to many delay and disruption events. Subsequently, there is a deterioration of the work schedule, expensive activities are performed simultaneously, weather sensitive work is performed in poor weather, extension of time (E.O.T) is denied which leads to the contractor implementing acceleration actions (Stage 3). Additional labourers may be require, labourers may work overtime and/or night work. This results in labourers becoming fatigued, a decrease in motivation and morale, the learning curve is impacted, stacking of trades and overcrowding. The control process is summarised in Figure 3.9.

This all culminates in a loss of productivity on unchanged work. Figure 3.10 shows the cause and effect matrix for the secondary effects of V.Os. The figure illustrates how V.Os trigger various delay and disruption events that have been previously discussed.

The Phase 2 delay and disruption events were confirmed, via questionnaire, by contractors in South Africa (Neff and Wium 2014).
3.7. Changes in the South African Construction Industry

Figure 3.9: Summarised Project Control Process for Delay and Disruption Events (Lee 2007).
Figure 3.10: The Cause and Effect Matrix of the Cumulative Impact of Change (Neff, 2014)
3.7. Changes in the South African Construction Industry

3.7.6 Section Summary

The cumulative impact of change considers the impact of all V.Os issued on a project. A contractor will not anticipate the cumulative impact until all V.Os have been issued. This lends importance to the word “synergy” as the synergistic impact refers to the fact that the cumulative impact of V.Os is greater than the sum of impacts between singular V.Os. This may be attributed to the indirect losses of labour productivity due to delay and disruption events.

So it stands, the cumulative impact of change is defined as delay and disruption events resulting in the loss of productivity and an increase in project cost on unchanged work because of the synergistic effect of multiple V.Os (Hanna, Camlic, Peterson, and Lee 2006; Ibbs 2005; Jones 2001).

Although delay and disruption events may appear to be insignificant, small changes to work sequence, short interruptions and other influences may have a great impact on productivity. The factors affecting labour productivity, and associated with V.Os, generally fall under two categories: difficult working conditions and human factors. The cumulative impact of change and all subsequent delay and disruption events may contribute to a deterioration of the following project characteristics:

1. Communication
2. Coordination
3. Quality
4. Productivity

These have been identified in Chapter 2 as factors affecting the cumulative impact of change.

It was established that V.Os cause delay and disruption events in two phases during a project. Phase 1 occurs before the V.O. is issued and is generally associated with information and approval delays. Phase 1 also includes the difficulties arising from the process to administer V.Os. Phase 2 may be broken down into three stages. The first stage is associated with management control actions, the second stage is associated with the portfolio effect of numerous V.Os and the third stage refers to the acceleration methods used to reach deadlines. Each stage has inherent delay and disruption events which impact labour productivity and result in, what has been defined as, the cumulative impact of change.
3.8 Global Understanding of the Cumulative Impact of Change

A study conducted by Lee (2007) identified that there are inconsistencies in naming and defining labour productivity factors resulting from change. Thus, that there is a need to systematically synthesize these factors. Furthermore it was identified that previous research quantifying the impacts of change looked at one factor at a time and overlooked the synergistic effect of change. Lee (2007) summarized all comparable data, excluding that from questionable and replicated data sources, to illustrate the overall trends in overtime productivity impacts published by various studies for schedules (Gelisen and Griffis 2013). This was to identify, rename and redefine the interrelationships between a variety of productivity factors while maintaining consistency.

Lee (2007) referred to a construction project as a system consisting of seven categories of productivity factors, namely:

1. Project and contract factors
2. Location and environmental factors
3. Project team factors
4. Managerial actions during project execution
5. Disruptive events
6. Human/workers’ reaction factors
7. External Factors

These seven factor categories represent the findings of many research documents. The information from the literature displayed in Table 3.2 was synthesized into the seven categories of productivity factors. It may be assumed that the following sections use these references unless otherwise explicitly stated. Figure 3.11 illustrates the general relation between categories and when the categories will have influence in a project.
3.8. Global Understanding of the Cumulative Impact of Change

Table 3.2: Literature used by Lee (2007) in developing Productivity Factor Categories.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dallavia</td>
<td>1954</td>
<td>Estimating Construction and Production Costs</td>
</tr>
<tr>
<td>Brown</td>
<td>1986</td>
<td>Estimating Labour Productivity</td>
</tr>
<tr>
<td>Neil and Knack</td>
<td>1984</td>
<td>Predicting Productivity</td>
</tr>
<tr>
<td>Fazio, Chutter, Bourassa, and Russell</td>
<td>1984</td>
<td>Construction Industry Factors Impairing Productivity</td>
</tr>
<tr>
<td>Rusteika Jr and Boomer</td>
<td>1992</td>
<td>Budgeting for Changes in Construction</td>
</tr>
<tr>
<td>Coulter and Spruill</td>
<td>1983</td>
<td>Risk Planning and Cost Avoidance by Financial Statement-The First Step</td>
</tr>
<tr>
<td>Borcherding and Sebastian</td>
<td>1980</td>
<td>Factors Which Influence Productivity on Large Projects</td>
</tr>
<tr>
<td>Dieterle and DeStephanis</td>
<td>1992</td>
<td>Use of Productivity Factors in Construction Claims</td>
</tr>
<tr>
<td>Galloway</td>
<td>1983</td>
<td>Cumulative Impact</td>
</tr>
<tr>
<td>Bromberg</td>
<td>1988</td>
<td>Impact of Overtime on Construction</td>
</tr>
</tbody>
</table>

Figure 3.11: Project System Consisting of Productivity Factors (Lee 2007)
3.8. Global Understanding of the Cumulative Impact of Change

3.8.1 Project and Contract Factors

*Project and Contract* factors mainly originate in the planning phase of a project. These factors will be determined before construction starts, such as the expected/planned productivity which will be used in creating a work programme and cost estimating. Project and contract factors may include:

1. Project size and duration
2. Complexity
3. Project type
4. Regulations
5. Packaging/Multiple Contracts
6. Project delivery system
7. Contract Type
8. Construction Methods
9. Special requirements

3.8.2 Location and Environmental Factors

Similarly to *Project and Contract* factors, *Location and Environmental* factors are generally determined before the start of construction. These factors will also be used in estimations of productivity, however, these conditions may change unexpectedly. Changes could occur as a result of unforeseen weather patterns (high/low temperatures, rain, etc.), loss in labour availability due to competing projects or fluctuations of the local economy. The location and environmental factors are listed as follows:

1. Geological site conditions
2. Transportation network
3. Weather
4. Local labour climate
5. Local community/city
3.8.3 Project Team Factors

The factors in this category correspond to the dynamics between the business systems and practices of clients, architects and engineers, managers, contractors and subcontractors. The relationships between parties and the attitude employed by said parties may greatly affect the productivity of work conducted during the project. These factors will influence estimates prior to the start of construction as well as the ability of the project team to maintain control and adapt to changing circumstances. Project team factors effecting productivity are:

1. Contractor/Subcontractor business systems and practices
2. Project manager
3. Owner
4. Construction manager business systems and practices
5. All other project parties

Due to the need for the project team to adapt to these changes, this group does overlap somewhat with the fourth group of factors.

3.8.4 Managerial Actions and Decisions During Project Execution

Previously mentioned in this research are the trigger events for delays and disruptions. Fazio, Chutter, Bourassa, and Russell (1984) and Dallavia (1954) defines the managerial action and decisions during the project execution as the efforts taken to deal with these trigger events. It is the effort to maintain control of the project programme and cost. Although certain actions, if engaged properly, may reduce the impact of delay and disruption triggers, managerial actions may be forced due to a lack of alternatives. This may then result in a decrease in productivity. Examples of forced actions are the use of less skilled labourers or working out of sequence.

Similarly, some actions or the lack thereof can be viewed as a trigger event. These may be change orders, prolonged response time to an RFI, untimely decision making, inefficient management on site or directed/voluntary acceleration. These factors may be summarised as the following:

1. Contractor decisions and responses
   (a) Acceleration
   (b) Change in work sequence
   (c) Supporting work (tools, equipment, provisions of information, etc.)
3.8. Global Understanding of the Cumulative Impact of Change

(d) Ratio of crews and supervisors  
(e) Coordination of trades

2. Owner decisions and responses  
(a) Change orders  
(b) Acceleration orders  
(c) Processing of changes, reviews and approvals  
(d) Responding to RFIs  
(e) Differing site conditions

3.8.5 Disruption Events

Disruption Events are factors that occur on the job site and effect productivity immediately. This group of factors, as well as the following group (human reaction factors) together affect productivity and are somewhat related. The following are examples of disruptive events:

1. Congestion/trade stacking  
2. Lack of skilled labour  
3. Absenteeism  
4. Poor quality  
5. Slow work pace  
6. Waiting time  
7. Stop-and-go/Out-of-sequence work  
8. Learning curve effect  
9. Bad weather  
10. Rework

3.8.6 Human/Workers’ Reaction

The Human/Workers’ Reaction factors are sometimes referred to as the “soft” issues in construction (Riaz, Edwards, and Thorpe 2012). Human reactions (also termed “crew responses” by Halligan, Demsetz, Brown, and Pace 1994) are the ways in which labourers react to delays and disruptions. These factors may not only cause a direct loss in productivity, but may also result in further disruptions being triggered. The human factors that affect productivity are:
3.8. Global Understanding of the Cumulative Impact of Change

1. Fatigue
2. Reaction to difficult working conditions (hot, cold, hygiene, etc.)
3. Disturbed “body clock” i.e. working at night
4. Clumsiness
5. Negative attitude
6. Job rhythm
7. Social and domestic issues
8. Guess work

3.8.7 External Factors

The final group of labour productivity factors, the External Factors, are not related to the project team, location or workers. Although the project team may have no control over these factors, external factors may still influence productivity. External factors include:

1. Force majeure
2. Strike action
3. National/global economy
4. Political and international influences

3.8.8 Section Summary

The list of productivity factors in the seven categories is not complete, however, it is a more comprehensive list than other studies as it combines the information from many studies. To summarize these factors and the interrelationships between factors that affect productivity, Lee (2007) created an expanded disruption cycle model (Figure 3.12). The model illustrates the cause and effect relationship between external factors and managerial actions and decisions, and disruptive events and human reactions. The expanded disruption cycle model makes it easier to determine the responsible party and to identify factors to focus on, reducing redundancy, and the possible cumulative effect the factors may have.
3.8. Global Understanding of the Cumulative Impact of Change

Figure 3.12: Expanded Disruption Cycle Model (Lee, 2007)
3.9 Chapter Summary

The arrows in Figure 3.12 indicate the possible flow of influence amongst the factors. External events such as force majeure, strike actions, etc., may trigger the cause and effect cycle demonstrated while the managerial actions of contractors and owners may either be the trigger or the response to trigger events. The managerial actions taken may contribute to a loss of productivity and have a direct influence on onsite productivity. The onsite “symptoms” will be the effect of a cause and not occur by themselves. However, the reduction in productivity caused by these factors may not necessarily result in delays. The loop may either be controlled, or it will continually cycle through the inhibitors to productivity.

3.9 Chapter Summary

This chapter partially fulfilled the research objective of this study by (1) defining the cumulative impact of change, (2) investigating delay and disruption events triggered by the cumulative impact of change, and (3) investigating the factors influencing labour productivity.

The cumulative impact of change is defined as “disruption events resulting in the loss of productivity and an increase in project cost on unchanged work because of the synergistic effect of multiple V.Os”.

It was also found that the delay and disruptions caused by the cumulative effect of multiple V.Os are the result of losses in labour productivity following various changes to a project. Studies aimed at identifying factors affecting productivity, the interrelationships between these factors, and quantifying the cumulative impact of change were then identified.

The studies examined literature and case studies to derive definitions and terms for the factors affecting productivity. Neff and Wium (2014) used a cause and effect matrix (Figure 3.10) to establish the links between various factors affecting productivity. Lee (2007) created an expanded disruption cycle model (Figure 3.12) showing the influence of one factor on another as well as the possible triggers of these delay and disruption events.

Both models will be used as a guideline for the logic behind predicting the cumulative impact of change. Although the cumulative impact of change is understood, not all involved in construction will have such an understanding of these concepts. Furthermore, not everyone will have had read the report. Therefore, to manage this information so that all may benefit from the content acquired during this research, BIM software will be used. The next chapter will be a guideline how BIM may quantify the impact of change on labour productivity.
CHAPTER 4

Quantifying the Cumulative Impact of Change

4.1 Introduction

This chapter identifies previous methods used to quantify the cumulative impact of change. Understanding the limitations of individual methods of quantifying change impact will allow for the establishment of a holistic approach to quantifying the impact of change. Subsequently, this chapter presents a decision making process to quantify the cumulative impact of change that may later be implemented in a BIM model. The causes and effects of multiple change orders may then be predicted and summarised with this tool.

This chapter will continue to outline the logic behind the implementation of the decision making process. This will be described with an algorithm for the use of Autodesk Revit and Navisworks in quantifying the impact of change. Autodesk Revit and Navisworks will be utilised for all calculations and visualisations with the aid of Microsoft Project. The described logic will then be used in a case study in Chapter 5.

4.2 Limitations to Current Quantification Methods

The first challenge in analysing the cumulative impact of change is proving that the impacts exist. Secondly, and more difficult, is to quantify the impact. When it comes to quantifying the cumulative impact of change it is the norm to rely on traditional methods such as the measured mile analysis, industry indices or the total cost method. These methods are discussed below.

Unfortunately, these methods are considered as being somewhat unreliable and criticized for other limitations (Lee 2007). Therefore, there is a need for new and better methods of quantifying
4.2. Limitations to Current Quantification Methods

the cumulative impact of change.

4.2.1 Existing Methods for Quantifying Change Impact

The methods used to quantify the impact of change may generally be categorised as either being a cumulative approach or a discrete approach.

4.2.1.1 Cumulative Approach

Cumulative analysis of change seeks to quantify the effect of multiple changes collectively. This includes the previously mentioned traditional methods (measured mile analysis, industry indices or the total cost method).

The measured mile analysis is accepted as a favoured method used to calculate a loss in productivity (Schwartzkopf 2004). The method involves comparing the cost of “impacted” work with the costs of “unimpacted” work that is the same or similar to the aforementioned activity (De Vries 2012). The difference between the unimpacted and the impacted work would then be the loss in productivity.

Using industry indices to calculate the loss in productivity refers to the use of information from previous studies regarding the loss of productivity (Ibbs, Nguyen, and Lee 2007). The industry indices will be predetermined for an activity and give an approximate factor which a contractor may use for the calculation of productivity loss on a similar activity. For example, if a contractor were to calculate the loss of productivity due to stacking of trades, the MCAA (Mechanical Contractors Association of America) list of factors affecting productivity would allow a 10% loss in productivity for minor conditions, a 20% loss in productivity for average condition, or a 30% loss in productivity for the severe case (MCAA 1994).

The total cost method for calculating the loss of productivity is possibly the simplest method for calculating the lost productivity of a project. Losses are calculated by subtracting the bid amount from the actual project costs [Loss = total cost – bid amount] (Jones 2003; Klanac and Nelson 2004). To use this method the assumptions must be made that (1) the contractor performed all activities correctly, (2) the bid amount is correct, and (3) that all of the cost deficit is a result of the owner’s actions or inactions (Ibbs, Nguyen, and Lee 2007).

Most of these methods are used upon completion of a project to resolve the financial differences caused by multiple change orders. The cumulative approach is relatively new and although it may be able to quantify the effect of multiple change orders, explicitly relying on these studies may be dangerous. Some cumulative approach studies use statistical analysis techniques (Lee 2007). The reliability of each model is therefore determined by the reliability of source data.
4.3. Quantification Methodology

used. Furthermore, this data will depend on the scope of work, types of work observed (trades) as well as the data analyses technique used (Sanders and Nagata 2003). It will, therefore, be essential to objectively evaluate and compare the reliability and applicability of each method for a certain project.

4.2.1.2 Discrete Approach

The discrete approach refers to studies that try to quantify the individual factors affecting labour productivity (Lee 2007). That is, the discrete approach looks at each factor in isolation. Subsequently, the application of the discrete approach may be limited when a project incurs multiple factors that affect productivity. For example, if a project has fallen behind schedule due to a change order, the project may require overtime/shift work while also encountering bad weather.

Discrete approaches also suffer from a lack of reliability and applicability. This may be due to a lack of objective evaluation and consistent criteria (Lee 2007). Additionally, studies may be republications of old data that is no longer relevant or has lost important information when being cited. This is known as the “woozle effect”. The term “woozle effect” may be used “where a particular finding gets quoted and re-quoted because it sounds logical and has the ring of truth, regardless of the reliability of the original source” (Maiuro, Hagar, Lin, and Olson 2001). Therefore, the reliability of data should be taken into account when using the discrete method.

4.3 Quantification Methodology

Heretofore, there is a need to determine how to use both discrete and cumulative approaches to maximise the ability of previous studies and methods to quantify the impacts of change. This section will establish the way in which readers will be able to maximise the benefits and to minimise the disadvantages of using previous studies to quantify the cumulative impact of change.

Rynes, Bartunek, and Daft (2001) have identified that there is a substantial gap between organisational research (academia) and management practise (practitioners). Through studying existing literature, a possible avenue for the quantification of the cumulative impact of change was found. This decision process seeks to enable the user to access information from as many available sources as possible. This research does not develop a new model or method quantifying the impact of change. Instead, this research presents existing data so that it may be utilised and converted into a supplementary BIM program.
4.3. Quantification Methodology

4.3.1 General Process

The majority of discrete methods allow for the prediction of the impact of an individual V.O. Conversely, cumulative methods are not suitable for estimating the impacts of individual change orders, but may allow for the quantification of the synergistic effect of multiple change orders before project completion. Therefore, a combination of discrete and cumulative approaches may be used for prediction and resolution.

The process identified is not automated and therefore requires the input of user information. However, the method uses an extensive array of sources and research material that will allow for many different applications. The general decision making process that will enable the reader to quantify the impact of change of labour productivity is illustrated in Figure 4.1.

This approach is similar to the model developed by Ibbs, Nguyen, and Lee (2007) which focuses on the cumulative approach only. Similar models have also been developed by Gelisen and Griffis (2013) and Hanna, Lotfallah, and Lee (2002). The article by Gelisen and Griffis (2013) published in the Journal of Construction Engineering and Management frequently cites the study by Lee (2007). This study will focus on the implementation of BIM to discretely quantify the cumulative impact of multiple changes.

The general process (Figure 4.1) requires an initial decision to be made with regards to the amount and quality of information available to the reader (decision node 1). Depending on the available information this will lead to either the use of a discrete approach (if all 3 questions in decision node 1 are positive) or a cumulative approach. For the discrete approach, the reader will need to determine if there will be a single or multiple factor(s) requiring analysis (decision node 2). If a cumulative approach is required, the reader will once again need to determine the amount and quality available for the analysis (decision node 3). These three decisions seek to enable the reader to choose the best possible approach to quantifying the impact of change.

Following the previous three questions, the user will be able to choose one (or many) of the final node options (check point (CP) A to J). These final node options will be linked to specific quantification studies. Each study has advantages, disadvantages, and a degree of reliability or applicability for the case required by the user. Thus, the user will be able to choose the quantification method from the most appropriate study.

It must be noted that for the discrete analysis of factors, only six factors are included in this decision process (CP A to F). This is limited compared to the extensive number of factors previously presented in this research (see Figures 3.4, 3.11, and 3.12). Further investigation would be required to analyse other factors as there is an insufficient quantity and quality of data regarding other factors. However, should the user have adequate productivity information regarding another factor, this could be added to the existing decision process model.
4.3. Quantification Methodology

Figure 4.1: The General Decision Making Process for Quantifying the Impact of Change (Lee 2007)

*Neural Networks: The model requires selecting input variables (attributes). The quality and accuracy of the model results depend on the quality and quantity of the inputs.

**Decision Tree Models: The model needs to be developed for individual cases but the development procedure is complicated and complex. Thus, actual application of this type of model is not likely in reality.
4.3. Quantification Methodology

Including only six factors in the model is a limit to the scope of the study, however, it is also an attempt to reduce redundancy in calculations (Lee 2007). Redundant factors may result in an overestimation of the impact of change. For example, the overtime factor model used may already include employee fatigue. It is therefore important to understand the cause-effect relationship between factors to ensure that there is not an overlapping of factors. As a guideline, Figure 3.12 may be used in furthering the understanding of causes and effects of various productivity factors.

Nevertheless, a disadvantage of this decision model is that the user will need to understand the difference specifically between overmanning (CP B) and congestion (CP C) and when to apply either of the factors. This may require a causation analysis to determine that overmanning is not the cause of congestion. Overmanning generally refers to the number of workers more than the optimum number of workers. Congestion may refer to the space per person. (Lee 2007).

Nevertheless, the proposed decision model provides a detailed approach to quantify the impact of change on labour productivity. To illustrate this, Figure 4.2 is a map of the studies and methods analysed and available for the reader to use in quantifying the impact of change for a specific case. Although the studies listed in Figure 4.2 have been extensively analysed, the research is limited in scope by the activities performed in the studies analysed. Studies will only be useful in quantifying the cumulative impact of change if the activity in the study and the proposed changed activity are similar. Furthermore, in order to gain the most benefit from this study, the use of BIM in quantifying the impact of change will predominantly focus on the discrete approach mentioned. This will enable the most accurate quantification of the impact of change on labour productivity.
4.3. Quantification Methodology

Figure 4.2: Studies and Methods for Quantifying the Impact of Change (Lee 2007)
4.4 BIM Use and Software Interaction

In order to make the aforementioned process to quantifying the impact of change on labour productivity practical, it needs to be converted into a computer manageable algorithm. This section will explain how the user would proceed to quantify the costs and time delays associated with changes. The software development will guide the user to the appropriate study (Figure 4.2) and have the impact of a change automatically calculated.

Due to limitations imposed on this study, Autodesk Revit is the BIM software that will be utilised. Furthermore, due to limitations of the software in performing scheduling and the management of projects, Autodesk Navisworks is also required. It is therefore necessary to define the role of each software component so that an algorithm may be developed to assist the user in quantifying the impact of change.

4.4.1 The Process Using Revit

Autodesk Revit will be used as the central platform for all software interaction. Revit is the basic design tool that will be used on the project. Although the full Revit Suite is available (Architectural, Structural and MEP) for the study, the scope will be limited to the structural building components.

Once a Revit model of the project has been created, Revit will be used as the user interface to record all input information and model changes (specifically changes as a result of V.Os). This will enable the user to enter information from Chapter 4 as required by the process illustrated in Figure 4.1.

As mentioned in the description of the decision making process, once the user has inputted the required information, he/she will be guided to the results of a specific study or method, previously performed by others. Subsequently, current productivity data for the project will be required from the project programme. The assumption is made that once the model has been changed, the change in the model is reflected in the project programme. It will then allow for the calculation of new productivity values, based on the productivity studies/methods, to update the programme. The difference between key dates and the completion date for the new and old productivity information will allow for the calculation of the cumulative impact of change. Revit will then display these results, visually representing the time and cost impacts, by overriding the graphics of the affected elements. Further, and more detailed information will then be available by selecting the affected component.

The aforementioned process is logically represented in Algorithm 4.1. Lines 1 to 3 refer to the initial changes to the model and the decision process to select a quantification study/method.
Following the confirmation of any information delays and extended work durations (line 3), the information from Revit is sent to Navisworks (See Algorithm 4.2).

Once the information is returned to Revit, depending on the outcome of the analysis, different visual representations of the change will be displayed. Depending on whether the delay is critical and/or the delay is on a modified or dependant element, the element will highlight red (line 9), orange (line 12) or yellow (line 15). By selecting the highlighted element, the increased cost and duration will then be displayed in the element properties window native to Revit.

Algorithm 4.1: Revit Data Handling

Data: Layered Object Data

Input: Modifications to the project model

Output: Duration and cost changes to elements

1. User changes to the model;
2. for Model Change do
3. confirm project schedule;
4. run decision process;
5. sendto Navisworks ; /* Go to Algorithm 4.2 */
6. receive productivity data;
7. foreach modified element and dependant elements do
8. if critical delay AND modified element then
9. highlight element red;
10. display element cost/duration data in properties window;
11. else if critical delay AND dependant element then
12. highlight element orange;
13. display element cost/duration data in properties window;
14. else if delay on modified element OR dependant element then
15. highlight element yellow;
16. display element cost/duration data in properties window;

However, to enable the program to access the productivity data and alter the project schedule of activities, Autodesk Navisworks will be required.
4.4.2 The Role of Navisworks

4.4.2.1 Introduction to Navisworks

Navisworks is a software tool for project review (Autodesk 2016a). Navisworks enables all project parties to review integrated project data for enhanced project control. Some of the features of Navisworks are (Autodesk 2016b):

- Coordination of project participants
  - Clash detection and interference checking
- Model Review
  - Model file and data aggregation
  - Whole-project review
- Model Simulation and Analysis
  - 5D project scheduling (time and cost)
  - Model rendering and animation
- Project Viewing
  - Cloud rendering
  - Reality Capture
  - Realtime navigation

Although Navisworks does have the ability to create schedules of activities, the preferred medium for this task is through the use of Microsoft Project. Navisworks is able to import Microsoft Project files and use the data therein.

The user will need to link the Revit model to an activity schedule. This is done by creating component sets in Navisworks. A set will be compiled of all components to be constructed under a specific activity (i.e. {foundation footings}; {foundations walls}; {ground floor slab}; etc.). This should be done in a logical manner. The sets may be as detailed or as broad as the user would prefer. However, the more detailed a set is, the more accurate the analysis will be. Each activity from the imported Microsoft project file will then be allocated a specific set. This enables Navisworks to determine the duration and cost of each activity.
4.4.2.2 The Process Using Navisworks

Once the project activity schedule has been linked to Navisworks and the Revit model, Revit will transfer the information obtained from the decision process to Navisworks. In Navisworks the activity schedule will be updated. This will result in a shift of the activity schedule. The shift in the activity schedule may result in a delay if it occurs on a critical path. This will need to be identified. Furthermore, the dependencies between activities will be an important factor in this shift of the activity schedule. When using Microsoft Project, there are four possible task dependencies that may be allocated to a task (Microsoft 2016). These dependencies will be allocated when the contractor has constructed the project Gantt Chart at the start of a project (see Figure 5.5). The four types of dependencies are:

- Finish-to-Start [ FS ]
  - Task 1 must finish before Task 2 may start
- Start-to-Start [ SS ]
  - Task 2 must start when Task 1 starts
- Finish-to-Finish [ FF ]
  - Task 2 must finish when Task 1 finishes
- Start-to-Finish [ SF ]
  - Task 2 cannot finish before the start of Task 1

These dependencies will allow the program to identify interrelated activities and calculate the subsequent delays. The process by which Navisworks will extract this information is explained logically in Algorithm 4.2.

Information is first obtained from Revit which will state the modified elements and the choice of quantification study from literature to be used. The algorithm is enclosed by a Foreach loop so that all modified elements will be analysed. Similarly, the second Foreach loop on line 6 performs the same task as the first loop, however, the dependant activities are now included. The dependent activities are those identified from predefined dependencies listed previously in this section. Line 7 identifies if there will be a critical delay due to the changed element. If there is a critical delay, the revised program is calculated and the schedule is adjusted. If there is not a critical delay, only the revised productivity for the Weather, Learning curve and cumulative quantification studies are analysed. This is because the changes made will not require

\[^1\] Dependences may also have a lag added for extra time separation between activities
acceleration methods to be employed as there will be no critical delays. However, the project may still incur a critical delay as a result of weather or the learning curve effect. This recognises the impact a change may have on unchanged work. Once the necessary productivity has been calculated, the duration and cost data for each element is returned (line 10 and line 15).

The "element" mentioned in Algorithm 4.2 may refer to a set of elements as defined by the user for a specific activity.

**Algorithm 4.2: Naviswork Data Handling**

**Data:** Received from Revit

**Input:** The modified model element/s and the quantification study used

**Output:** Revised work schedule and time and cost increase of effected elements

```plaintext
1 Input received from Revit;
2 foreach modified element do
3     access MS Project;
4     calculate current productivity;
5     calculate current productivity of dependant/successor activities;
6     foreach modified element and dependant elements do
7         if Element change causes critical delay then
8             calculate revised productivity; /* Using quantification study/method
9                 from previous research */
10            adjust MS Project schedule;
11            return [Increased duration and cost data for each element]
12         else
13             if Quantification method is Weather/Learning Curve/Cumulative then
14                 calculate revised productivity; /* Using quantification study/method
15                     from previous research */
16                 adjust MS Project schedule;
17                 return [Increased duration and cost data for each element]
18             else
19                 No acceleration required
20             return null
21     else
22     No acceleration required
23 return null
```

The ability of the logical processes, identified in Algorithm 4.1 and 4.2, to quantify the secondary and cumulative impacts of change will be demonstrated using a case study. These algorithms will be the backbone of the coding for a future software package development. The method and results of the case study will then be validated by industry professionals.
4.5 Chapter Summary

This chapter proposes a methodological process by which a contractor will be able to quantify the impact of change. This chapter analysed construction contracts and found that (between the GCC, the JBCC, and the NEC3) the NEC3 contract document was the most tailored to dealing with the unforeseen impacts of change. The process to be followed when implementing change orders under the NEC was also briefly described.

Current methods of quantification were considered and limitations were identified that show a need for a holistic approach, however, it was determined that using the discrete approach would be more beneficial. Finally, a study by Lee (2007) was identified and explained as a plausible method that would give contractors access to a broad array of quantification studies and methods. Although limited in scope (number of factors analysed), the available research offers a high level of detail and a variety of cases that may be applied to any similar project.

The process of selecting a quantification method from literature was then streamlined in two processes; the Revit process and the Navisworks process. This would allow the contractor to have the ability to quantify change impact using a BIM model. Furthermore, the quantification of changes implemented in the model will be graphically illustrated in the model for further understanding. The next step is therefore, to implement the proposed process in a case study that will then be validated.
CHAPTER 5

BIM as a Solution for Change Management

5.1 Introduction

Thus far, this research has identified a manner in which a contractor may quantify the unforeseen, or unexpected, losses associated with variation orders (V.O.). However, the question still remains: how can it be visualised for better understanding using Building Information Modelling (BIM)?

This chapter uses a case study to highlight the BIM process and demonstrates how BIM software may be used to streamline the method for quantifying change impact. This is based on the preliminary understanding of BIM and supplementary BIM software identified in Chapter 2.

From the case study information, the author developed a BIM model. Several changes to the project are analysed. Using the developed model, it is possible to identify and predict the cumulative impact of change so that a contractor may manage changes more accurately and prevent delays occurring due to lost productivity.

Ideally the tool is used to manage changes, thus preventing any unforeseen costs occurring as the contractor may predict the losses in labour productivity and can make the necessary adjustments to the schedule. However, for this research, the developed tool will be used as a means to determine the unforeseen costs associated with change. These unforeseen costs can then be claimed by the contractor. This is a demonstration of how BIM may be used for resolution of cost differences incurred as a result of changes impacting labour productivity.

5.2 Case Study to Demonstrate BIM Quantification Method

In order to select an appropriate case study, a project was identified that was neither too simple to reflect a real scenario, nor too complicated to accurately model. With collaboration from an
industry participant, a residential home was used to investigate the ability of BIM as a tool to predict the cumulative impact of change.

5.2.1 Project Description

The project analysed is the construction of a double storey residential house (See Figure 5.1). The case study was restricted to the structural components as well as the windows, doors and roof of the house.

![Figure 5.1: 3D View of the Residential House used for a Case Study](image)

Architectural designs were received as well as structural detailing from the engineer. The drawings, such as floor plans, elevations and sections may be found in the appendix. From this information and through collaboration with the client, a 3D BIM model of the house was developed by the author. Also supplied by the Client for use in the case study was a priced Bill of Quantities (BOQ) (Appendix C) and a project schedule of activities. The BOQ and activity schedule were used to calculate the impact of the changes.

In the real project the design was altered as the project developed. Fortunately for the Client, these changes were made at an early phase of the project and did not effect construction. However, for the purpose of this study, the changes will be implemented at intervals during construction of the project to demonstrate the impact of change on construction labour productivity. The Client, also a reputable contractor in Port Elizabeth, aided in estimating the direct...
impacts of the changes.

5.2.2 Description of Changes to the Project

Three major changes to the design were chosen as those that will best demonstrate the impact of change on labour productivity. These changes will be discussed briefly.

5.2.2.1 Width of the House

The first change that was considered resulted from an error by the architect. The architect initially designed the house to be 14615mm wide.

The initial design of the house was too wide which resulted in the east wall of the house being located over the building line, too close to the perimeter of the property. The house was designed 460mm too wide which was discovered by the surveyor when setting out the boundary pegs. By appointing the surveyor, the client narrowly avoided a serious complication. The width of the house was then simply reduced by 460mm by moving the eastern wall in the design. All windows and doors remained unchanged except for one window on the north face of the House. The change is displayed in Figure 5.2.

![Figure 5.2: The Ground Floor Plan View Displaying the Before (left) and After (right) for the Change to the House Width.](image)

This change could have resulted in a serious delay. As the timing of the delay was early, there
was a relatively small effect. If the error was only found later, there may have been more serious consequences.

For the purpose of this study, this change was implemented later than the real life case to better demonstrate the impact of change. The timing of this change was chosen to occur after the footing reinforcement had been placed and before the concrete was poured for the footings. This required the contractor to remove the reinforcement in the footings, cut the reinforcement appropriately, re-excavate the footings and lay the reinforcement in the correct location. Once this was done, the project could proceed as normal.

If the delay were to occur at this stage during construction, it was estimated that the direct impact on schedule of this item would be three days.

### 5.2.2.2 First Floor Slab Dimensions

The next change that was analysed was a modification to the dimensions of the first floor slab. This change occurred during the preliminary design phase of the project and did not have an effect on the actual construction of the project. However, similarly to the first change, the altering of the dimensions of the floor slab was manipulated in the study to occur later in the project.

The first change to the dimensions of the floor slab was a result of the Client’s instruction. The client wished to increase the size of the double volume opening in the first floor slab from having a length of 2500mm to 3000mm.

The second change was also as a result of the client’s instruction. The client requested that the balconies on the south side of the house be pulled back away from the street building line. In the initial design, both of the balconies on the south side of the house extended 2000mm beyond the supporting wall. The new design resulted in the Bedroom 1 balcony being reduced to 1000mm wide so that it was aligned with the 2000mm wide lounge balcony.

So as not to over exaggerate the impact of these changes, the changes were implemented after the formwork and the reinforcing had been placed, but before the concrete was poured. If the concrete had already been poured, this would have resulted in a much more serious delay.

These changes both required fixing and cutting of the reinforcing as well as adjustments to the placing of the formwork. To change the void size it was estimated that there would be a one day delay, while the pulling back of the balcony would result in a two day delay. See Figure 5.3 for an illustration of the changes made to the first floor slab.
5.2. Case Study to Demonstrate BIM Quantification Method

5.2.2.3 Height of the Roof

The third change occurred due to an error by the architect. In designing the house, the architect failed to adhere to municipal regulations and designed the house to be too high. The area in which the house was built imposes a regulation that houses may not exceed a certain height at the apex of the roof. In reality, this error was identified by the municipality while the project was awaiting approval. However, at a later stage in the project this change would have serious ramifications.

In order to resolve the issue two adjustments were made to the design. The first adjustment was to the wall plate level, which was reduced by 85 mm. The second adjustment resulted in the pitch of the roof being change from 22 degrees to 17.5 degrees (See Figure 5.4).

This change was implemented after the brickwork for the first floor had been completed. At this stage in the construction, the roof trusses would already have been ordered and be on-site. Therefore, to implement the change at this stage in the project, the brick work was to be broken down to the correct level and new trusses were to be ordered/remade.

This delay was estimated to take one day to redo the brickwork, while the total delay of the brickwork and waiting for the trusses to be remade would take one week.
5.3 Quantifying the Changes

The initial completion date of the project was the 21st of October, 2016. This assumed that construction of the foundations had started on the 11th of April and took 17 days to complete. Construction of the house structure would then start on the 5th of May, 2016, and take 121 days (See Figure 5.5). The timeline includes public holidays on the 27th of April, the 2nd of May and the 16th of June, 2016. Table 5.1 lists the BOQ summary items supplied by the Client, with quantities obtained from relevant components of the model, showing the total cost of the project to be R4 687 293, 26.

**Figure 5.4:** The West Elevation View Displaying the Before (above) and After (below) for the Change to the Roof Height.
5.3. Quantifying the Changes

### Table 5.1: Initial Project Costs

<table>
<thead>
<tr>
<th>Bill</th>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preliminaries</td>
<td>R345 050.00</td>
</tr>
<tr>
<td>2</td>
<td>Earthworks</td>
<td>R35 128.93</td>
</tr>
<tr>
<td>3</td>
<td>Concrete</td>
<td>R425 076.55</td>
</tr>
<tr>
<td>4</td>
<td>Masonry</td>
<td>R246 826.36</td>
</tr>
<tr>
<td>5</td>
<td>Waterproofing</td>
<td>R26 636.93</td>
</tr>
<tr>
<td>6</td>
<td>Roof Coverings</td>
<td>R136 100.00</td>
</tr>
<tr>
<td>7</td>
<td>Carpentry</td>
<td>R120 288.00</td>
</tr>
<tr>
<td>8</td>
<td>Ceilings</td>
<td>R87 425.00</td>
</tr>
<tr>
<td>9</td>
<td>Floor Coverings</td>
<td>R121 228.00</td>
</tr>
<tr>
<td>10</td>
<td>Ironmongery</td>
<td>R15 000.00</td>
</tr>
<tr>
<td>11</td>
<td>Metalwork</td>
<td>R300 000.00</td>
</tr>
<tr>
<td>12</td>
<td>Plastering</td>
<td>R165 415.68</td>
</tr>
<tr>
<td>13</td>
<td>Tiling</td>
<td>R40 910.00</td>
</tr>
<tr>
<td>14</td>
<td>Plumbing and Drainage</td>
<td>R117 500.00</td>
</tr>
<tr>
<td>15</td>
<td>Painting</td>
<td>R98 493.42</td>
</tr>
<tr>
<td>16</td>
<td>External Works</td>
<td>R329 410.70</td>
</tr>
<tr>
<td>17</td>
<td>Provisional Sums</td>
<td>R1 330 840.00</td>
</tr>
<tr>
<td></td>
<td><strong>SUBTOTAL</strong></td>
<td><strong>R3 961 660.76</strong></td>
</tr>
<tr>
<td></td>
<td>Contingencies</td>
<td>R150 000.00</td>
</tr>
<tr>
<td></td>
<td><strong>SUBTOTAL</strong></td>
<td><strong>R4 111 660.76</strong></td>
</tr>
<tr>
<td></td>
<td>VAT (14%)</td>
<td>R575 632.51</td>
</tr>
<tr>
<td></td>
<td><strong>Carried to Tender</strong></td>
<td><strong>R4 687 293.26</strong></td>
</tr>
</tbody>
</table>

Due to the study being focused on the impact of change on labour productivity, the BOQ items will be broken down into the separate plant, material and labour components. Ultimately, it will be the cost of labour that is affected by the productivity calculations. In future the model may be further developed to reflect the increase in plant and P&G (preliminary and general) costs due to the delays. P&G costs are one of the highest value items in terms of claims. If the developed model were to be updated, once the amount of time caused by the delays is calculated, the P&G cost increase will be based on the monthly rate for P&G expenses. However, for simplicity, this report will focus on only the impact of change on labour.
### FOUNDATIONS & SURFACE BED

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
<th>Predecessors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Set up site</td>
<td>17 days</td>
<td>Mon 4/11/16</td>
<td>Thu 5/5/16</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Site set up</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Site test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Safety test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Set tempts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Foundation trench</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Foundation trench</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Set out full line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Setting out</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Backfill &amp; G5 to floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Concrete to floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### STRUCTURE

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
<th>Predecessors</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>121 days</td>
<td>Thu 5/11/16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Backfill G - 1st FL</td>
<td>10 days</td>
<td>Fri 5/19/16</td>
<td>Thu 5/26/16</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Formwork to 1st FL, stair</td>
<td>12 days</td>
<td>Tue 5/17/16</td>
<td>Wed 5/18/16</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Reinforcement</td>
<td>1 day</td>
<td>Tue 5/11/16</td>
<td>Tue 5/11/16</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Concrete</td>
<td>1 day</td>
<td>Tue 5/11/16</td>
<td>Tue 5/11/16</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Back prop-ty</td>
<td>10 days</td>
<td>Thu 5/6/16</td>
<td>Thu 5/16/16</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Backfill 1st FL, wall plate</td>
<td>10 days</td>
<td>Fri 5/18/16</td>
<td>Fri 5/28/16</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Formwork 1st FL, wall plate</td>
<td>10 days</td>
<td>Fri 5/28/16</td>
<td>Fri 6/7/16</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Reinforcement</td>
<td>1 day</td>
<td>Wed 6/2/16</td>
<td>Wed 6/2/16</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Concrete to stair</td>
<td>1 day</td>
<td>Thu 6/2/16</td>
<td>Thu 6/2/16</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Formwork to up-stand beams</td>
<td>2 days</td>
<td>Fri 7/1/16</td>
<td>Mon 7/4/16</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Concrete to up-stand beams</td>
<td>1 day</td>
<td>Thu 7/1/16</td>
<td>Thu 7/1/16</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Roof trusses</td>
<td>1 day</td>
<td>Thu 7/1/16</td>
<td>Thu 7/1/16</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Roof coverages</td>
<td>1 day</td>
<td>Thu 7/1/16</td>
<td>Thu 7/1/16</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Paint GFL - back</td>
<td>10 days</td>
<td>Fri 7/1/16</td>
<td>Thu 7/11/16</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Paint GFL - back</td>
<td>10 days</td>
<td>Fri 7/1/16</td>
<td>Thu 7/11/16</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Waterproofing to showers</td>
<td>4 days</td>
<td>Wed 7/6/16</td>
<td>Thu 7/10/16</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Plumbing 1st fix</td>
<td>20 days</td>
<td>Mon 8/15/16</td>
<td>Mon 9/25/16</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Electrical 1st fix</td>
<td>15 days</td>
<td>Mon 8/29/16</td>
<td>Mon 9/25/16</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Tiling</td>
<td>15 days</td>
<td>Wed 8/31/16</td>
<td>Wed 9/15/16</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Set out fndt bkw</td>
<td>2 days</td>
<td>Fri 8/5/16</td>
<td>Fri 8/7/16</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Set out fndt bkw</td>
<td>2 days</td>
<td>Fri 8/5/16</td>
<td>Fri 8/7/16</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Roof trusses</td>
<td>1 day</td>
<td>Thu 8/5/16</td>
<td>Thu 8/5/16</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Roof coverages</td>
<td>1 day</td>
<td>Thu 8/5/16</td>
<td>Thu 8/5/16</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Roof coverages</td>
<td>1 day</td>
<td>Thu 8/5/16</td>
<td>Thu 8/5/16</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The above tasks and their durations are illustrative and may vary based on the actual project requirements.
5.3. Quantifying the Changes

With this information at hand, following the process described in Algorithm 4.1, the model must first be adapted to reflect the changes. The changes will be implemented chronologically, i.e., the change in the width of the house, then the changes to the slab dimensions, and finally the changes to the roof pitch and wall plate level.

5.3.1 House Width Change Quantification

As mentioned in the house width change description, the direct impact of this change would be three days. This is manually entered into the project schedule with the resource requirement as follows:

- Setting out: 1 x surveyor x 4 hrs (0.5 days)
- Excavate effected footings: 4 x labourers x 16hrs (2 days)
- Reinforcing strip and re-fix: 1 x fixer x 4 hrs and 2 x labourers x 4 hrs (0.5 days)

When confirming the project schedule (Line 3 of Algorithm 4.2), the contractor must enter any activity duration changes caused by an increase or decrease in the quantities of work required. For this change, the resulting change in quantities has a negligible impact on the timeline as a new activity cannot be started with only a fraction of a day remaining. Therefore, the original estimates for the activities’ durations will be used. The new project completion date with the direct impact of the changes is the 26th of October, 2016. This is assuming that no control actions take place. However, the Client does not wish to extend the project deadline and the contractor must implement a control action (acceleration) to manage the delay. The contractor decides that this will be done with overtime labour. The overtime labour will occur on the activities: “Foundation Brickwork” and “Backfill & G5 Layer”.

In order to recover the lost 24 hours (3 days) of work, the contractor identifies that a 6 day work week will be required, as well as having to work on the public holiday on the 27th of April. This will result in a 6 day work week with 9 hours in each day for the duration of the two activities, with the last day of “Backfill & G5 Layer” being a 10 hour day. Therefore, the 24 hour delay is recovered by working 9 hours on the public holiday, 9 hours on a Saturday and a total of 6 hours of overtime on regular working days. For this change, the contractor will need to quantify the following productivity factor:

- Overtime

\[ 3 \text{ days} \times 8 \text{ hour work day} = 24 \text{ hours} \]

\[ \text{The project originally finished on a Friday, therefore the delay to the 26th of October includes the weekend} \]
The above should be the case in theory; however, the prediction has not accounted for productivity losses due to overtime work. The contractor will also need to include the cost of additional supervision for any periods where the supervisor would not normally be working. Algorithms 4.1 and 4.2 will then be used to calculate the overall effect of this change.

In the BIM change management process, the contractor has the option to choose whether the learning curve effect should be quantified, to determine if he has overestimated the productivity of the labourers. The learning curve effect will not be calculated for this change. The learning curve effect on 4 hours of work for both the setting out and the reinforcing activities will be negligible. Additionally, the original duration of the activity Excavate Footings was two days (16 hours) to complete $77\ m^3$. The rework consists of re-excavating approximate $12\ m^3$. Therefore, the direct change given by the contractor (16 hours for $12\ m^3$) will take into account the setting up of the site with tools and materials and not be impacted upon by productivity losses (learning curve effect).

5.3.1.1 Quantification

The first step in Algorithm 4.1 is for the contractor to adapt the Revit model to reflect the direct impacts of the change. Once the change has been made to the model, the contractor updates the project schedule to reflect the three day increase in project duration due to the changed activities and then the reduced duration due to overtime work (6 day week at 9 hours per day).

Next, the contractor will be asked to perform the decision process (Figure 4.1). For this case, and all others for the project, it can be assumed that there are sufficient project records and data to perform a discrete analysis. Subsequently, the contractor performs an analysis on a single factor (Overtime).

The studies available for analysing the effect of overtime are listed in Table 5.2 and 5.3. By considering Table 5.2 and 5.3, the contractor can now select the most appropriate model for quantification. For this project, the study by Adrian (1987) will be used. This study by Adrian (1987) has quantified the same overtime schedule to be implemented by the contractor and a similar period of use to the overtime required in the case study. The format of the Schedules Studied column refers firstly to the number of work days per week followed by the hours worked each day (e.g. 5-8s for a five day work week with eight hours worked per day). Although the study by Adrian (1987) (highlighted in bold) predominantly focused on concrete work, the case study too involves concrete work and the activities requiring overtime work are in preparation of pouring the ground floor slab. The project information and the information in this study are then sent to Navisworks (see Algorithm 4.2).

---

3Direct impact of the change given in the previous list
46 day week with a 9 hour work day
### Table 5.2: Overtime Studies with Additional Information

<table>
<thead>
<tr>
<th>Study</th>
<th>Time Frame</th>
<th>Project Type</th>
<th>Schedules Studied</th>
<th>Period of Use</th>
<th>Notable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kossoris [BLS] 1947 (Bulletin No. 917)</td>
<td>1939 - 1946</td>
<td>78 cases in industrial plants</td>
<td>7 day week (8 hours per day)</td>
<td>6-12 months</td>
<td>Highly repetitive work; Indoors; Machine paced; Wartime; Wage incentives</td>
</tr>
<tr>
<td>O’Connor [Foster Wheeler] 1969</td>
<td>1963 - 1968</td>
<td>Construction of Fossil Boilers</td>
<td>5-9s;5-10s;6-8s;6-9s;6-10s</td>
<td>N/A</td>
<td>No info about source data; Length of Overtime use unknown</td>
</tr>
<tr>
<td>Howerton [Qualified Contractor] 1969</td>
<td>1964</td>
<td>Unknown</td>
<td>6-9s;6-10s;6-12s;7-8s;7-9s;7-10s;7-12s</td>
<td>4 weeks</td>
<td>Subjective opinion of 5 NECA members; Same study as NECA 1969</td>
</tr>
<tr>
<td>Smith 1975</td>
<td>Prior to 1975</td>
<td>N/A</td>
<td>5-10s;6-10s</td>
<td>16 weeks</td>
<td>Nothing known how previous data was manipulated for efficiency factors</td>
</tr>
<tr>
<td>Adrian 1987</td>
<td>1982</td>
<td>Single Project of Concrete Work</td>
<td>5-9s;5-10s;5-11s;6-9s;6-10s;6-11s;7-8s;7-9s;7-10s;7-11s</td>
<td>1 and 3 weeks</td>
<td>Results from claim analysis (Possible bias); ideal weather conditions; Overtime not longer than 3 weeks, but large % of project</td>
</tr>
<tr>
<td>NECA 1962</td>
<td>Prior to 1962</td>
<td>Responses from NECA members</td>
<td>Sporadic: 5-8s;6-8s;7-8s Continuous: 6-10s;7-10s</td>
<td>Sporadic: 1 week Continuous: several weeks</td>
<td>Subjective survey; 289 respondents was a small sample size (100s of members); No original report</td>
</tr>
<tr>
<td>NECA 1969</td>
<td>-</td>
<td>-</td>
<td>6-9s;6-10s;6-12s;7-8s;7-9s;7-10s;7-12s</td>
<td>4 Weeks</td>
<td>Howerton Article 1969</td>
</tr>
<tr>
<td>NECA 1989</td>
<td>1969 - 1989</td>
<td>Electrical Jobs</td>
<td>5-10s;5-12s;6-9s;6-10s;6-12s;7-8s;7-9s;7-10s;7-12s</td>
<td>16 Weeks</td>
<td>No info about source data or projects; Provides ranges of productivity losses i.e. high, med, low;</td>
</tr>
<tr>
<td>US Army Corps</td>
<td>-</td>
<td>Unknown</td>
<td>5-9s;5-10s;6-8s;6-9s;6-10s;6-12s;7-8s;7-9s;7-10s</td>
<td>4 Weeks</td>
<td>Unknown data sources</td>
</tr>
</tbody>
</table>
Table 5.3: Overtime Studies with Additional Information (continued)

<table>
<thead>
<tr>
<th>Study</th>
<th>Time Frame</th>
<th>Project Type</th>
<th>Schedules Studied</th>
<th>Period of Use</th>
<th>Notable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRT [1974:1980]</td>
<td>1960s</td>
<td>Process Plant</td>
<td>50 hr week; 60 hr week</td>
<td>12 Weeks</td>
<td>Use of &quot;Bogey&quot; Standard (Relative measurement); Lacks objectivity</td>
</tr>
<tr>
<td>CII 1988</td>
<td>1984-1988</td>
<td>Refinery Refurbishment</td>
<td>4-10s;5-8s;5-10s;6-8s;6-10s;7-10s</td>
<td>4-6 Weeks and 13+ Weeks</td>
<td>Detailed info about source data and projects; Inconsistent productivity trends for crews</td>
</tr>
<tr>
<td>CII 1994 [1997]</td>
<td>1989-1992</td>
<td>Paper mill; Manufacturing process plant; refinery</td>
<td>50 hr week; 60 hr week</td>
<td>2-7 Weeks</td>
<td>Normalised productivity data; 4-10s day baseline; Overtime used to maintain schedule</td>
</tr>
<tr>
<td>Bromberg 1988</td>
<td>-</td>
<td>Piping on process plants</td>
<td>5-9s;5-10s;5-11s;5-12s;6-8s;6-9s;6-10s;6-11s</td>
<td>Unknown</td>
<td>Lack of consistency in adjustment of factors; Similar to MCA and BRT study</td>
</tr>
<tr>
<td>Haneiko &amp; Henry 1991</td>
<td>1985-1989</td>
<td>Concrete Work on Power Plant</td>
<td>+60 hr week</td>
<td>8 Weeks</td>
<td>50% standard time and 50% overtime; Small sample size</td>
</tr>
<tr>
<td>MCAA 1968; 1994</td>
<td>-</td>
<td>Manufacturing Plant</td>
<td>5-9s;5-10s;5-11s;5-12s;6-8s;6-9s;6-10s;6-11s;6-12s;7-8s;7-9s;7-10s;7-11s;7-12s</td>
<td>Unknown</td>
<td>Manipulation doesn't have any correlation to original data; adjustment method unknown</td>
</tr>
<tr>
<td>Hanna &amp; Sullivan 2004</td>
<td>Prior to 2004</td>
<td>Electrical and Mechanical</td>
<td>Percent Overtime</td>
<td>Not Specific</td>
<td>Mathematical Model; Different impact for industrial and non-industrial projects</td>
</tr>
<tr>
<td>Hanna, Taylor &amp; Sullivan 2005c</td>
<td>Prior to 2005</td>
<td>Residential; Commercial; Manufacturing; Industrial; Electrical; Mechanical; etc.</td>
<td>4-10s;5-8s;5-10s;6-10s</td>
<td>Broad Range</td>
<td>Mathematical Model; Ignores difference in types of project/trades; Impact increases accurately proportionally to total work hours; Ignores method of overtime</td>
</tr>
</tbody>
</table>
5.3. Quantifying the Changes

The results of the study by Adrian (1987) are displayed in Table 5.4. From this table, it can be seen that there is a 3-5% loss in productivity when overtime (6 day week, 9 hours per day) occurs for a duration of one week. Therefore, even though the contractor has predicted that the overtime will shorten the duration of the activities “Foundation Brickwork” and “Backfill & G5 Layer” to 3.625 days and 2.25 days respectively, the duration of these activities will increase by 5% (higher value taken as the final day consists of a greater amount of overtime). This will result in the project falling behind by three hours.

Table 5.4: Loss of Productivity Due to Overtime from Adrian 1987

<table>
<thead>
<tr>
<th>Days</th>
<th>Daily Hours</th>
<th>Total Weekly Hours</th>
<th>Inefficiency (%)</th>
<th>At: 7 Days</th>
<th>21 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>9</td>
<td>45</td>
<td>2-4</td>
<td>6-8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>50</td>
<td>5-7</td>
<td>11-13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>55</td>
<td>9-11</td>
<td>16-18</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>54</td>
<td><strong>3-5</strong></td>
<td><strong>7-11</strong></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>60</td>
<td>6-8</td>
<td>13-17</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>66</td>
<td>11-13</td>
<td>19-22</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>56</td>
<td>8-10</td>
<td>18-20</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>63</td>
<td>10-12</td>
<td>21-23</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>70</td>
<td>13-15</td>
<td>26-29</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>77</td>
<td>19-21</td>
<td>38-41</td>
<td></td>
</tr>
</tbody>
</table>

The new activity durations will be added to the project schedule. These activities lie on the critical path and will result in a delay in the completion date of the project. The new completion date of the project is on the 24th of October, 2016. The original project completion date was at the end of a Friday and therefore, the small delay (3 hours) resulted in the work only being completed the following Monday. The summary of labour costs associated with this change is found in Table 5.5.

Table 5.5: Summary of Labour Costs Associated with Width Change

| Estimated Cost of Accelerated Activity* | R20 803, 93 | R31 101, 52 |
| Adjusted Cost of Accelerated Activity** | R21 947, 92 | R31 101, 52 |
| Unforeseen Impact on Cost | R1 144, 00 |

* - The contractors estimate to accelerate
** - The adjusted cost due to the productivity calculation

From Table 5.5, it is shown that the unforeseen impact of this change is R1 144, 00. Additionally, any penalties for a late hand over as a result of the three hour delay would also be included.

6The selected value has been listed in bold writing
5.3. Quantifying the Changes

The cost calculations for Table 5.5 will be explained in the following paragraph. Figure 5.6 and Table 5.6 show the change in hours for the contractor’s acceleration estimate and the adjusted productivity calculation. Figure 5.6 displays the regular (REG) and overtime (OT) hours worked for each accelerated activity. Overtime labour is charged at 1.5 times the standard rate. Table 5.6 summarises the number of hours overtime and the regular hours worked for each activity. When the activities’ rates are applied to the work schedule in Figure 5.6, the results calculated are those presented in Table 5.5.

<table>
<thead>
<tr>
<th>Contractors Estimate for the Accelerated Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
</tr>
<tr>
<td>8am</td>
</tr>
<tr>
<td>9am</td>
</tr>
<tr>
<td>10am</td>
</tr>
<tr>
<td>11am</td>
</tr>
<tr>
<td>12pm</td>
</tr>
<tr>
<td>1pm</td>
</tr>
<tr>
<td>2pm</td>
</tr>
<tr>
<td>3pm</td>
</tr>
<tr>
<td>4pm</td>
</tr>
<tr>
<td>5pm</td>
</tr>
<tr>
<td>6pm</td>
</tr>
<tr>
<td>7pm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Adjusted Schedule for Accelerated Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
</tr>
<tr>
<td>8am</td>
</tr>
<tr>
<td>9am</td>
</tr>
<tr>
<td>10am</td>
</tr>
<tr>
<td>11am</td>
</tr>
<tr>
<td>12pm</td>
</tr>
<tr>
<td>1pm</td>
</tr>
<tr>
<td>2pm</td>
</tr>
<tr>
<td>3pm</td>
</tr>
<tr>
<td>4pm</td>
</tr>
<tr>
<td>5pm</td>
</tr>
<tr>
<td>6pm</td>
</tr>
<tr>
<td>7pm</td>
</tr>
</tbody>
</table>

Figure 5.6: Schedule Shift for the House Width Change Acceleration.

The updated project schedule and increased duration (and subsequently cost) for each effected
5.3. Quantifying the Changes

Table 5.6: Difference in Overtime and Standard Hours Worked for the Width Change

<table>
<thead>
<tr>
<th></th>
<th>Masonry Foundation</th>
<th>Backfill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contractor Estimate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Hours Worked</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Overtime Hours Worked</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Total Hours Worked</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td><strong>Adjusted Productivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Hours Worked</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>Overtime Hours Worked</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Total Hours Worked</td>
<td>42</td>
<td>25</td>
</tr>
</tbody>
</table>

element was returned to the Revit model. In accordance with Algorithm 4.1 (Lines 7 - 16), the model elements are highlighted with a graphics override depending on the status of each element. The highlighted model is displayed in Figure 5.7 with different colours (Red/Yellow/Orange). By clicking on each element, the user is able to see the associated delay and a description of the effect on the overall project. Being able to highlight individual elements aids the contractor in determining which activities require remedial action.
5.3. Quantifying the Changes

![Revit Output for the Quantification of the Change in Width of House Smart](image)

**Figure 5.7:** Revit Output for the Quantification of the Change in Width of House Smart.
5.3.2 Slab Dimension Quantification

As mentioned in the slab dimension change description, the direct impact of this change would be three days. This is manually entered into the project schedule with the resource requirement as follows:

Change to void size (One Day):

- Formwork: 1 x carpenter x 3 hrs & 2 labourers x 3 hrs
- Reinforcing: 1 x fixer x 2 hrs & 1 x labourer x 2 hrs

Change to Balcony (Two Days):

- Formwork: 1 x carpenter x 12hrs & 2 labourers x 12 hrs
- Reinforcing: 1 x fixer x 8 hrs & 3 x labourer x 8 hrs

Following on from the previous change (completion date on the 24th of October), the direct changes to the project will result in the overall project completion date moving to the 27th of October. This is without control actions to manage the delay. Once again, the owner does not extend the project due date and requests that the contractor accelerates work. Therefore, a total of three work days (24 hours) needs to be made up for the slab dimension change, as well as the extra day delay due to the lost productivity of the previous change. It is important to note this delay from the previous change as it will contribute to what has been defined as the cumulative impact of change.

The contractor decides to make up this time later in the project under the activities Plaster GFL (Ground Floor) Brickwork and Timber Flooring. Two activities will have to be accelerated as the activity Painting ends on the 27th of October (4 days behind schedule) and the activity Carpets, on a different activity path to Painting, now finishes on the 26th of October (3 days behind the End Date).

Plaster GFL Brickwork is expected to take 10 days to complete. The contractor decides to hire additional workers to decrease the duration of this activity by the 4 days required. This will revert the end date of the painting activity from the 27th of October to the 21st of October. Congestion will not be considered for this activity as it is assumed that there is ample space for the additional workers. Congestion does not automatically occur when there is overmanning on a project. Other dynamics are present for productivity losses due to overmanning. Congestion,
5.3. Quantifying the Changes

however, refers to a function of the number of workers present in a limited or confined space. (Gunduz [2004])

Once the activity *Plaster GFL Brickwork* has been accelerated, the new project end date will be the 26th of October\(^8\). The *Timber Flooring* activity has an initial duration of 15 days which will be decreased by 3 days so that the final project completion date is reverted to the 21st of October, 2016. This activity will be subject to congestion as it is performed indoors and by adding additional labourers it reduces the working space per labourer.

It is assumed that the original crew sizes for these activities were the optimum crew sizes. Therefore, each member added to a crew will increase the productivity of the crew by less than the previous worker added (Corps [1979]). This is unaccounted for in the contractor’s prediction. Once again, Algorithms 4.1 and 4.2 are used to calculate the overall effect of this change.

For this change, the contractor will need to quantify the following productivity factors:

- Learning curve
- Overmanning
- Congestion

5.3.2.1 Quantification

The first step in the process (Algorithm 4.1) is to adapt the model to reflect the required changes. Once the change has been made to the model, the contractor will update the project schedule with the rework required and the contractor’s prediction for the effect of hiring additional labourers (Overmanning). For the activity *Plaster GFL Brickwork*, the original crew consisted of 10 labourers (10 labourers for a 10 day activity at 8 hours per day equals 800 manhours). Therefore, the contractor will need to hire an additional 7 labourers in order to complete the task in 6 days\(^9\). For the activity *Timber Flooring*, the original crew consisted of 10 labourers. Therefore three additional labourers are required for the first 10 days of the 15 day activity.

Next, the contractor will be asked to perform the decision process (Figure 4.1). From here the contractor may perform an analysis on multiple factors (Overmanning and Congestion). The only additional step will require the contractor to select which activity will be analysed for overmanning and which activity will be analysed for congestion. Each productivity factor is applied to a different activity. The productivity losses associated with congestion occur as a result of overmanning and therefore, the studies that analyse multiple factors on a single

---

\(^8\)This is due to the Carpet activity being located on a different activity path

\(^9\)17 x 8 x 6 = 816 manhours, therefore finish an hour early on the last day
5.3. Quantifying the Changes

activity need not be consulted. However, before this can occur, the rework needs to be analysed for productivity losses due to the learning curve effect.

It was decided to check whether the learning curve would have any effect on productivity of the rework required. It was assumed that the original formwork and reinforcement requirement totalled 200 $m^2$ and a total activity duration was 17 days (Formwork to 1st FL & stair and Reinforcing). Therefore, the productivity of the planned work was applied to the Straight-line learning curve model. This model by Wright (1936) is a simple model that is most commonly used (Everett and Farghal 1994). The model was manipulated to find the appropriate learning rate and labour hours to produce the first unit. The Straight-Line learning curve is defined using Equation 1 Wright [1936].

$$Y = A.X^{-n}$$  

Where:

- $Y =$ labour hours to produce $X^{th}$ unit
- $A =$ labour hours to product the first unit
- $X =$ unit number
- $n =$ slope of Log curve

The learning curve for the planned work was plotted (Figure 5.8 - Blue Line). This shows that as the task is performed, the labourers increase their productivity. Although the initial productivity for the activity is slow, because of learning and job rhythm, the labourers are able to increase their productivity and complete the task in the specified time. However, when the activity is stopped, there is a break in job rhythm and a loss in productivity. Therefore, rework does not continue at the same productivity as the planned work.

It is therefore necessary to determine whether the contractor assumed the work would continue unaffected, or whether a provision was made in the contractor’s estimate of the rework for losses in productivity. From the information in Figure 5.8 it was found that the time allocated for approximately 8 units of rework (24 hours) was the same as the planned time for the first 8 units of the learning curve (23.01 hours). This means that the estimate from the contractor does not need to be adjusted for the learning curve effect as it already forms part of the estimate. This could be because the contractor included the time to relocate site tools and materials for the change in his estimate. The red line in Figure 5.8 shows how productivity will be effected when the labourers need to start over. Following this calculation, the program may proceed with the analysis of other factors.
5.3. Quantifying the Changes

Figure 5.8: The Log-Log Scale Learning Curve for the Slab Dimension Change at a Learning Rate of 70%
5.3. Quantifying the Changes

**Overmanning** Once overmanning has been selected from the decision process, the contractor will be directed to a table with information regarding different approaches to quantifying the impact of overmanning on a project. The studies available for analysing the effect of overmanning are listed in Table 5.7. These studies have ranges of approximate workforce sizes and some of the studies will in turn have more than one set of results.

<table>
<thead>
<tr>
<th>Study</th>
<th>Applicable Ranges of Overmanning</th>
<th>Approximate Workforce Size</th>
<th>Project Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappaz</td>
<td>Ave: 355 to 980 (0-176%) Peak: 750 to 2380 (0-217%)</td>
<td>200-2500</td>
<td>Unknown (Various)</td>
</tr>
<tr>
<td>Corps</td>
<td>0-100%</td>
<td>-</td>
<td>Unknown</td>
</tr>
<tr>
<td>Thomas and Jansma</td>
<td>Ratios: 1 to 4 (0-300%)</td>
<td>-</td>
<td>Concrete Placement</td>
</tr>
<tr>
<td>O'Connor</td>
<td>0 to 50-60%</td>
<td>100, 200, 300</td>
<td>Construction of 5 Large Boiler Units</td>
</tr>
<tr>
<td>Waldron</td>
<td>0-53%</td>
<td>-</td>
<td>Data from O’Connor</td>
</tr>
<tr>
<td>Thomas and Smith</td>
<td>Ratios: 0 to 50-60%</td>
<td>600</td>
<td>Unknown</td>
</tr>
<tr>
<td>Hanna et al</td>
<td>Peak/Ave Ratios: 1.7-3.76 Actual manpower peak: 4-50</td>
<td>700-208’451 labour hours</td>
<td>Mechanical and Sheet metal trades (Labour Intensive)</td>
</tr>
</tbody>
</table>

The first six studies listed in Table 5.7 present the contractor the graphical result displayed in Figure 5.9. Contractor A and Contractor B, found in Figure 5.9 are from the results of the study by Thomas and Smith (1990). The study by Hanna, Chang, Lackney, and Sullivan (2005) (highlighted in bold) is not included in this figure as the method is not comparable to the other studies. A mathematical calculation of productivity loss as a function of the peak man hours for an activity and the average man hours is used by Hanna, Chang, Lackney, and Sullivan (2005). This function is:

\[
\% \text{LostEfficiency} = -0.305 + 0.116 \times \frac{\text{ActualPeakManpower}}{\text{AverageManpower}} + 0.163 \times \log(\text{ActualPeakManpower})
\]
5.3. Quantifying the Changes

Figure 5.9: Comparison of the Results of Various Overmanning Studies
To demonstrate how this change is quantified, the study by Hanna, Chang, Lackney, and Sullivan (2005) will be used because the activity for the case study project requiring overmanning is also labour intensive and involves similar labour hours to the study by Hanna, Chang, Lackney, and Sullivan (2005).

As previously stated, to shorten the activity duration from 10 days to 6 days, the original ten man crew will need an additional seven labourers for this task. This implies that the Actual Peak Manpower is equal to 17, while the Average Manpower is equal to 10. If the graphical results were used, the percentage overmanning would be equal to 70% \(((17-10)/10 \times 100)\). The equivalent inefficiency value would then be used from the corresponding study. The equation formed by Hanna et al (2005) calculates a loss in efficiency equal to 9.3%. The initial productivity calculated (0.292 units per hour) decreases to 0.265 units per hour. This means that the estimated duration of the activity with overmanning would increase from the planned 800 manhours to 884 manhours, delaying the project by approximately 1 day of working time.

Table 5.8 shows the difference in labour cost predictions.

<table>
<thead>
<tr>
<th></th>
<th>Plaster</th>
<th>GLF</th>
<th>Brickwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Cost of Accelerated Activity</td>
<td>R15 245, 25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted Cost of Accelerated Activity</td>
<td>R17 287, 19</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unforeseen Impact on Cost</strong></td>
<td><strong>R 2 041, 94</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.8 shows that there is an unaccounted for amount in estimating the change totaling R2 041, 94. This is the difference between the contractor’s estimate and the revised productivity calculation.

It must be noted that the 9.3% increase in the duration of this activity is relatively conservative as the results from the graph in Figure 5.9 range from an efficiency loss of 12-30% when an overmanning rate of 50% is present. Furthermore, if we neglect the cumulative impact of change (delay caused by the previous delays on the project) and only accelerate the project to account for the direct impact of this change, only three days would need to be recovered. To do this, only five extra labourers would be needed (overmanning percentage of 50%). Therefore, a productivity loss of only 6.07% would be experienced according to the equation by Hanna, Chang, Lackney, and Sullivan (2005). This shows how the previous change has impacted the current change, further decreasing productivity.

**Congestion** For the calculation of the effect of congestion, the contractor will be guided to the list of studies available in Table 5.9.

The column "Start density of Productivity loss" refers to the density of workers where no
5.3. Quantifying the Changes

Table 5.9: Congestion Studies with Additional Information

<table>
<thead>
<tr>
<th>Study</th>
<th>Measurement of Congestion</th>
<th>Applicable Ranges</th>
<th>Start density of Productivity loss</th>
<th>Reliability and Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappaz 1977</td>
<td>Square feet (sf) per person at average workforce</td>
<td>225-80 sf/person</td>
<td>200sf per person</td>
<td>Apparent data existence but no related info. Impact expressed as multiplier</td>
</tr>
<tr>
<td>Corps 1979</td>
<td>% Crowding</td>
<td>0-35%Crowding</td>
<td>-</td>
<td>Possible subjective survey. Calculating % crowding may be inconvenient</td>
</tr>
<tr>
<td>Smith 1987</td>
<td>Square meter per person</td>
<td>30-10 m² per person</td>
<td>323sf (30m²) per person</td>
<td>Impact value given as range. 10m² per person as minimum</td>
</tr>
<tr>
<td>Thomas &amp; Smith 1990</td>
<td>Square feet per person</td>
<td>200-110; 250-150 sf per person</td>
<td>200 or 250 sf per person</td>
<td>Obtained from second hand literature. Two curves for contract type provided.</td>
</tr>
</tbody>
</table>

sf = square feet

inefficiency is experienced. Therefore, from this level, any increase in worker density would result in a productivity loss. For the activity *Timber Flooring* there is a maximum of 190 square meters available to the workers. Therefore, with a crew size of 10 labourers, there are 19 square meters per person, or 204 square feet per person. For a 13 member crew, there would be 157 square feet per person. Therefore, the contractor may be inclined to choose either the study by Kappaz (1977) or the study by Thomas and Smith (1990). The two contract types provided for in the study by Thomas and Smith (1990) are for a directly hired workforce and a subcontracted workforce. Using this study by Thomas and Smith (1990), there would be an 11% loss in productivity due to the additional labourers for this activity.

The loss in efficiency for this activity would result in the activity extending from 1200 manhours to 1315 manhours (approximately one and a half days delayed). The efficiency loss is only applied to the ten days where congestion occurred (1040 manhours). The efficiency loss during this period requires 114.5 hours of extra work to be covered by the regular crew. Table 5.10 displays the associated cost impact of the change. Table 5.10 show that there is an unforeseen cost impact of R4 027, 25 due to this change.

\[^{10}\text{area of the floor slab}\]
5.3. Quantifying the Changes

Table 5.10: Summary of Labour Costs Associated with the Slab Dimension Change

<table>
<thead>
<tr>
<th></th>
<th>Plaster</th>
<th>GLF</th>
<th>Brickwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Cost of Accelerated Activity</td>
<td>R37 576,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted Cost of Accelerated Activity</td>
<td>R41 603,25</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unforeseen Impact on Cost</strong></td>
<td><strong>R4 027, 25</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3.2.2 Change Summary

Following the revised productivity calculation, the project completion date will be delayed from the planned, Friday the 21st of October to the Tuesday, 25th of October 2016. The total unforeseen cost associated with this impact is R6 069, 18.

This is displayed graphically in the revit model in Figure 5.10. The contractor will be able to use this model to identify where cost increases occur. The model shows that this change has caused the completion date to move from the 24th of October (before the change) to the 25th of October. Therefore, the overall project completion date is four days (two working days) behind the original planning.

---

\footnote{Overmanning - R2 041, 94; Congestion - R4 027, 25}
Figure 5.10: Revit Output for the Quantification of the Change in the First Floor Slab Dimensions of House Smart.
5.3.3 Roof Height Change Quantification

The final change to be considered for this case study is the change in the roof height. This is an important delay for the case study project as it will result in a week overrun to the project. Additional work will need to be performed to drop the wall plate level and the project will be put on hold waiting for the roof trusses to be reordered and delivered.

In order to make up the lost time, the contractor will need to allocate additional roofing crews for the placement of the roof elements (trusses, sheeting, etc.). This additional labour will take the form of shift work, working after hours to make up for the lost time. Additionally, the activities *Joinery Fitting 1st Fix* and *Painting* will require acceleration to bring the due date forward. The extra crews, working for one week, should bring the project back on time. However, this does not include the loss in productivity associated with shift work as well as the cumulative impact of change from the previous changes.

For this change, the contractor will need to quantify the following productivity factors:

- Shift Work
- Overtime

5.3.3.1 Quantification

Following the same process as the previous changes, the model is first updated. In accordance with Algorithm 4.1, the project timeline is updated to reflect changed quantities, rework and the effect of the contractor’s planned acceleration measure. In order to recover the lost time from the changes and the cumulative impact of the changes, acceleration will need to be performed on the roofing activities, being the activity *Joinery Fittings 1st Fix* and *Painting*. The cumulative delays from the previous changes requires the contractor to recover two extra days. Performing the decision process in Figure 4.1 will then lead the contractor to a factor influencing productivity loss. The learning curve effect will not be calculated here as there is only one day of rework. Any loss of productivity will result in only a fraction of a day being added. This can simply be done by working the extra hours for that specific day.

**Roof Acceleration** Shift work will be used to recover lost time in the roofing activities. Although the map of studies (Figure 4.2) lists two sources of data that may be used, the first source, MCAA (1994) is not recommended for use by the contractor. This study does show that there are possible inefficiencies caused by shift work, however, the study does not explicitly state whether the productivity losses are caused by accidents, absenteeism or the time it takes the human body to adjust to the shift work (Lee 2007). Other studies (Haneiko and Henry
5.3. Quantifying the Changes

Smith [1987] and Walden [1986] also attempted to quantify productivity losses due to shift work. These studies calculate productivity losses over the entire project and give broad ranges of possible outcomes. Therefore, it is recommended that the study by Hanna, Chang, Sullivan, and Lackney (2005) be used until further databases are available.

The study by Hanna, Chang, Sullivan, and Lackney (2005) calculated productivity loss based on the percentage shift work. Obtained from statistical regression, the loss in productivity due to shift work may be calculated from Algorithm 5.1.

**Algorithm 5.1: Calculating the Productivity Loss due to Shift Work**

**Data:** Received from Project Schedule

**Input:** Total Shift Work Manhours & Budgeted Total Manhours

**Output:** Productivity Loss

1. Input received from schedule;
2. for activity do
3. 
4. \[ \%\text{ShiftWork} = \frac{\text{TotalShiftWorkManhours}}{\text{BudgetedTotalManhours}} \]
5. 

\[ \text{ProductivityLoss} = 0.22052 + 0.07152 \times \ln(\%\text{ShiftWork}) \]

Total Shift Work Manhours refers to the total labour hours performed by the second and subsequent shifts. The Total Budgeted Manhours refers to the original planned manhours required for a task. The results for Algorithm 5.1 are display in Figure 5.11. This graph shows that, in small amounts, shift work may actually increase productivity. Productivity losses range from -11% to 17% for 1% to 50% shift work implementation. Hanna, Chang, Sullivan, and Lackney (2005) state that these values correspond closely to other studies performed in non-construction industries.

The initial work force for the roofing activities consisted of two crews for each activity, with each crew consisting of five labourers. The total planned manhours for the activities is then equal to 1600 manhours (10 days for each activity). In order to decrease the duration of the activities to 6 days for Roof Trusses and 6 days for Roof Coverings, a total of 640 hours of shift work is required. This is 40% of the Budgeted Total Manhours. Therefore, according to Algorithm 5.1, there will be a 15.5% loss in productivity on the task (Indicated by the red line in Figure 5.1).

The total roof area is 220 m². To calculate the cost of this change, the contractor estimates that working at the original productivity, the work performed at normal working hours will complete 132 m² and the shift work will complete 88 m². However, the shift work’s reduction in productivity means that it will only complete 74.36 m² of roof area. Therefore, the standard working crews will have to make up the uncompleted work. To complete this unaccounted work will take a further 99 manhours, or just more than one day. Table 5.11 displays the costs
5.3. Quantifying the Changes

Figure 5.11: Loss of Efficiency from Shift Work (Hanna, Chang, Sullivan, and Lackney 2005)

associated with this change.

Table 5.11: Summary of Labour Costs Associated with the Roof Height Change

<table>
<thead>
<tr>
<th>Roof Trusses and Coverings</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Cost of Accelerated Activity</td>
<td>R24 127, 00</td>
</tr>
<tr>
<td>Adjusted Cost of Accelerated Activity</td>
<td>R25 334, 61</td>
</tr>
<tr>
<td>Unforeseen Impact on Cost</td>
<td>R1 207.61</td>
</tr>
</tbody>
</table>

This will result in an extension of the activities Roof Trusses and Roof Coverings by 5 hours each.

Joinery Fittings 1st Fix  
This activity has an original duration of 15 days which needs to be reduced to 13 days for the project to be completed on time. For this activity, overtime will be used for acceleration. The employed overtime schedule will be an 11 hour day for the first five days of the activity, after which the work hours will return to normal.

In selecting the appropriate study from Table 5.3, the contractor may select the study by Adrian (1987), Bromberg (1988), or the study MCAA (1994). These studies all have productivity loss factors for a five day work week with an eleven hour work day. The study by the MCAA (1994) is based on the manufacturing industry and the overtime schedules used occurred over an extended
5.3. Quantifying the Changes

period of time (6 months to a year). The study by Adrian [1987] was used in the Width Change quantification and therefore, for the purpose of demonstration, the study by Bromberg [1988] will be used. The study by Bromberg [1988] involved the piping activities for the construction of process plants. The results from the study by Bromberg [1988] are displayed in Figure 5.12.

![Average Efficiency for Various Overtime Schedules](image)

**Figure 5.12:** Results of the Overtime Study by Bromberg (1988) for 5 and 6 Day Work Weeks with 8 to 12 Hour Work Days

Figure 5.12 shows that for a 5 day work week with an 11 hour day, one can expect an 88% efficiency (12% loss in productivity). Therefore, when applied to the period of the activity that experiences overtime, there is 6.6 hour delay caused by productivity losses. The resulting losses from this acceleration measure are listed in Table 5.12.

<table>
<thead>
<tr>
<th>Joinery Fitting</th>
<th>Estimated Cost of Accelerated Activity</th>
<th>R14 551, 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adjusted Cost of Accelerated Activity</td>
<td>R15 301, 40</td>
</tr>
<tr>
<td><strong>Unforeseen Impact on Cost</strong></td>
<td><strong>R750, 30</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Painting**  The final step that needs to be taken in ensuring the project meets it’s completion date is the acceleration of the activity *painting*. This activity has a duration of 60 days. In

---

13The study by Adrian [1987] would have an equivalent productivity loss of 9-11%
5.3. Quantifying the Changes

To reduce the duration of this activity by one day, the contractor decides to add a four-hour shift to the first two days of the activity. This means that the % shift work is equal to 1.67% \( (8/480) \). Therefore, according to Algorithm 5.1, there will not be any delay caused by this acceleration. The equation suggests that there is an increase in productivity. As such there will be no unforeseen expenses associated with this acceleration measure.

5.3.3.2 Summary of Roof Height Change

The three acceleration measures associated with this change will have a significant impact on the project. The changes to the roof activities resulted in the following delays:

- Roof activities acceleration - 10 hours
- Joinery acceleration - 6 hours
- Painting acceleration - 0 hours

The final project completion date will be the 25th of October, 4 days later than originally planned. This may be attributed to the unforeseen secondary and cumulative impacts of change. The subsequent delay needs to be made up by the contractor. The summarised costs of this change are listed in Table 5.13. This would be displayed visually as represented by the BIM model view in Figure 5.13.

Although the completion date of the project is the same as the completion date after the revised productivity had been calculated for the previous change (25th of October), the cumulative impact of change manifests in this change as the additional acceleration required for the activities Joinery Fittings 1st Fix and Painting. If this change was to be quantified independently of the other changes, only acceleration of the roofing activities would be required to return the project to the original estimate. Therefore, the additional costs of accelerating Joinery Fittings 1st Fix and Painting are costs associated with the cumulative impact of change.

<table>
<thead>
<tr>
<th>Unforeseen Losses</th>
<th>Unforeseen Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Trusses and Coverings</td>
<td>R1 207, 61</td>
</tr>
<tr>
<td>Joinery Fitting</td>
<td>R750, 29</td>
</tr>
<tr>
<td><strong>Total Unforeseen Impact on Cost</strong></td>
<td><strong>R1 957, 90</strong></td>
</tr>
</tbody>
</table>
5.3. Quantifying the Changes

Figure 5.13: Revit Output for the Quantification of the Change in the First Floor Slab Dimensions of House Smart.
5.4 Summary of the Changes

This case study demonstrated the use of the decision making process identified by Lee [2007] and that BIM is a tool that will allow a contractor (or quantity surveyor) easy access to a variety of studies quantifying different productivity factors.

The case study made use of the quantification studies for overtime, overmanning, and shift work. The case study also briefly touched upon the use of the linear learning curve model developed by Wright [1936] and how productivity may increase during an activity, and the subsequent loss of productivity when there is a disruption in the activity.

Although the studies quantifying the impact of weather on labour productivity were not used in this case study, they may be applied in a similar manner to the other productivity factors. The productivity factor results from each study will be available in the appendix for comparison. The results of this study will need to be validated by industry professionals.

The case study used BIM as a tool to facilitate quantifying the cumulative impact of change. This allows the contractor to account for the unforeseen costs in construction and make the necessary claims so that there are no unnecessary losses incurred. Alternatively, the contractor may use the tool to manage the changes. Table 5.14 summarises the unforeseen costs of each change, showing the total unforeseen cost to be R9 171, 08. Without this tool for quantifying the impact of change, this is a cost that the contractor would have to bear.

**Table 5.14: Summary of the Unforeseen Losses for the Case Study.**

<table>
<thead>
<tr>
<th>Unforeseen Losses</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>House Width Change</td>
<td>R1 144, 00</td>
</tr>
<tr>
<td>Slab Dimension Change</td>
<td>R6 069, 18</td>
</tr>
<tr>
<td>Roof Height</td>
<td>R1 957, 90</td>
</tr>
<tr>
<td><strong>Total Unforeseen Impact on Cost</strong></td>
<td><strong>R9 171, 08</strong></td>
</tr>
</tbody>
</table>

To put this into perspective, the total labour costs for the changes made to this project totalled R152 575, 89. Therefore, the unforeseen costs due to the impact of change on labour productivity are approximately 6% of the total labour cost of the affected activities. Although R9 171, 08 may not seem like a large amount, this is a relatively simple project. For larger construction projects that have more changes, the monetary value of 6% of the labour costs may be a large value. It must also be noted that this amount does not include the penalties for late hand over of the project, the additional time plant will be needed on site, nor does it include the extra P&G (Preliminary and General) associated costs for the delays. Additionally, this unforeseen amount that the contractor will need to claim for includes the cumulative impact of change. Calculating
each change in isolation would have a reduced amount as the delay from the previous change’s productivity losses would not need to be made up.

It must also be noted that the unforeseen costs do not need to be a sum of money that the contractor should claim for. If this tool is used skillfully, the unforeseen costs may be calculated before the project is accelerated. This would allow the contractor to adjust the acceleration measures taken so that there are no additional delays, allowing him/her to manage the impact of a change. Alternatively, the losses due to the impact of change may motivate the client not to institute the change at all.
CHAPTER 6

Validation

6.1 Introduction

Following the development of the proposed BIM (Building Information Modelling) plug-in, it was necessary to validate the model and its application. This chapter will summarise the results of consultations with industry participants on the strengths, weaknesses and applicability of the proposed model. The consultation took the form of a presentation and interview with the industry participants. This was to provide the participants with an overview of the topic and then allow for a critical discussion of the application of the process in the construction industry.

The sample size used in validating the model was relatively small. However, the format of using personal interviews was viewed as being more beneficial than an impersonal email questionnaire. Therefore, the results of the validation process were seen as being more valuable, considering that experienced practitioners were approached. Furthermore, in the event that the validation process obtained similar results from each participant, an increase in the sample size would not yield different results. The sample group consisted of 4 contractors and 1 consultant. All participants worked for different companies. In order to maintain confidentiality, the participants will be referred to as Participant 1 or P1, P2, etc.

6.2 Validation Objectives

The objective of the validation process was to answer the following questions about the BIM approach to quantify the impact of change on labour productivity:

- Is labour productivity considered when quoting a change in construction?
- Do contractors currently understand or have knowledge that the cumulative impact of change exists?
6.3 Methodology

- Would being able to quantify the impact of change on labour productivity add value to the construction industry?
- What criticism is there of the BIM process of quantifying the impact of change on labour productivity?
- What are the positive aspects of the proposed BIM plug-in?
- What recommendations can be made to achieve the successful implementation of the plug-in?
- Would contractors use the proposed BIM plug-in?

6.3 Methodology

This section briefly covers the content of the presentation used to obtain input from industry participants. A presentation of 15 minute duration was made to inform the participants of the research. The presentation briefly identified the differences between direct, indirect, and cumulative impact with the aid of a simple example. The purpose of this was not to create an understanding of the cumulative impact of change, but to demonstrate the need to quantify the impact of change on labour productivity and that one change may have an influence on another.

Following this, the BIM process of quantifying change impacts was briefly described. Subsequently, the main focus of the presentation was the case study. A project description was given and the changes were quantified step-by-step, similarly to the format of Chapter 5. However, as the plug-in has not been coded, the presentation made use of available PowerPoint visual cues to quantify the changes as if the plug-in had already been developed. This was to represent the real life application of the plug-in. The overall results were then presented to the participants in a similar format to Table 5.14.

The presentation demonstrated that the tool may be used to claim for unforeseen losses, to manage change more effectively, or to cancel changes that may have too great an impact on cost and time. Following the presentation, the participants were asked several questions.

6.4 Question Response

Only eight questions were asked of the participants with emphasis placed on the quality of the answers and not the quantity of the answers. This section summarises the responses obtained from participants. The answers will be evaluated in terms of the similarities and differences in the answers between participants as well as the findings from other studies.
6.4. Question Response

The title of the following subsections will be questions asked of the participants.

6.4.1 In your experience, is labour productivity considered when quoting changes?

The first question was used to determine if the construction industry has a need for the plug-in software. By gauging whether labour productivity is considered when quoting changes, it is possible to identify whether there will be a use for the plug-in. The participants were required to answer with a rating from 0 to 5 (0 – not at all; 1 – rarely; 2 – Only if required; 3 – roughly half; 4 – regularly; 5 – always).

This question yielded fairly consistent answers from the participants. All participants bar one of the participants stated that labour productivity is rarely (score of 1) considered when quoting changes. The exception, Participant 1, gave an answer of 2 i.e. only if required.

The consistency in the answers of the participants demonstrates that there is a need in the construction industry for the plug-in to quantify labour productivity.

6.4.2 Were you previously aware of the Cumulative Impact of Change or the indirect impacts of changes?

This question aimed to determine whether the participants already had sufficient knowledge to understand the problem and therefore, give reliable feedback. If a participant was unaware of the cumulative impact of change or the indirect impacts of change, this would imply that the participant may be reluctant to acknowledge the research or the need to quantify the impact of change on labour productivity. Table 6.1 lists the results from the participants for this question.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Yes</td>
</tr>
<tr>
<td>P2</td>
<td>Yes: Understood, but ignored as engineer as it may be the job of the QS</td>
</tr>
<tr>
<td>P3</td>
<td>Yes</td>
</tr>
<tr>
<td>P4</td>
<td>Yes, but not aware of the various studies</td>
</tr>
<tr>
<td>P5</td>
<td>Yes</td>
</tr>
</tbody>
</table>

From the results it is clear that the majority of the participants were aware of the cumulative or indirect impact of change on labour productivity. Therefore, the feedback from the participants on later questions will be valuable to the research.
6.4.3 Following the presentation, do you see value in quantifying the indirect and cumulative impact of changes?

This question is a step towards validating the model for use in the industry. By confirming or denying the value that quantifying the impact of change on labour productivity would have in the construction industry, would determine if there is a need for the plug-in to be developed further.

Once again, all participants had fairly consistent answers. The majority of participants agreed that there is value in quantifying the impact of change on labour productivity. Several of the participants also added comments with regards to challenges and recommendations of quantifying the indirect and cumulative impact of change. The participants also made comments that confirmed the previous research chapters of this study. The results from this question are displayed in Table 6.2.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Yes. It can help maximise delay claims and aid in management of resources on site.</td>
</tr>
<tr>
<td>P2</td>
<td>Yes. Using Navisworks as the management tool rather than Revit.</td>
</tr>
<tr>
<td>P3</td>
<td>Yes. It results in unforeseen delays and costs which mostly are only recognised when it is too late.</td>
</tr>
<tr>
<td>P4</td>
<td>Yes. However, only when BIM has been fully adopted and the process is fully automated to avoid a large amount of work for a relatively small impact.</td>
</tr>
<tr>
<td>P5</td>
<td>Yes. This will lead to a more objective review on cost as opposed the the current JBCC approach.</td>
</tr>
</tbody>
</table>

6.4.4 Do you use BIM on your projects?

This question was to determine whether the participants had adopted BIM and subsequently, whether they would be able to understand and benefit from the plug-in. It is also used, in conjunction with the next question asked to determine if one of the aims of the study was achieved: Identify the capability of BIM to promote the use of BIM in the South African Construction Industry.

The replies from this question showed that the sample varied in terms of their current use of BIM. Scores from 0 to 5 were obtained to reflect the usage of BIM on project. The results are displayed in Table 6.3. The sample is not a reflection of the construction industry as a whole. However, even in a small sample, there was a varied response. Due to the variety of the answers

\[1\] 0 – not at all; 1 – rarely; 2 – only if required; 3 – roughly half; 4 – regularly; 5 – always
to this question, it will be possible to validate the research if all participants found the plug-in useful, regardless of their current BIM adoption.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2 - Only if required</td>
</tr>
<tr>
<td>P2</td>
<td>5 - Always</td>
</tr>
<tr>
<td>P3</td>
<td>1 - Rarely</td>
</tr>
<tr>
<td>P4</td>
<td>1 - Rarely</td>
</tr>
<tr>
<td>P5</td>
<td>4 - Regularly</td>
</tr>
</tbody>
</table>

**6.4.5 Would you consider using the proposed BIM plug-in?**

Considering the diverse response from the previous question, the answers obtained for this question show the success of the project. Once again, the participants were asked to give a score from 0 to 5 for the likelihood of using the proposed BIM plug-in. The answers obtained are displayed in Table 6.4. Consequently, it has been found that the BIM plug-in will be useful in the construction industry regardless of the participants current level of BIM implementation.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4</td>
</tr>
<tr>
<td>P2</td>
<td>Such a plug-in would be better in Navisworks as opposed to Revit.</td>
</tr>
<tr>
<td>P3</td>
<td>4</td>
</tr>
<tr>
<td>P4</td>
<td>Yes, if automated</td>
</tr>
<tr>
<td>P5</td>
<td>4</td>
</tr>
</tbody>
</table>

**6.4.6 List all criticism you may have for the proposed method of quantifying change impact**

In order to make recommendations for the proposed plug-in, it is necessary to determine what limitations the program may have. Participants were asked to present all criticism of the model, which is presented in Table 6.5.

One of the main criticisms listed by the participants was the use of Revit as the main program through which the plug-in will run. Suggestions were made of integrating the plug-in across other platforms, specifically, using Navisworks.

---

20 – Strongly Disagree; 5 – Strongly Agree
6.4. Question Response

Table 6.5: Contractor Response: Question 6 Results

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>The challenge will be in getting the consultants/clients to agree with the basis of the cost calculations.</td>
</tr>
<tr>
<td>P2</td>
<td>Your contractor’s QS will not grasp the theory well enough to use or prove it in Revit. Navisworks could prove the theory much easier.</td>
</tr>
<tr>
<td>P3</td>
<td>-</td>
</tr>
<tr>
<td>P4</td>
<td>It looks like it is a lot of effort. A challenge is getting it integrated into cost estimation packages. Until fully automated, other methods may exist that are easier.</td>
</tr>
<tr>
<td>P5</td>
<td>Need to verify the method as well as define the factors more substantially. The model does not address how specialist sub-contractors will affect calculations.</td>
</tr>
</tbody>
</table>

Some of the participants also mentioned that the process may include extra effort, and factors (overmanning, congestion, etc.) need to be explained. This could have been as a result of the short presentation which did not cover some of these topics. The tool is also meant to be user friendly and requires as little input from the contractor as possible.

Furthermore, a challenge with be obtaining acceptance from the client or consultant. The response implies that either there will be uncertainty with the validity of the information in the study, the process of quantifying the change, or that the contractor has selected the appropriate study. Selecting the appropriate study is somewhat subjective. However, it can be assumed that a competent person will have the necessary knowledge and experience to make the correct decision.

The responses to this question show that although all participants would use the proposed plug-in, there is a need to develop the model further to mitigate the challenges faced.

6.4.7 List any positive aspects you may have from the presentation

To determine whether the concept of quantifying the impact of change on labour productivity was understood, as well as to find what each participant obtained from the presentation, the participants were asked to list the positive aspects from the presentation.

The results from the question are presented in Table 6.7.

The participants noted that it is a tool, not only to claim for losses, but to be used for management in communication and collaboration across a project. The participants were all previously aware of the cumulative impact of change, however, the topic of labour productivity is viewed as somewhat subjective. Therefore, the research is recognised for the benefit of creating an objective and scientific method for calculating the losses due to changes.
6.4. Question Response

Table 6.6: Contractor Response: Question 7 Results

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Also a management tool</td>
</tr>
<tr>
<td>P2</td>
<td>Great to see good use of Revit being made and also the use of BIM to communicate and collaborate</td>
</tr>
<tr>
<td>P3</td>
<td>It has made me think about aspects that I intuitively am aware of</td>
</tr>
<tr>
<td>P4</td>
<td>It is a good idea to provide objective and scientific basis for productivity loss estimation. I think it is a variable often not considered due to the perceived subjectivity of it. The use of BIM will likely eventually make its calculation easy and more widely accepted as standard</td>
</tr>
<tr>
<td>P5</td>
<td>It is a very good approach to using BIM for integrating a construction related matter (changes) with the design model in REVIT. I believe it will be a very good tool to visually demonstrate to Clients &amp; consultants the impact of changes on the construction process</td>
</tr>
</tbody>
</table>

6.4.8 List any recommendations you may have for the proposed method of quantifying change impact

The final question asked was to obtain professional input and guidance for how the model should be developed.

Table 6.7: Contractor Response: Question 8 Results

<table>
<thead>
<tr>
<th>Participant</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>-</td>
</tr>
<tr>
<td>P2</td>
<td>Further testing is required to develop the tool. It would be much more appropriate to develop the tool in Navisworks as a QS tool with the collaboration of other disciplines.</td>
</tr>
<tr>
<td>P3</td>
<td>-</td>
</tr>
<tr>
<td>P4</td>
<td>The model must still be able to work in an environment of imperfect information and consider the cumulative impacts. When choosing studies, the viewing tables presented should be shortlisted to display only the recommended studies for the project type.</td>
</tr>
<tr>
<td>P5</td>
<td>The method needs more explaining as to how the costs are calculated so that they may be proven. Navisworks would be better for the development of this tool.</td>
</tr>
</tbody>
</table>

Once again, the participants recommended that the plug-in be developed as a Quantity Surveying (QS) tool in Navisworks. Another key point mentioned was that the process relies on the contractor having all the necessary information to complete the analysis. In practise, this is often difficult to achieve and the contractor may not have control over specialist subcontractors. It was, therefore, recommended that the process performs calculations on the information that is available, rather than ending the process when not enough information is present. This is to take
into account that the construction industry is often an environment of imperfect information.

6.5 Chapter Summary

The validation of the process quantifying the cumulative impact of change through BIM involved consultation with six industry participants. Five of the participants were contractors, with the exception of one consultant, with varying knowledge and current use of BIM. All of the participants had some knowledge of the cumulative impact of change, however, consensus was reached that the factors affecting labour productivity are rarely considered when quoting changes. Although this study only considered a small sample of participants, the results were valuable. Experienced practitioners were approached to obtain the best results. Furthermore, the participants were in relative agreement with the questions asked. Therefore, increasing the sample size would probably not have yielded significantly different results.

Following the presentation, the participants validated the model by confirming the model’s role as a management tool. The participants highlighted that the plug-in may be used to visually communicate and collaborate amongst project parties. The process was also recognised as an objective and scientific approach to quantifying the impact of change on labour productivity, as opposed to the current subjective means of analysing labour productivity.

However, the model was criticised for the platform in which it was presented i.e. using Revit. Participants generally believed the tool to be of more use as a QS tool to be used through Navisworks. This criticism may be disregarded to some extent as the concept behind calculating the unforeseen labour costs was valued by the participants. The final development of the model may use different software packages that are more relevant to the users.

Some issues were pointed out with regards to the ease of use and the automation of the process. However, as the process is still in early development, it will be a goal to make the process as user friendly as possible. The final issue of concern is the validity of the productivity factors used in calculations and the method of calculating costs. It was mentioned in the validation that it is potentially difficult to get acceptance from the client or consultant. Therefore, more testing is required to fully develop the model as a tool that will benefit the industry.

Nevertheless, the participants agreed that it is a tool that they would use once the challenges have been corrected. This validates the model and the research as a manner in which more contractors may benefit from the use of BIM.
CHAPTER 7

Conclusion

7.1 Introduction

The research question addressed in this investigation was if it is possible to use BIM to manage the unforeseen impacts of multiple V.Os? Similarly, can BIM be practically applied to this problem to quantifiably measure the cumulative impact of change?

The research aimed to identify causes and trigger events of the cumulative impact of change so that a relationship may be developed to better predict the cumulative impact. It was an aim of this research to identify the capability of BIM in managing the cumulative impact of change.

7.2 Results from the Investigation

Understanding BIM  Many definitions for Building Information Modelling (BIM) exist. However, it is still difficult to define BIM in a manner that includes all features of BIM. As such, BIM may be viewed as an activity of adding information to a model and/or model elements throughout the life cycle of a project. By adding information to a model, it will be possible to better manage a project compared to traditional 2D drawings or 3D CAD (Computer Aided Drafting).

Furthermore, each project participant may benefit from implementing BIM. These benefits include:

1. improved coordination
2. increased productivity
3. improved communication
4. improved quality control
7.2. Results from the Investigation

These benefits were identified in Chapter 2 (Section 2.7.6) as factors affecting the cumulative impact of change. However, there are risks inherent with implementing BIM. Several of the issues inhibiting the implementation of BIM in the construction industry include:

1. human factors
2. program compatibility
3. legal concerns
4. cost of BIM software

Nevertheless, it is evident from research that the benefits of BIM outweigh the risks. Many of the risks may be mitigated adding to the value of BIM. As a result, BIM is a tool that may benefit the South African Construction industry. In order to illustrate how the construction industry may benefit through BIM and this research, Autodesk’s Revit was be used as the means for presenting the conceptual process of quantifying the cumulative impact of change.

**The Cumulative Impact of Change**  Historically, the cumulative impact of change was legally recognised in 1967 by the abolishment of the Rice doctrine (Jones 2001). Subsequently, research has attempted to define and predict the cumulative impact of change. However, the synergistic effect of multiple variation orders and the subsequent impact on labour productivity remains relatively unforeseen by contractors (Ibbs and McEniry 2008). This may be attributed to the gap between academia and practise (Rynes, Bartuneck, and Daft 2001).

Labour productivity is continually changing during a project due to a vast number of external and internal factors. Not only will variation orders effect changed work, but together, variation orders may result in a loss of productivity on unchanged work (Neff and Wium 2014). This leads to delay and disruption events that prevent a contractor from completing work as planned, at an increased project cost.

Lee (2007) created an expanded disruption cycle model in an attempt to identify the relationships between productivity factors (Figure 3.12). The model by Lee (2007) was also an attempt to reduce redundancy and synthesise multiple researchers’ definitions of various productivity factors.

However, due to time constraints, it was not possible to quantify all of the factors given in the expanded disruption cycle model. Therefore, only six of these factors were analysed for quantification in this investigation.
Quantifying the Cumulative Impact of Change  Chapter 3 identified that, in the United States of America, the abolishment of the Rice doctrine legalised claims for the cumulative impact of change. However, it needed to be determined whether South African building contracts allow for claims against the cumulative impact of change. By analysing the General Conditions of Contract for Construction Works (GCC), the Joint Building Contracts Committee (JBCC) and the New Engineering Contract (NEC), it was found that while the contracts do allow some provision for claims against the cumulative impact of change, it is the NEC document that acknowledges the effect a change has on unchanged work. For that reason, it is recommended when considering the cumulative impact of change, the NEC contract be used as the quotation of a change involves collaboration between the contractor and project manager. This also demonstrates that the development of a method of quantifying the impact of change on labour productivity in South Africa will add value to the industry.

Existing methods of quantification were then analysed. Subsequently, a decision making process by Lee (2007) was used as the basis for the development of a BIM plug-in to quantify the impact of change on labour productivity. The process to be followed in quantifying the effect of change on labour productivity entails the contractor being guided to a specific study. The specific study will then have results showing how a productivity factor may be calculated. BIM plays an important role in providing the contractor with access to the study information that would have previously been unknown to the contractor. Thereby, reducing time and, to some extent, automating the process of quantifying the impact of change on labour productivity.

Case Study  Chapter 5 was used to demonstrate the BIM process of quantifying the impact of change on labour productivity. A case study was analysed whereby changes on a project were quantified.

The subsequent unforeseen costs due to the cumulative impact of change were approximately 6% of the labour costs for the activities. The project was also delayed by an unforeseen four days. For large projects, if this 6% increase in cost is unaccounted for, the contractor’s profits may be reduced substantially. Furthermore, for projects that incur a greater number of changes, it can be assumed that the unforeseen costs associated with the cumulative impact of change may be greater than 6% of the activity labour costs.

It must also be noted that the unforeseen losses calculated in this study only refer to the labour costs. Therefore, the contractor can expect the delays to result in additional increased P&G (preliminary and general) costs as well as other overheads such as plant hire. The updated project program will allow for the calculation of the additional P&G costs as P&Gs are dependant on a monthly rate.

The case study and application of BIM in quantifying the cumulative impact of change needed to
be verified in order to determine if the results obtained and process developed reflected the real life construction industry. The process was validated by consulting with industry participants. Although a small sample group was used, the group consisted of experienced professionals. Furthermore, the format of using personal interviews was viewed as being more beneficial than an impersonal email questionnaire. The results from the validation were fairly consistent. Users from varying BIM backgrounds had common thoughts on the BIM plug-in.

The plug-in was mainly criticised for the software package in which it was presented (i.e. Autodesk Revit). Contractors would benefit more if the main programme ran in Navisworks. Additionally, it was suggested to be a QS (quantity surveying) tool.

Acceptance of the productivity factors was also of concern. Some believed that the model would require further live testing in order to increase acceptance of the process by the client or consultant.

Nevertheless, the participants agreed that it is a tool that they would use once the challenges have been corrected. The BIM process was identified as a beneficial management tool that may increase communication and collaboration on a project. This validates the model and the research as a manner in which more contractors may benefit from the use of BIM.

7.3 Conclusion

This thesis achieved its stated objectives by presenting the definitions of the direct, indirect and cumulative impact of change.

The study investigated delay and disruption events triggered by the cumulative impact of change. Several models and processes were discovered both qualitatively and quantitatively calculating the impact of change. Furthermore, lists of productivity factors were compiled. The literature from many sources was used to investigate the subsequent productivity factors associated with delay and disruption events.

From the numerous productivity factors, six were quantified using a process similar to that defined by Lee (2007). The quantification method that was found was adapted and conceptually implemented in a BIM process.

The proposed BIM solution used software packages such as Autodesk Revit, Navisworks, and Microsoft Project. A brief literature study was conducted focusing on the advantages and disadvantages of BIM, as well as the potential a BIM plug-in may have in quantifying the impact of change on labour productivity.

The subsequent BIM model was validated by industry participants. The participants identified
possible challenges to the proposed model, however, it was found useful.

BIM can be used to manage the unforeseen impacts of multiple variation orders and quantify the time and cost impacts variation orders have on productivity.

The cumulative impact of change is known or understood by contractors. However, there is not enough information to quantify these impact or they are not quantified due to the subjectivity of the process.

The value of the BIM plug-in is in proving added costs due to variation orders and changes. Using BIM as a platform to deliver contractors information that allows for the objective and scientific quantification of changes will be beneficial for the construction industry.

It must also be noted that the unforeseen costs do not need to be a sum of money that the contractor should claim for. If this tool is used skillfully, the unforeseen costs may be calculated before the project is accelerated. This would allow the contractor to adjust the acceleration measures taken so that there are either less, or no additional delays. Alternatively, the losses due to the impact of change may motivate the client not to institute the change at all.

Industry professionals have recognised the value that the proposed plug-in may have. However, there is need for further work in order to perfect the tool and maximise the benefits gained from implementing BIM.
CHAPTER 8

Recommendations

With the goal of developing this tool into a real life, operable plug-in, the following recommendation are suggested.

8.1 Study Selection

The studies presented for the quantification of productivity factors contain much information that may cause confusion when selecting the appropriate study. The list of studies presented to the users of the plug-in will need to be altered to become more user friendly. In addition to this, a filter or shortlist should be present when the user selects a study. This implies obtaining input from the user with regards to the type of project or schedule requirement of the project. The plug-in should then generate a shortlist of studies that fit the project requirements.

A similar recommendation to the previous point concerns the acceptability of the calculations and studies used. When selecting a study, the contractor should be required to add motivation for selecting the study. This will aid in determining if the user was competent and whether they used the model correctly, as opposed to using the plug-in to try and maximise profits.

8.2 Validity of Data

The results of studies which can be used to quantify the impact of change on labour productivity should be submitted with the project tender documents. The purpose of this is to gain acceptance from the client prior to the actual quantification. This implies that the client will need to accept the studies or databases provided on condition that the contractor does not use the studies for malicious intent.

Ideally, this tool will be used by contractors that have access to sufficient project information. In order to gain maximum benefit from the plug-in, contractors should record their own produc-
tivity information for specific tasks or activities. Therefore, instead of trying to find the most appropriate study, the contractor may use data that represents their specific work practise. As clients may be unwilling to trust such data, the project information and productivity data used to formulate the database will need to be published and criticised. Additionally, the findings may require external auditing. Contractors should also be able to simulate different productivity losses (or use various studies) to determine if the project is sensitive to changes in labour productivity. This may negate the need for highly accurate data and allow the contractor to see the influence of changes in productivity.

However, the main assumption that the method relies on is that the contractor has access to all of the information necessary to perform the analysis. It was identified in the validation process that perfect information is rare in construction. Further development of the model should allow for the analysis to be performed in an environment of imperfect information. In addition to this point made, it is also advised that addition research perform a sensitivity analysis to determine what impact a change of productivity has on the project schedule. This will allow the model user to identify where more accurate data is needed and what studies/quantification results have more of a tolerance to allow for imperfect information.

8.3 Further Development

This research viewed the plug-in as a tool for contractors, however, contractors often work closely with specialist subcontractors. Further model development should include subcontractors and the additional requirements that may be needed.

Additionally, it was identified in the validation process that the tool may be more beneficial for quantity surveyors. Therefore, market research is required to determine the extent to which quantity surveyors, contractors, consultants, or other parties may use the plug-in. Furthermore, it was also identified that both contractors and quantity surveyors would benefit more if the plug-in was designed in Autodesk Navisworks. Navisworks was identified as the primary BIM tool of contractors and features such as the Planner tool in Navisworks may work in conjunction with the proposed plug-in.
References


REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


[94] SAICE (2010). General conditions of contract for construction work. South African Institute of Civil Engineers (SAICE).


REFERENCES


APPENDIX A

NEC Compensation Events

A.1 Introduction

The description of NEC compensation events is located in the appendix of this report as it is pertinent to the research, however, it is not the main focus of research. The investigation into NEC compensation events was performed as a background of understanding of the contract and how a contractor may claim for losses should a compensation event occur.

The information from this section is obtained from either the NEC Engineering and Construction Contract (NEC3 2005) or the NEC Engineering and Construction Contract Guidance Notes (NEC 2013). The NEC Engineering and Construction Contract (ECC) lists 19 possible compensation events under clause 60.1 (1-19). These compensation events are listed as follows:
A.2 Procedure for Compensation Events

Chapter 6 (clauses 60 – 65) of the NEC states the general guidelines for dealing with change on a project. Once the compensation events (Clause 60.1) have been identified, notification must be given to either the contractor or the project manager, depending on where the CE arises from.

A.2.1 Notification

If the compensation event arises as a result of the actions of the project manager or the supervisor, the project manager must notify the contractor at the time of the communication (clause 61.1). Alternatively, if the contractor believes that an event will become a compensation event, or if the project manager has not yet notified the contractor of the event, the contractor has eight weeks to notify the project manager. If the contractor takes longer than eight weeks, the contractor will not be entitled to a change in price, completion date, or any key date. The exception to this is if the event arises directly from instruction of the project manager or supervisor.

Although not all of the listed compensation events will arise from V.Os, these will be referred to in assigning responsibilities for the delay and disruption events identified in the Systematic Overview of the Cumulative Impact for Change, provided in Chapter 2.
A.2. Procedure for Compensation Events

Upon notification by the contractor, the project manager checks the following to determine if the compensation event is valid:

1. If the CE arises from a contractor fault
2. Has not happened or is not expected to happen
3. Has no effect on the cost, completion or meeting a key date
4. Is not one of the CE events of clause 60.1

If the event meets any of these requirement, the project manager will notify the contractor that there will be no change to the completion date, pricing, or key dates (clause 61.4). Alternatively, if the compensation event is valid, the project manager must notify the contractor one week after the original notification from the contractor. The time period could be extended, with agreement from the contractor, in special circumstances. Additionally, if the project manager does not reply to the contractor within two weeks, it is assumed that the compensation event is accepted and the contractor should submit proposals (clause 61.4).

A.2.2 Quotation

The NEC recommends a collaborative approach between the project manager and the contractor in determining the appropriate way of dealing with the compensation event (clause 62.1). The contractor will then submit quotes for methods recommended by the project manager as well as other methods that the contractor think practicable (clause 32.1). This should be done within three weeks of being notified to do so by the project manager (clause 62.3). The quotations submitted by the contractor include changes to completion and keys dates, as well as prices. Furthermore, the contractor may include alterations to the original program if the remaining (unchanged) work is altered (clause 62.2). The project manager may then accept a quotation or explain to the contractor reasons for the need of a revised quotation. The project manager has two weeks to do this and the contractor will have a further three weeks to submit the revised proposal (clause 62.3 and 62.4). If the project manager does not reply within the two weeks allocated, the contractor may notify the project manager of the recommended method and it will be treated as an acceptance of the method (Clause 62.6)

A.2.3 Assessment

Any changes to the prices are assessed as the effect that the compensation event has on the actual cost of work already performed, the defined cost of work still to be performed, as well as
the resulting fee for completing the works (clause 63.1). The date that divides the work done from the work yet to be completed is the date for which instruction was given by the supervisor or project manager to change the works information, or the date that the notification was given of the compensation event (clause 63.1).

Included in the time and cost assessment of the compensation event are the risk allowances for the contractor that have a significant chance of occurring (clause 63.6). The assessments are based on the assumptions given to the contractor by the project manager (clause 61.1), as well as the assumption that the contractor is competent and reacts promptly to the compensation event (Clause 63.7).

The project manager will in turn assess the compensation event if the contractor has not submitted a quotation, the submitted quotation is believed to be incorrect, if there is no updated programme submitted with the compensation event, or if the project manager has not accepted the contractor’s most recent programme (clause 64.1). However, if several compensation event occur within a short space of time, it is not reasonable to expect the contractor to submit a revised proposal for all of them. Instead, all compensation events notified within a month may be grouped in one revised program (clause 62.2).

An important feature of the NEC contract is stated in clause 65.2, whereby the clause states “the assessment of a compensation event is not revised if a forecast upon which it is based is shown by later recorded information to have been wrong”. This demonstrates the finality of the assessment. Although the contractor may provide a contingency for the cumulative impact of change in the quotation, it cannot be changed once the quotation is finalised. It is, therefore, important that a tool be developed to predict the cumulative impact of change.
Productivity Factors from Quantification Studies

This chapter of the report lists the results of available studies that quantify different productivity factors. However, not all of the studies previously mentioned in the report are available here. Certain studies require specific information to populate the results. As such, studies showing general results are listed. For the other studies, the reader is required to consult the original sources.

B.1 Overtime Studies

B.1.1 Kossoris (1947)

The study by Kossoris (1947) uses the change in work hours to calculate a change in productivity. Figure B.1 displays the results of the study in which the initial work hours were increased by the hours in the day, the number of days worked in a week, or both. From this table, the contractor may select the appropriate output ratio. An output ratio of 0.66 means that 3 hours are needed to perform 2 hours worth of work.
B.1. Overtime Studies

B.1.2 O'Connor (1969)

Figure B.2 displays the results from the study by O'Connor (1969). The results show the efficiency of work as a percentage of "normal" productivity for varying work schedules.
B.1.3 Howerton (1969)

Figure B.3 displays the results from the study by Howerton (1969). The results show the decrease in the efficiency of work as a percentage for varying work schedules over different periods of time.

![Table of efficiency loss percentages for different schedules and periods.]

Figure B.3: Howerton (1969)
B.1.4 Smith (1975)

Figure B.4 displays the results from the study by Smith (1969). The results show the decrease in the inefficiency of work as a percentage for a 5 and 6 day week with 10 hours worked per day.

<table>
<thead>
<tr>
<th>Week</th>
<th>Inefficiency Factor for Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6--10</td>
</tr>
<tr>
<td>1</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.152</td>
</tr>
<tr>
<td>6</td>
<td>0.165</td>
</tr>
<tr>
<td>7</td>
<td>0.181</td>
</tr>
<tr>
<td>8</td>
<td>0.198</td>
</tr>
<tr>
<td>9</td>
<td>0.215</td>
</tr>
<tr>
<td>10</td>
<td>0.23</td>
</tr>
<tr>
<td>11</td>
<td>0.244</td>
</tr>
<tr>
<td>12</td>
<td>0.257</td>
</tr>
<tr>
<td>13</td>
<td>0.569</td>
</tr>
<tr>
<td>14</td>
<td>0.28</td>
</tr>
<tr>
<td>15</td>
<td>0.286</td>
</tr>
<tr>
<td>16+</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Figure B.4: Smith (1969)
B.1.5 NECA (1962, 1969, 1989)

Figure B.5 displays the results from the study by Association (1962). The contractor will be able to select different work schedules for sporadic or continuous overtime. The relative productivity of the work schedule is then given as a percentage of normal productivity.

<table>
<thead>
<tr>
<th>Sporadic Overtime Implementation</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled Days</td>
<td>Scheduled Hours</td>
<td>Actual Extended Hours</td>
<td>Productivity (%)</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>10</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>11</td>
<td>95</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>12</td>
<td>92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sporadic Extended Weeks</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled Days</td>
<td>Scheduled Hours</td>
<td>Productivity (%)</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>98</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Continuous Extended Weeks</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled Days</td>
<td>Scheduled Hours</td>
<td>Productivity (%)</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>78</td>
</tr>
</tbody>
</table>

Figure B.5: Association (1962)

Figure B.6 displays the results from the 1969 study by NECA (National Electrical Contractors Association). The results show the efficiency loss of work as a percentage for a 6 and 7 day week with various hours worked per day.
### Figure B.6: Association 1969

<table>
<thead>
<tr>
<th>Work Days</th>
<th>Weekly Hours</th>
<th>Hours per</th>
<th>Efficiency Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>54</td>
<td>9</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>12</td>
<td>33</td>
</tr>
<tr>
<td>7</td>
<td>56</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>63</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>10</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>84</td>
<td>12</td>
<td>52</td>
</tr>
</tbody>
</table>

Figure B.6 displays the results from the 1989 study by the NECA. The results show the relative productivity for various work schedules over different periods of time.
### B.1.6 The US Army Corps of Engineers (1979)

Figure B.8 displays the results from the 1979 study by The US Army Corps of Engineers. The results show the relative productivity for various work schedules over different periods of time.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>1</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>5--10</td>
<td>98</td>
<td>86</td>
<td>83</td>
<td>80</td>
<td>77</td>
<td>74</td>
<td>72.5</td>
<td>67.5</td>
</tr>
<tr>
<td>6--9</td>
<td>96</td>
<td>84</td>
<td>81</td>
<td>77</td>
<td>75</td>
<td>72.5</td>
<td>70</td>
<td>64</td>
</tr>
<tr>
<td>6--10</td>
<td>95</td>
<td>79</td>
<td>75</td>
<td>71</td>
<td>67.5</td>
<td>65</td>
<td>61</td>
<td>57</td>
</tr>
<tr>
<td>7--8</td>
<td>90</td>
<td>73</td>
<td>69</td>
<td>65</td>
<td>64</td>
<td>61.33</td>
<td>58.67</td>
<td>56</td>
</tr>
<tr>
<td>5--12</td>
<td>87</td>
<td>70</td>
<td>65</td>
<td>60</td>
<td>57.5</td>
<td>54.67</td>
<td>51.83</td>
<td>49</td>
</tr>
<tr>
<td>7--9</td>
<td>85</td>
<td>67.5</td>
<td>62.5</td>
<td>58</td>
<td>55</td>
<td>52</td>
<td>49</td>
<td>46</td>
</tr>
<tr>
<td>7--10</td>
<td>80</td>
<td>65</td>
<td>60</td>
<td>56</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>6--12</td>
<td>75</td>
<td>60</td>
<td>55</td>
<td>52</td>
<td>49</td>
<td>46.33</td>
<td>43.67</td>
<td>41</td>
</tr>
<tr>
<td>7--12</td>
<td>70</td>
<td>55</td>
<td>50</td>
<td>47</td>
<td>44</td>
<td>41.33</td>
<td>38.67</td>
<td>36</td>
</tr>
</tbody>
</table>

*Figure B.7: Association [1989]*
B.1. Overtime Studies

B.1.7 Blough (1973)

Figure B.8 displays the efficiency of labourers for a 50 and 60 hour work week for different time intervals.
B.1.8 Bromberg (1988)

Figure B.10 displays the results from the study by Bromberg (1988). The results show the efficiency of work for varying work schedules.
B.1.9 Haneiko and Henry (1991)

Figure B.11 displays the decrease over time in productivity of labourers for a 60 hour work week.
B.1. Overtime Studies

127

Figure B.11: Haneiko and Henry (1991) Productivity for a 60 Hour Overtime Week

![Bar chart showing productivity percentages for varying work schedules.]

**Figure B.11: Haneiko and Henry [1991]**

B.1.10 Mechanical Contractors Association of America (1994)

Figure B.12 displays the results from the study by MCAA [1994]. The results show the efficiency of work for varying work schedules.

The study by Hanna and Sullivan (2004) derived the formula found in Figure B.13. The partial results of the formula for varying actual and budgeted overtime hours are given in the table of Figure B.13.
### Lost Efficiency

\[
\text{Lost Efficiency} = -0.0388 + 0.378 \times \text{(OT / Actual)} - 0.378 \times \ln \left(\text{OT/Actual}\right) + 0.832 \times \log(\text{OT/Budgeted}) - 0.0854 \times \text{Industrial}
\]

---

**Figure B.13: Hanna and Sullivan [2004]**

<table>
<thead>
<tr>
<th>OT / Budgeted</th>
<th>OT / Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>0.1</td>
<td>28</td>
</tr>
<tr>
<td>0.15</td>
<td>42.7</td>
</tr>
<tr>
<td>0.2</td>
<td>53.1</td>
</tr>
<tr>
<td>0.25</td>
<td>61.2</td>
</tr>
<tr>
<td>0.3</td>
<td>67.7</td>
</tr>
<tr>
<td>0.35</td>
<td>73.3</td>
</tr>
<tr>
<td>0.4</td>
<td>78.1</td>
</tr>
</tbody>
</table>
The table in Figure B.14 displays the productivity of work for different weekly work loads based on the size (total hours) of a project.

<table>
<thead>
<tr>
<th>Actual Work Hours</th>
<th>32</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
</tr>
</thead>
<tbody>
<tr>
<td>200000</td>
<td>1.09</td>
<td>1.06</td>
<td>1.02</td>
<td>0.97</td>
<td>0.92</td>
<td>0.88</td>
<td>0.83</td>
<td>0.78</td>
</tr>
<tr>
<td>210000</td>
<td>1.09</td>
<td>1.06</td>
<td>1.02</td>
<td>0.97</td>
<td>0.92</td>
<td>0.87</td>
<td>0.83</td>
<td>0.78</td>
</tr>
<tr>
<td>220000</td>
<td>1.09</td>
<td>1.06</td>
<td>1.02</td>
<td>0.97</td>
<td>0.92</td>
<td>0.87</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>230000</td>
<td>1.09</td>
<td>1.06</td>
<td>1.01</td>
<td>0.96</td>
<td>0.92</td>
<td>0.87</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
<td>240000</td>
<td>1.08</td>
<td>1.06</td>
<td>1.01</td>
<td>0.96</td>
<td>0.91</td>
<td>0.87</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
<td>250000</td>
<td>1.08</td>
<td>1.05</td>
<td>1.01</td>
<td>0.96</td>
<td>0.91</td>
<td>0.86</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
<td>260000</td>
<td>1.08</td>
<td>1.05</td>
<td>1</td>
<td>0.96</td>
<td>0.91</td>
<td>0.86</td>
<td>0.81</td>
<td>0.77</td>
</tr>
<tr>
<td>270000</td>
<td>1.08</td>
<td>1.05</td>
<td>1</td>
<td>0.95</td>
<td>0.91</td>
<td>0.86</td>
<td>0.81</td>
<td>0.77</td>
</tr>
<tr>
<td>280000</td>
<td>1.08</td>
<td>1.05</td>
<td>1</td>
<td>0.95</td>
<td>0.9</td>
<td>0.86</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>290000</td>
<td>1.07</td>
<td>1.04</td>
<td>1</td>
<td>0.95</td>
<td>0.9</td>
<td>0.86</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>300000</td>
<td>1.07</td>
<td>1.04</td>
<td>1</td>
<td>0.95</td>
<td>0.9</td>
<td>0.85</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>310000</td>
<td>1.07</td>
<td>1.04</td>
<td>0.99</td>
<td>0.95</td>
<td>0.9</td>
<td>0.85</td>
<td>0.8</td>
<td>0.76</td>
</tr>
<tr>
<td>320000</td>
<td>1.07</td>
<td>1.04</td>
<td>0.99</td>
<td>0.94</td>
<td>0.9</td>
<td>0.85</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>330000</td>
<td>1.06</td>
<td>1.04</td>
<td>0.99</td>
<td>0.94</td>
<td>0.89</td>
<td>0.85</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>340000</td>
<td>1.06</td>
<td>1.03</td>
<td>0.99</td>
<td>0.94</td>
<td>0.89</td>
<td>0.84</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>350000</td>
<td>1.06</td>
<td>1.03</td>
<td>0.98</td>
<td>0.94</td>
<td>0.89</td>
<td>0.84</td>
<td>0.79</td>
<td>0.75</td>
</tr>
<tr>
<td>360000</td>
<td>1.06</td>
<td>1.03</td>
<td>0.98</td>
<td>0.93</td>
<td>0.89</td>
<td>0.84</td>
<td>0.79</td>
<td>0.75</td>
</tr>
<tr>
<td>370000</td>
<td>1.06</td>
<td>1.03</td>
<td>0.98</td>
<td>0.93</td>
<td>0.89</td>
<td>0.84</td>
<td>0.79</td>
<td>0.74</td>
</tr>
<tr>
<td>380000</td>
<td>1.05</td>
<td>1.02</td>
<td>0.98</td>
<td>0.93</td>
<td>0.88</td>
<td>0.84</td>
<td>0.79</td>
<td>0.74</td>
</tr>
<tr>
<td>390000</td>
<td>1.05</td>
<td>1.02</td>
<td>0.98</td>
<td>0.93</td>
<td>0.88</td>
<td>0.83</td>
<td>0.79</td>
<td>0.74</td>
</tr>
<tr>
<td>400000</td>
<td>1.05</td>
<td>1.02</td>
<td>0.97</td>
<td>0.93</td>
<td>0.88</td>
<td>0.83</td>
<td>0.78</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Figure B.14: Hanna, Chang, Lackney, and Sullivan (2005)
B.2 Congestion Studies

B.2.1 The US Army Corps of Engineers (1979)

Figure B.15 displays the inefficiency of work relative to the percentage crowding experienced on site.

![The US Army Corps of Engineers (1979) Effect of Crowding on Labour Efficiency](image)

**Figure B.15: Corps 1979**

B.2.2 Kappaz (1977)

Figure B.16 displays the productivity multiplier of work relative area per person for a task. The productivity multiplier refers to the amount of time to complete 1 unit of work i.e. a productivity multiplier value of 1.5 means that it will take 1.5 times longer to complete the task.
B.2. Congestion Studies

B.2.3 Smith (1987)

The results from the study by Smith (1987) show how productivity decreases as the area per person on site decreases.
B.2. Congestion Studies

Figure B.17: Smith (1987) Effect of Congestion on Productivity
This chapter lists some of the Bill of Quantities (BOQ) items used in the investigation. Not all items are inserted to save space. Furthermore, in the interest of confidentiality, the rates from the BOQ have been removed. If the reader wishes for more information they may contact the research supervisor.
### BILL NO. 2

**EARTHWORKS (PROVISIONAL)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site clearance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demolish existing house including all brick and concrete paving. Demolitions exclude outbuildings but include garages. See list of item to be salvaged for re-use.</td>
<td>Sum 1</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td><strong>EXCAVATION, FILLING, ETC. OTHER THAN BULK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EXCAVATIONS, ETC.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavation in earth not exceeding 2 m deep and depositing material on a prescribed stock pile on site</td>
<td>m3 68.616</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Trenches. Extra over all excavations for carting away surplus material from excavations and/or stock piles on site to a dumping site to be located by the Contractor.</td>
<td>m3 8.88157</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Risk of collapse of excavations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sides of trench and hole excavations not exceeding 1.5 m deep.</td>
<td>m2 51.462</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Keeping excavations free of water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FILLING, ETC.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backfilling to trenches, holes, etc.</td>
<td>m3 32.43443</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Under floors in layers not exceeding 300 mm thick.</td>
<td>m3 27.3</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Ditto with imported G5 material</td>
<td>m3 27.3</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>coarse river sand filling supplied by the Contractor.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under floors, etc.</td>
<td>m2 182</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Compaction of surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compaction of ground surface under floors etc. Including scarifying for a depth of 150 mm, breaking down oversize materials, adding suitable material where necessary and compacting to 93% Mod. AASHTO density.</td>
<td>m2 182</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL CARRIED TO SUMMARY**

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure C.1:** Earthworks
<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>REINFORCED CONCRETE CAST ON/IN FORMWORK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 MPa/19 mm concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Filling to cavity walls in foundations (Provisional)</td>
<td>m3</td>
<td>9</td>
<td>*</td>
</tr>
<tr>
<td>5 Slabs including beams and inverted beams.</td>
<td>m3</td>
<td>80</td>
<td>*</td>
</tr>
<tr>
<td>6 Isolated beams.</td>
<td>m3</td>
<td>2</td>
<td>*</td>
</tr>
<tr>
<td>8 Columns.</td>
<td>m3</td>
<td>1</td>
<td>*</td>
</tr>
<tr>
<td>Surface beds cast on waterproofing 120mm thick</td>
<td>m3</td>
<td>20</td>
<td>*</td>
</tr>
<tr>
<td>REINFORCED CONCRETE CAST AGAINST EXCAVATED SURFACES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 Mpa/19 mm concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Trenches and bases</td>
<td>m3</td>
<td>20</td>
<td>*</td>
</tr>
<tr>
<td>TEST CUBES (PROVISIONAL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Making and testing 150 x 150 x 150 mm concrete strength test cubes.</td>
<td>No.</td>
<td>30</td>
<td>*</td>
</tr>
<tr>
<td>ROUGH FORMWORK (DEGREE OF ACCURACY 11)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough formwork to sides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Steppings in foundations (Provisional)</td>
<td>m2</td>
<td>2</td>
<td>*</td>
</tr>
<tr>
<td>12 Beams (downstand &amp; upstand)</td>
<td>m2</td>
<td>50</td>
<td>*</td>
</tr>
<tr>
<td>13 Isolated beams.</td>
<td>m2</td>
<td>7</td>
<td>*</td>
</tr>
<tr>
<td>14 Columns.</td>
<td>m2</td>
<td>3</td>
<td>*</td>
</tr>
<tr>
<td>Rough formwork to soffits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Slabs and cantilever slabs</td>
<td>m2</td>
<td>230</td>
<td>*</td>
</tr>
</tbody>
</table>

**Figure C.2:** Concrete
### BILL NO. 4

#### MASONRY

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BRICKWORK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FOUNDATIONS (PROVISIONAL)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brickwork of NFX bricks (14 MPa nominal compressing strength) in Class 2 mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 One brick wall in foundations.</td>
<td>m2</td>
<td></td>
<td>Rate only</td>
</tr>
<tr>
<td>330 mm Hollow walls of two half brick skins including wire ties.</td>
<td>m2</td>
<td>84.17</td>
<td></td>
</tr>
<tr>
<td>2 350 mm Hollow walls in two half brick skins including wire ties.</td>
<td>m2</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>E.O. for sandstone finish to fnld brickwork</td>
<td>m2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>SUPERSTRUCTURE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brickwork of NFP in Class 2 mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Half brick walls.</td>
<td>m2</td>
<td>47.15</td>
<td></td>
</tr>
<tr>
<td>6 Half brick wall four courses high.</td>
<td>m2</td>
<td>20.077</td>
<td></td>
</tr>
<tr>
<td>7 One brick walls.</td>
<td>m2</td>
<td>171.526</td>
<td></td>
</tr>
<tr>
<td>8 Half brick walls in beam filling</td>
<td>m2</td>
<td>15.0578</td>
<td></td>
</tr>
<tr>
<td>9 270 mm Hollow walls in two half brick thick skins including galvanised wire ties.</td>
<td>m2</td>
<td>249.612</td>
<td></td>
</tr>
<tr>
<td>10 350 mm Hollow walls in two half brick thick skins including galvanised wire ties.</td>
<td>m2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>BOE set splayed to form core for window cills</td>
<td>m</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td><strong>BRICKWORK SUNDRIES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Splayed mortar fillets one course high in 50 mm cavity.</td>
<td>m</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Closing 50 mm cavities of hollow walls vertically with brickwork half brick wide.</td>
<td>m</td>
<td>104.4</td>
<td></td>
</tr>
</tbody>
</table>

**Figures:**

- Figure C.3: Masonry
<table>
<thead>
<tr>
<th>Item Description</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof covering as per drawing</td>
<td>Sum 1</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Allow for flashing around 250mm diameter vent pipes</td>
<td>No 2</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Ditto 110mm diameter</td>
<td>No 3</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

**Insulation**

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Quantity</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubblefoil fixed between battens and roof sheeting including straining wires as per drawing</td>
<td>Sum 1</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL CARRIED TO SUMMARY**

|        |        | R     |        |
APPENDIX D

Case Study Floor Plans and Elevations
Figure D.1: Original House Elevation
Figure D.2: Final House Elevation
Figure D.3: Original House Floor Plan
Figure D.4: Final House Floor Plan
Figure D.5: Section Through House Smart