



Libraries and Learning Services

University of Auckland Research Repository, ResearchSpace

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognize the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the [Library Thesis Consent Form](#) and [Deposit Licence](#).

**Developing Leading Safety Indicators for the New
Zealand Construction Industry—
A Systems Thinking Approach**

Brian H.W. Guo

June 2016

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy in Civil Engineering,
the University of Auckland

Thesis Consent Form

This thesis may be consulted for the purposes of research or private study provided that due acknowledgement is made where appropriate and that permission is obtained before any material from the thesis is published. Students who do not wish their work to be available for reasons such as pending patents, copyright agreements, or future publication should seek advice from the Graduate Centre as to restricted use or embargo.

Author of thesis	Brian H.W. Guo
Title of thesis	Developing Leading Safety Indicators for the New Zealand Construction Industry - A Systems Thinking Approach
Name of degree	PhD
Date Submitted	8 June 2016

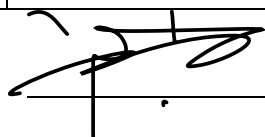
Print Format (Tick the boxes that apply)	
<input checked="" type="checkbox"/>	I agree that the University of Auckland Library may make a copy of this thesis available for the collection of another library on request from that library.
<input type="checkbox"/>	I agree to this thesis being copied for supply to any person in accordance with the provisions of Section 56 of the Copyright Act 1994.

Digital Format - PhD theses
I certify that a digital copy of my thesis deposited with the University is the same as the final print version of my thesis. Except in the circumstances set out below, no emendation of content has occurred and I recognise that minor variations in formatting may occur as a result of the conversion to digital format. Access to my thesis may be limited for a period of time specified by me at the time of deposit. I understand that if my thesis is available online for public access it can be used for criticism, review, news reporting, research and private study.

Digital Format - Masters theses
I certify that a digital copy of my thesis deposited with the University is the same as the final print version of my thesis. Except in the circumstances set out below, no emendation of content has occurred and I recognise that minor variations in formatting may occur as a result of the conversion to digital format. Access will normally only be available to authenticated members of the University of Auckland, but I may choose to allow public access under special circumstances. I understand that if my thesis is available online for public access it can be used for criticism, review, news reporting, research and private study.

Copyright (Digital Format Theses) (Tick ONE box only)	
<input checked="" type="checkbox"/>	I confirm that my thesis does not contain material for which the copyright belongs to a third party, (or) that the amounts copied fall within the limits permitted under the Copyright Act 1994.
<input type="checkbox"/>	I confirm that for all third party copyright material in my thesis, I have obtained written permission to use the material and attach copies of each permission, (or) I have removed the material from the digital copy of the thesis, fully referenced the deleted materials and, where possible, provided links to electronic sources of the material.

Signature



Date

8 June 2016

Comments on access conditions

Faculty Student Centre / Graduate Centre only: Digital copy deposited Signature

Date

Co-Authorship Form

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 3 A Pragmatic Method for Systematically Developing Leading Indicators

The content of this chapter is based on the article:

Guo, B. H.W., Yiu, T., 2015. Developing Leading Indicators to Monitor the Safety

Conditions of Construction Projects. Journal of Management in Engineering, 04015016.

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected and analysed data, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70

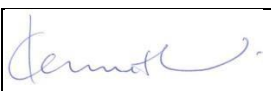
CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He provided guidance on the validation of proposed leading indicators and responses to reviewers' comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Tak Wing Yiu		21/10/2015
		Click here
		Click here
		Click here
		Click here

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 4 Understanding Complexity of Construction Safety

The content of this chapter is based on the article:

Guo, B.H.W., Yiu, T.W., González, V.A., 2015. Identifying behaviour patterns of construction safety using system archetypes. *Accident Analysis & Prevention* 80, 125-141

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected data, drew all archetypes, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70

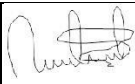

CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He reviewed the original manuscript and offered constructive comments to improve the manuscript. He also provided suggestions as to how to respond reviewers comments.
Vicente A. González	He reviewed the original manuscript and offered constructive comments to improve the manuscript. He also provided suggestions as to how to respond reviewers comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Vicente Gozalez		21/10/2015
Tak Wing Yiu		21/10/2015
		Click here
		Click here
		Click here

Co-Authorship Form

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 5 Monitoring Safety Conditions of a Construction Project Using System Dynamics

Modelling

The content of this chapter is based on the article:

Guo, B.H.W., Yiu, T.W., González, V.A., 2015. Monitoring Safety Risk of Construction Projects Using System Dynamics Modeling. Accident Analysis & Prevention (revised version under review).

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected data, drew all archetypes, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70



CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He reviewed the original manuscript and provided suggestions about how to improve it. He also provided suggestions as to how to respond reviewers comments.
Vicente A. González	He reviewed the original manuscript and provided suggestions about how to improve it. He also provided suggestions as to how to respond reviewers comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Vicente Gonzalez		21/10/2015
Tak Wing Yiu		21/10/2015
		Click here
		Click here
		Click here

Co-Authorship Form

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 6 Predicting Workers' Safety Behaviour

The content of this chapter is based on the article:

Guo, B.H.W., Yiu, T.W., González, V.A., 2016. Predicting Safety Behavior in the Construction Industry: Development and Test of an Integrative Model. *Safety Science*, 84, 1-11.

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected data, drew all archetypes, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70



CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He offered comments on the original manuscript with regard to research aims, sample size, and some other technical issues. He also provided suggestions as to how to respond reviewers comments.
Vicente A. González	He reviewed the original manuscript and provided inputs to improve it. He also provided suggestions as to how to respond reviewers comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Tak wing Yiu		21/10/2015
Vicente A. González		21/10/2015
		Click here
		Click here
		Click here

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 7 Validation of the Integrative Model across Small and Large Construction Companies

The content of this chapter is based on the article:

Guo, B.H.W., Yiu, T.W., González, V.A., 2016. Does company size matter? Validation of a theoretical model of safety climate across small and large construction companies. Submitted to Journal of Safety Research

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected data, drew all archetypes, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70

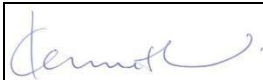

CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He reviewed the original manuscript and provided constructive comments. He also provided suggestions as to how to respond reviewers comments.
Vicente A. González	He reviewed the original manuscript and provided constructive comments. He also provided suggestions as to how to respond reviewers comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Tak wing Yiu		7/06/2016
Vicente A. González		7/06/2016
		Click here
		Click here
		Click here

This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 8 Development and Test of Leading Indicators

The content of this chapter is based on the article:

Guo, B.H.W., Yiu, T.W., González, V.A., Goh Yang Miang, 2016. Using a Pressure-State-Practice Model to Develop Safety Leading Indicators for Construction Projects. Submitted to Journal of Construction Engineering and Management

Nature of contribution by PhD candidate

The PhD candidate was the idea originator. He reviewed relevant literature, collected data, drew all archetypes, and wrote and submitted this paper.

Extent of contribution by PhD candidate (%)

70




CO-AUTHORS

Name	Nature of Contribution
Tak wing Yiu	He reviewed the original manuscript and provided constructive comments.
Vicente A. González	He reviewed the original manuscript and provided constructive comments.
Goh Yang Miang	He reviewed the original manuscript and provided constructive comments.

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Tak wing Yiu		8/06/2016
Vicente A. González		7/06/2016
Goh Yang Miang		7/06/2016
		Click here
		Click here

Abstract

Construction remains one of the top contributors for workplace injuries and fatalities in many countries. Due to the inability of lagging indicators (e.g., accident rates) to provide early warnings of accidents, the development of leading safety indicators has been a topic of increasing concern for both academics and practitioners in recent years. A review of existing leading indicators in the construction industry reveals that they have the following limitations: (1) ambiguous definitions, (2) problematic simplification process, and (3) a lack of development method.

Therefore, the overarching goal of the research is to develop a set of descriptive safety leading indicators that can be used to (1) simplify complex safety phenomena, (2) measure safety performance, and (3) predict the trend in safety. To achieve the goal and address the limitations of existing construction leading indicators, this research first develops a pragmatic method for developing leading indicators, which consists of four steps: conceptualization, operationalization, indicators generation, and validation and revision. The development method provides a systematic process for developing leading indicators.

In order to offer systemic insights into simplification process of complex safety realities, this research then explores the dynamics and complexity of construction safety management at the industry and project level. Eight construction safety archetypes are identified, which capture the common behaviour patterns of construction safety management. In addition, a system dynamics model is developed and simulated to monitor the dynamics of safety level at the project level.

Furthermore, this research develops and tests an integrative model of safety behaviour using structural equation modelling (SEM). The results improve an understanding of safety behaviours shaping mechanisms and thus help to determine leading indicators with predictive validity. The validity of the integrative model is tested across small and large construction companies. Results suggest that the relationships among safety climate factors and safety behavior were equivalent across the two groups.

Finally, a pressure-state-practice (PSP) model is developed to provide an overall framework for developing leading indicators. The safety level of a construction project is conceptualized as a high-level abstract construct that can be assessed by state indicators, pressure indicators, and practice indicators. Criterion validity (i.e., concurrent validity and predictive validity), practicability and cost-effectiveness of the leading indicators were qualitatively tested and supported by the empirical evidence collected from three construction projects.

Overall, the research adds to the body of scientific knowledge of leading safety indicators. It improves the understanding of complexity and dynamics of safety management in the construction industry. In addition, the safety leading indicators developed in this paper provide the construction industry with a promising tool to measure safety performance proactively and facilitate safety assessment.

Acknowledgements

Foremost, I would like to express my sincere gratitude to my main supervisor Dr. Tak-wing Yiu for his continuous support and guidance throughout my PhD journey. I have been fortunate to have a supervisor who gave me the freedom to explore on my own and at the same time provided me with kind encouragement and support. His prompt inspirations and timely suggestions with kindness, enthusiasm and dynamism have enabled me to complete this thesis.

My co-supervisor Dr. Vicente A. González has been always there to listen and give advice. I am deeply grateful to him for his constructive comments and suggestions with regard to almost every aspect of my PhD study. Without his guidance and encouragement, I would have not been able to complete this thesis.

Special appreciation also goes to my advisor Professor Suzanne Wilkinson for her constructive suggestions for this research project. I would like to thank Dr. Alice Chang-Richards, Garry Miller and all other staff of construction management group for their help and support. My sincere appreciation is also given to the staff of the Department of Civil and Environmental Engineering for their helpful assistance: Magdalene Woo, Pervin Suntoke, Santha Pollayah, and Cathrine Taylor.

I would like to express my appreciation to the BRANZ Ltd. (New Zealand) and the Building Research Levy for the financial assistance for my PhD. I would also like to thank Johan Bosch, Russell Parker, Blake Kyle, and Richard Giddings from Site Safe New Zealand for their assistance with data collection. I also would like to thank David Harris and Grant Wilson from Fletcher Construction for their kind help and assistance. My sincere gratitude is also extended to my friends and colleagues: Johannes Dimyadi, Shushu Zhang, Nathaniel Burbery, Mani Poshdar, Danial Qadir, Johnson Adafin,

Sheila Belayutham, Nariman Ghodrati, and Chia Kuang Lee. Special thanks are given to the students who worked with me: Fady Ghanima, Sam Ni, Ting Kwan Chan, Wei Chun Su, and Liqiao Zeng.

Finally, special thanks to my parents, parents-in-law, sister for their patience, support, and unconditional love. My wife Leila Zheng deserves all my appreciation. Her love, patience, and support helped me get through tough times and completed this thesis.

I dedicate this thesis to my beloved daughter, Yiyi Guo.

List of publications for PhD research

Refereed Journal Articles (published)

1. Guo, B.H.W., Yiu, T.W., González, V.A., 2015. Identifying behavior patterns of construction safety using system archetypes. *Accident Analysis & Prevention*, 80, 125-141.
2. Guo, B.H.W., Yiu, T.W., González, V.A., 2015. A System Dynamics View of Safety Management in Small Construction Companies. *Journal of Construction Engineering and Project Management*, 5(4)
3. Guo, B. H.W., Yiu, T., 2016. Developing Leading Indicators to Monitor the Safety Conditions of Construction Projects. *Journal of Management in Engineering*, 32(1) 04015016.
4. Guo, B.H.W., Yiu, T.W., González, V.A., 2016. Predicting safety behavior in the construction industry: Development and test of an integrative model. *Safety Science*, 84, 1-11

Paper submitted for publication in refereed journals

1. Guo, B.H.W., Yiu, T.W., González, V.A., Goh Yang Miang, 2016. Using a Pressure-State-Practice Model to Develop Safety Leading Indicators for Construction Projects. Submitted to *Journal of Construction Engineering and Management*
2. Guo, B.H.W., Yiu, T.W., González, V.A., 2016. Does company size matter? Validation of a theoretical model of safety climate across small and large construction companies. Submitted to *Journal of Safety Research*

Conference Proceedings

1. Guo, B.H.W., 2015. Change Safety Climate. Build,151 December
2. Guo, B.H.W., Yiu, T.W., González, V.A., 2015. A System Dynamics View of Safety Management in Small Construction Companies, The 6th International Conference on Construction Engineering and Project Management, Busan, Korea, October 11-14, 2015 (**Best Paper Award**)
3. Guo, B.H.W., Yiu, T.W., How Traditional Construction Safety Performance Indicators Fail to Capture the Reality of Safety. 38th AUBEA International Conference, Auckland, New Zealand; 11/2013
4. Guo, B.H.W., Yiu, T.W., The Application of Control Theory and Complex Systems Theory to Construction Safety – A Preliminary Study. Research, Development and Practice in Structural Engineering and Construction; 01/2012

Table of Contents

Abstract.....	I
Acknowledgements.....	III
List of publications for PhD research	VI
Table of Contents.....	VIII
List of Figures.....	XVI
List of Tables	XIX
Glossary	XXI
Chapter 1 Introduction	1
1.1 Background	1
1.2 Statement of problem	4
1.3 Research objectives	5
1.4 Scope of the research.....	8
1.5 Research methods.....	8
1.6 Significance of research	11
1.7 Overview of the research.....	12
Chapter 2 The Nature of Leading Safety Indicators	16
2.1 Introduction	16
2.2 Definitions of leading indicators	16
2.3 Purpose, function, and role of leading indicators.....	18

2.4 Essential attributes of leading indicators.....	19
2.5 Debate on leading and lagging Indicators	20
2.6 Application and practices of leading indicators	22
2.6.1 Nuclear power industry.....	22
2.6.2 Chemical process industry.....	24
2.6.3 Oil and gas industry	25
2.6.4 Construction industry.....	26
2.7 Types of leading indicators	29
2.7.1 Event based indicators	30
2.7.2 Barrier based leading indicators	30
2.7.3 Safety practices based leading indicators	31
2.7.4 Safety constructs based leading indicators	31
2.7.5 Limitations of existing leading indicators in the construction industry	32
2.8 Summary	36
Chapter 3 A Pragmatic Method for Systematically Developing Leading Indicators	38
3.1 Introduction	38
3.2 A conceptual framework to develop leading indicators.....	39
3.2.1 An overview of the proposed conceptual framework.....	42
3.3 A proposed development process.....	46
3.3.1 Conceptualization	46
3.3.2 Operationalization.....	47

3.3.3 Indicator generation	48
3.3.4 Validation and revision.....	49
3.4 An application of the development process	50
3.4.1 Conceptualization	50
3.4.2 Operationalization	53
3.4.3 Indicator generation	56
3.4.4 Validation and revision.....	58
3.5 Summary	63
Chapter 4 Understanding Complexity of Construction Safety	65
4.1 Introduction	65
4.2 Construction safety management	65
4.3 Systems thinking in safety	67
4.4 Study aims	71
4.5. Methodology	72
4.5.1 Development process.....	72
4.5.2 Data collection.....	74
4.5.3 Data analysis.....	77
4.6 Results	80
4.6.1 Safety regulations	80
4.6.2 Incentive programs	84
4.6.3 Procurement and safety	88

4.6.4 Safety management in small businesses	93
4.6.5 Production and safety	96
4.6.6 Workers' conflicting goals	99
4.6.7 Blame on workers	102
4.6.8 Reactive and proactive learning.....	105
4.7 Discussion	108
4.7.1 Dynamics of construction safety	109
4.7.2 Implications for construction safety management.....	112
4.8 Summary	114
Chapter 5 Monitoring Safety Conditions of a Construction Project Using System Dynamics Modelling.....	115
5.1 Introduction	115
5.2 Background of the study	116
5.2.1 Safety (risk) assessment.....	116
5.2.2 Safety (risk) assessment in the construction industry.....	118
5.3 Study aims	120
5.4 Research method	121
5.4.1 System dynamics	121
5.4.2 Subject of study	123
5.4.3 Data collection and analysis	124
5.5 Results	126
5.5.1 Causal loop diagram	127

5.5.2 Stock and flow diagram.....	130
5.5.3 Model validation and testing	132
5.6. Discussion	140
5.6.1 Multi-dimensional and dynamic risk.....	141
5.6.2 Implications for the development of leading indicators	144
5.7 Summary	145
Chapter 6 Predicting Workers' Safety Behaviour	147
6.1. Introduction	147
6.2. Background of the study	148
6.3. Literature review	150
6.3.1 Safety climate	150
6.3.2 Key safety climate factors	153
6.3.3 Safety behaviour	156
6.4. Research aim and hypotheses.....	156
6.5. Methodology	158
6.5.1 Sample and procedure	158
6.5.2 Survey instrument.....	159
6.5.3 Data analysis.....	161
6.6 Results	165
6.6.1 Exploratory factor analysis	165
6.6.2 Descriptive statistics	165

6.6.3 Testing the measurement model	166
6.6.4 Structural model assessment.....	168
6.7. Discussion	173
6.7.1 Implications for construction safety management.....	174
6.8 Summary	176
Chapter 7 Validation of the Integrative Model across Small and Large Construction Companies.....	178
7.1 Introduction	178
7.2 Background	179
7.3 Method	184
7.3.1 Sample and procedure.....	184
7.3.2 Measures	185
7.3.3 Statistical analysis.....	185
7.4 Results	189
7.4.1 Observed variable characteristics	189
7.4.2 Testing for ME.....	189
7.4.4 Testing for latent mean differences	191
7.4.5 Testing validity of the integrative model.....	191
7.5 Discussion	193
7.6 Summary	198
Chapter 8 Development and Test of Leading Indicators	200
8.1 Introduction	200

8.2 Methodology	200
8.2.1 Conceptualization	201
8.2.2 Operationalization and indicator generation.....	201
8.2.3 Validation and revision.....	202
8.3 Results	203
8.3.1 Step 1: Conceptualization.....	203
8.3.2 Step 2: Operationalization	207
8.3.3 Step 3: Indicator generation.....	210
8.3.4 Step 4: Validation and revision	213
8.4 Discussion	224
8.5 Summary	226
Chapter 9 Conclusions and Recommendations for Future Research.....	228
9.1 Introduction	228
9.2 Review of research objectives.....	228
9.3 Original contributions and significance of the research.....	235
9.4 Research limitations and recommendations for future research	237
Bibliography	243
Appendix A: Ethics approval and documents.....	263
Appendix B: Validation questionnaire.....	281
Appendix C: Construction safety questionnaire	287
Appendix D: Safety Climate Survey.....	295

List of Figures

Figure 1.1 Trend of fatal injuries in construction	2
Figure 1.2 Research framework.....	11
Figure 2.1 Functions of leading indicators	19
Figure 3.1 A conceptual framework for developing leading indicators	41
Figure 3.2 Rasmussen’s two safety models	42
Figure 3.3 Dynamics of safety condition.....	45
Figure 3.4 Four steps to develop leading indicators	46
Figure 3.5 A safety condition map of a construction project.....	52
Figure 3.6 Safety practices as effects of a safety construct	53
Figure 3.7 Safety practices as causes of a safety construct.....	54
Figure 3.8 Safety practices as buffers against pressures.....	54
Figure 4.1 A reinforcing loop	74
Figure 4.2 A balancing loop.....	74
Figure 4.3 Data analysis.....	77
Figure 4.4 Safety regulations	81
Figure 4.5 Behaviour pattern of the ‘safety regulations’ archetype.....	84
Figure 4.6 Incentive programs	85
Figure 4.7 Behaviour patterns of the ‘incentive programs’ archetype.....	88
Figure 4.8 Procurement and safety	89
Figure 4.9 Behaviour pattern of feedback loops of R and B1	91
Figure 4.10 Behaviour pattern of feedback loops of R, B1 and B2.....	92
Figure 4.11 Behaviour pattern of the ‘procurement and safety’ archetype	93
Figure 4.12 Safety management in small businesses.....	94

Figure 4.13 Behaviour pattern of the ‘safety management in small businesses’ archetype	95
Figure 4.14 Production and safety	96
Figure 4.15 Behaviour pattern of the ‘production and safety’ archetype	98
Figure 4.16 Workers’ conflicting goals	99
Figure 4.17 Behaviour pattern of the ‘Workers’ conflicting goals’ archetype	101
Figure 4.18 Dynamics of unsafe behaviour under different conditions.....	102
Figure 4.19 Blame on workers	103
Figure 4.20 Behaviour pattern of the “blame on workers” archetype	105
Figure 4.21 Behaviour pattern of a systemic approach.....	105
Figure 4.22 Reactive and proactive learning	106
Figure 4.23 Behaviour pattern of the “reactive and proactive learning” archetype	108
Figure 4.24 Interactions between system levels.....	111
Figure 5.1 Stock and flow	123
Figure 5.2 Causal loop diagram of safety conditions	128
Figure 5.3 Stock and flow diagram of safety conditions	131
Figure 5.4 Base run of TRI/AFR	132
Figure 5.5 Incident/Accident rate of “base case” and “no-practice” case	134
Figure 5.6 Incident/Accident rate of “base case” and “minimum commitment to safety” case.....	134
Figure 5.7 Comparison of actual and simulated TRI/AFR	135
Figure 5.8 TRI/AFR from 200 runs of the simulation	138
Figure 5.9 Vensim percentile intervals for TRI/AFR	138
Figure 5.10 Correlation coefficients for the nine inputs to the model	140
Figure 5.11 Dynamics of MC’s and SC’s MCS	142

Figure 5.12 Comparison of decrease and increase in MC's MCS.....	142
Figure 5.13 Dynamic behaviour of social support.....	143
Figure 5.14 Dynamics of WSM and WSC.....	143
Figure 5.15 Causes tree of workers' safety motivation	144
Figure 6.1 <i>A priori</i> model.....	157
Figure 6.2 Competing models.....	170
Figure 6.3 Final structural model (Model 8).....	172
Figure 7.1 Final structural model.....	193
Figure 8.1 A pressure-state-practice model of safety level.....	203
Figure 8.2 A framework for interpreting leading indicators.....	210
Figure 8.3 Safety level of project A at three different time points	220
Figure 8.4 Comparison of leading indicator scores	222

List of Tables

Table 2.1	Definitions of leading indicator	17
Table 2.2	Essential attributes of leading indicators.....	20
Table 2.3	The WANO standardized performance indicators	23
Table 2.4	Developments of safety indicators in the construction industry	28
Table 2.5	Definition of safety indicators in the construction industry.....	33
Table 3.1	Dimensions of first order safety constructs.....	50
Table 3.2	The mechanisms that pressures worsen the safety condition.....	51
Table 3.3	Mechanisms of safety practices to change safety condition	54
Table 3.4	A proposed set of leading indicators	57
Table 3.5	Validation: a two-phase approach.....	58
Table 3.6	Experts' Profile	61
Table 3.7	Results of experts' ratings.....	62
Table 4.1	Archetypes development process.....	73
Table 4.2	Coding chart example	78
Table 4.3	Example of Words-and-arrow diagrams of causal arguments.....	79
Table 5.1	A summary of data collection process	125
Table 5.2	Stock variables and initial values	132
Table 5.3	Results of extreme condition test	133
Table 5.4	Summary of inequality statistics.....	136
Table 5.5	Uncertain parameters	137
Table 6.1	Safety climate factor structures for the construction industry.....	152
Table 6.2	Profile of respondents	159
Table 6.3	Exploratory factor analysis of safety behaviour.....	165
Table 6.4	Descriptive statistics and correlations among variables.....	166

Table 6.5 Factor loadings of items.....	167
Table 6.6 The convergent and discriminant validity of factors.....	168
Table 6.7 Goodness-of-fit indexes for the seven competing models	171
Table 7.1 Means, standard deviations, alpha coefficients, and correlations for the safety climate scales in large companies (n=123) and small companies (n=130)..	189
Table 7.2 Goodness of fit indices of ME models.....	190
Table 7.3 Latent means and variances	191
Table 7.4 Goodness of fit indices of multiple groups tested.....	192
Table 8.1 Core constructs	207
Table 8.2 Measurement methods	210
Table 8.3 State indicators.....	211
Table 8.4 Pressure indicators	212
Table 8.5 Details of three projects	213
Table 8.6 Scoring system of leading and lagging indicators.....	216
Table 8.7 Safety state of three projects	218
Table 8.8 Safety practices implemented in three projects	219
Table 8.9 Results of evaluation.....	224

Glossary

ACC	Accident Compensation Corporation, New Zealand
ANOVA	Analysis of variance
ASV	Average Shared Variance
AVE	Average Variance Extracted
CFA	Confirmatory factor analyses
CFI	Comparative fit index
CLD	Causal loop diagrams
CR	Composite reliability
CRI	Critical ratio index
DSHA	Defined Situations of Hazard and Accidents
EPRI	Power Research Institute
GOF	Goodness of fit
GTM	Grounded theory method
HFACS	Human Factors Analysis and Classification System
HR	Human resource
HSE	Health and safety Executive
IFI	Incremental Index of Fit
JSA	Job Safety Analysis
KPIs	Key performance indicators
LHS	Latin Hypercube Sampling
LIOH	Leading Indicators of Organizational Health
MAPE	Mean Absolute Percentage Error
MBIE	The Ministry of Business Innovation & Employment
MC	Main contractor
MCS	Management commitment to safety
ME	Measurement equivalence
MLE	Maximum likelihood estimation
MSE	Mean-square-error
MSV	Maximum Shared Variance
NFI	Normed Fit Index
NOHSC	National Occupational Health & Safety Commission of Australia
NPP	Nuclear power plants
OECD	The Organisation for Economic Co-operation and Development
OHS	Occupational health and safety
PAOWF	Proactive Assessment of Organizational & Workplace Factors
PHI	Project hazard index

PPIs	Positive performance indicators
QRA	Quantitative risk assessments
QSD	Qualitative system dynamics
RMSEA	Root mean square error approximation
SA	Systems analysis
SC	Subcontractors
SCI	Safety climate index
SCM	Swiss Cheese Model
SD	System dynamics
SEIs	Safety effectiveness indicators
SEM	Structural equation modelling
SMS	Safety management system
STAMP	Systems-Theoretic Accident Model and Processes
STS	Socio-technical system
TLI	Tucker-Lewis Index
TRI/AFR	Total recordable incident/accident frequency rate
TRIFR	Total recordable injury frequency rate
WANO	Nuclear Power Plant Operators
WSC	Workers' safety competency
WSD	Workplace Safety Discount
WSM	Workers' safety motivation
WSMP	Workplace Safety Management Practices

1.1 Background

Construction is an inherently dangerous industry. It has been one of the top contributors for workplace injuries and fatalities in many countries such as the USA, China, UK, Australia, and New Zealand (Pinto et al., 2011, Shin et al., 2014, Waehrer et al., 2007, Zhou et al., 2015, Wamuziri, 2008). Those accidents and injuries have resulted in huge personal, social and financial costs (Veltri, 1990, Feng et al., 2015). Despite the fact that improvements have been made over the last decades (Howell et al., 2002, Hinze et al., 2013a, Guo et al., 2015b), accidents and injuries still occur repeatedly on sites. It appears that construction safety has reached a plateau (Howell et al., 2002, Bhattacharjee et al., 2011, Statistics New Zealand, 2013, Lingard et al., 2010). Figure 1.1 describes the trend of construction fatal injuries in five nations and regions (i.e. UK, Australia, New Zealand, Hong Kong, and Singapore) between 2004 and 2013. It is evident that the number of fatal injuries tends to fluctuate and that there is not much improvement in these nations and regions, except that UK experienced significant a decline between 2006 and 2009.

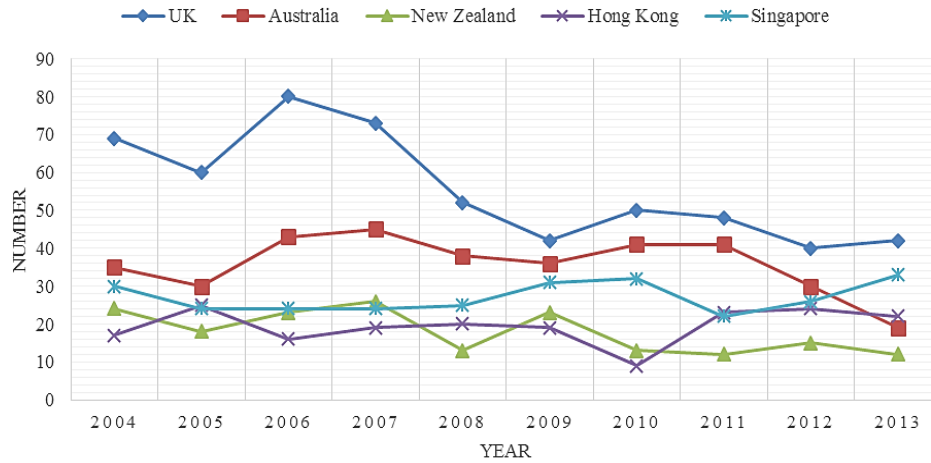


Figure 1.1 Trend of fatal injuries in construction

To improve construction safety performance, continuous efforts have been made by both researchers and practitioners. In many countries (e.g., New Zealand and UK), safety legislation systems have shifted toward a performance-based approach, with an aim to motivate companies themselves to take “all practicable steps” to ensure health and safety of their employees (Wilson, 2012, Gribble et al., 2006). In addition, over the last three decades, considerable research attention has been paid on identifying contributory factors (e.g., safety motivation, management commitment to safety, and safety knowledge) of accidents (Fang et al., 2004, Ismail et al., 2011, Sawacha et al., 1999, Haadir and Panuwatwanich, 2011). Research findings of these studies have enhanced an understanding of construction accidents and offered important insights into accident prevention strategies. They also help to design practical safety practices (e.g., toolbox meeting, safety training, hazard management, and tasks analysis) and accident prevention strategies (Zhou et al., 2015, Hinze et al., 2013a, Choudhry et al., 2008, Dedobbeleer and German, 1987). These practices are usually designed and implemented as a safety management system (SMS), with attempt to manage safety in a systematic fashion.

Safety performance measurement is an essential part of safety management system. The popular adage—“You cannot manage what you cannot measure”—underlines the importance of safety performance measurement. A main purpose of safety performance measurement is to identify safety problems, develop intervention strategies, and avoid future accidents (Grabowski et al., 2007b). It aims to assess safety conditions and aid decision making. Traditionally, governmental agencies and companies rely heavily on lagging indicators such as accident rates, total recordable injury frequency rate (TRIFR) (Hinze et al., 2013b). Like other industries, the pursuit of safety in the construction industry started from investigating and analysing accidents. The obsession with analysing these failures has led to a strong preference for recording accidents as a primary tool to measure safety performance. As a consequence, lagging indicators (e.g., accident rates, TRIFR (Total Recordable Injury Frequency Rate), or fatality rates) have been widely used by them to evaluate the level of safety on sites. Despite the fact that recording safety outcomes is objective and time-saving, this approach has been widely criticized for a number of significant limitations. First, lagging indicators provide little information about the cause of accidents (Hinze et al., 2013b). They may be able to reflect the level of safety in a reactive way (where we were) and help establish safety objectives (where we should go), but they are unable to provide guidance to assist people to fulfil the objectives (how to get there) (Hale et al., 1997b, Grabowski et al., 2007a, Sgourou et al., 2010). This means that relying on recording incidents and accidents cannot generate insights into accident prevention strategy (OECD, 2008). Second, lagging indicators are historical in nature ((HSE(Health and Safety Executive), 2006, Hinze et al., 2013b)). Safety efforts are made only after accidents occur. Due to this limitation, this approach

is “too late and too costly”. Last but not least, lagging indicators place emphasis on the negative side of safety (the presence/absence of accident), instead of the positive side (how safety is achieved). Rose (1984) asks the question of “If we are in the business of promoting OHS, why do we use failures as the measure of our success?” It is true that the positive side of safety includes many confounding and ambiguous variables which are difficult to define and measure. But our understanding of safety will not improve with the avoidance of such a difficulty.

1.2 Statement of problem

In recent years, the design of leading safety indicators (“leading indicators” thereafter) is a topic of increasing concern for both academics and practitioners (Øien et al., 2011a, 2011b, OECD, 2008, Reiman and Pietikainen, 2012, HSE(Health and Safety Executive), 2006, Aksorn and Hadikusumo, 2008b, Hinze et al., 2013b, Dingsdag et al., 2008, Cipolla et al., 2009, Guo and Yiu, 2015). Leading indicators have taken on such importance because they monitor the level of safety in a system, identify safety problems and motivate people who are in a position to take remedial actions (Hale, 2009). They help decision makers prevent accidents and improve safety by providing early warnings of accidents (OECD, 2008). In addition, the use of leading indicators can facilitate benchmarking programs that enable construction firms to track their safety performance (National Occupational Health & Safety, 1999). They can also be learning tools by which organizations can make sense of what is happening and what may go wrong (Mearns, 2009). The concept is theoretically associated with proactive safety management, since leading indicators are designed and used to provide early

warning of accident so that proactive efforts can be made. Due to the attraction of the concept, there has been a wide search for leading indicators and various sets of leading indicators have been developed. They tend to measure different things, such as system structure and safety practices (Dingsdag et al., 2008, Cipolla et al., 2009, National Occupational Health & Safety, 1999, Hinze et al., 2013b), attributes or principles of resilience (Øien et al., 2010, Costella et al., 2009, Saurin et al., 2008b), pre-warning signals in accident investigation (Körvers and Sonnemans, 2008), and safety risk (DeArmond et al., 2011, Michael et al., 2005).

Parallel efforts were made in the construction industry (National Occupational Health & Safety, 1999, Cipolla et al., 2009, Dingsdag et al., 2008, Site Safe New Zealand, 2012a, Toellner, 2001, Hinze et al., 2013b, Hallowell et al., 2013). Although these studies advance the development and implementation of leading indicators in the construction industry, they have the following limitations: (1) ambiguous definitions, (2) problematic simplification process, (3) a lack of development method, and (4) a lack of validation. These limitations will be discussed in details in Chapter 2.

1.3 Research objectives

The ultimate goal of the research is to develop and test a set of descriptive leading safety indicators that can be used to: (1) simplify complex safety phenomena, (2) measure safety performance, and (3) predict the trend in safety. To achieve the goal, the objectives of the research project are to:

Objective 1: Develop a pragmatic method for systematically identifying a set of leading indicators for construction projects.

A closer examination of previous developments of leading indicators in the construction industry reveals that no development methods exist. Our current understanding of the nature of safety has been limited and it may be conceptually difficult to identify valid and useful leading indicators based on one-off effort. It is essential that leading indicators are developed to describe and monitor specific safety conditions through a systematic development process. A systematic development method can improve the process of developing leading indicators and thus enhance their quality. In addition, the quality of the indicators plays a significant role in improving the effectiveness of a safety management system. Hence, they should not be picked just because they are easily available. Rather, they should be developed based upon a theoretical framework (or model), in which the causal links between indicators and outcomes are explicit. Therefore, it is important to develop a theoretical framework that defines the role and function of leading indicators in safety management and the causal links between indicators and outcomes.

Objective 2: Explore and understand the dynamics and complexity of construction safety management

In order to provide early warnings of accident, leading indicators must be able to describe and monitor the safety conditions of a system (e.g., a company or project). The challenge here is that safety conditions are a complex phenomenon and therefore it is conceptually difficult to decompose and simplify the complex safety conditions into a list of indicators. To address this challenge, it becomes important to explore and understand the dynamics and complexity of safety management. Such an exploration can provide systemic insights into how safety conditions change over time at different system levels (e.g., government, company, project, and individual). These insights can

potentially be helpful to the development of leading indicators. Since the ultimate purpose of this research project is to develop a list of leading indicators for safety management at the project level, leading indicators must be able to capture the safety level of a construction project. Thus, an understanding of the dynamics and complexity of safety at the project level can provide both the theoretical and empirical basis for developing leading indicators.

Objective 3: Investigate workers' safety behaviour shaping mechanisms

A theoretical challenge associated with the concept of leading indicator is to determine “what is measured” (i.e., measurement bases). Measurement bases are function of a safety (or accident) model (Mohagheh and Mosleh, 2009b). The model includes key factors and explicates casual relationships between these factors and safety outcomes. Thus, it plays a role in identifying measurable proxies that are causally linked with safety outcomes. Some accident models, such as Swiss cheese model (Reason, 1997) have extended the causes of accidents to organisational factors and emphasizing the interactions between organisational deficiencies (latent failures) and human errors (active failures).

Therefore, an investigation of the relationships among organizational, group, individual factors and safety behaviour can generate insights into measurement bases. In fact, site safety relies heavily on workers' safety behaviours. If leading indicators are to predict the next accident, the development process must address and integrate the mechanisms by which safe behaviours occur on site. In addition, such an investigation can provide evidence for the analytic and predictive power of some individual leading indicators, such as safety climate.

Objective 4: Develop and validate a set of leading indicators for the construction industry

As emphasized above, leading indicators should be developed by following a systematic process. Before they are implemented in real construction projects, their validity should be tested by theoretical and empirical evidence. This objective aims to provide the construction industry with a set of valid and useful leading indicators and help the industry to manage safety in a proactive safety manner.

1.4 Scope of the research

Limits to the research are noted from the start. Firstly, leading indicators developed in this research project are mainly aimed at predicting accidents and safety problems. “Health” issues (e.g., stress, burnout, and musculoskeletal) are largely ignored in the research, although occupational health is a major problem for construction (Rowlinson, 2004).

Secondly, this research projects made no attempt to address the implementation of leading indicators. Focus has been placed on developing leading indicators to simply complex safety reality, monitor safety performance, and predict safety trend. As a result, this research does not provide normative reference points for evaluating the information generated by leading indicators.

Lastly, this research is concerned with safety management during the construction phase of a project and it does not consider the effects of construction process and structural design on safety.

1.5 Research methods

A research framework is designed in order to guide research efforts and achieve those six objectives. As shown in Figure 1.2, research objectives are derived from a review of the nature of leading indicators (definition, purpose, function, attribute, and type) and applications of leading indicators in various industries (e.g., nuclear, chemical process, oil and gas, and construction industry) (Chapter 2).

Chapter 3 addresses the first research objective by developing a pragmatic method for leading indicator development. The method was developed based on a thorough literature review of safety literature. A hypothetical construction project was used to demonstrate the method.

Chapter 4 and 5 address the second objective. In specific, the objective was to better understand the complexity and dynamics of construction safety management at the industry and project level. These two chapters were aimed at providing insights into dynamics of safety conditions and simplification process of complex safety phenomena. Thus, these two chapter lay a solid foundation for the development of leading indicators.

Chapter 6 focuses on testing the predictive validity of safety climate as a leading indicator and investigating the mechanisms by which workers' safety behaviours are shaped. Cross-sectional data are collected using questionnaires and structural equation modelling is used to analyse the relationships between contributory factors and safety behaviours. An integrative model of safety behaviour is developed, which captures the relationships between factors at organizational, group, and individual level and their effects on safety behaviour. The results offer insights into selecting appropriate factors that have predictive power for safety outcomes. Chapter 7 is concerned with testing the validity of the integrative model across small and large construction companies.

Data were collected from 253 construction workers in New Zealand using a safety climate measure. This study used multi-group confirmatory factor analyses (MCFA) to test the measurement equivalence of the safety climate measure. The structural model of relations among key safety climate factors and safety behavior was also examined to investigate its cross-group invariance. These two chapters, as a whole, offer insights into the safety behaviour shaping mechanisms, which facilitate the development of leading indicators with regard to “what to measure”.

Chapter 8 develops a set of leading indicators by synthesising results of previous chapters. In specific, it applies the conceptual framework and development method proposed in Chapter 3. Appropriate leading indicators are chosen based on the research findings of Chapter 4, 5, 6, and 7. The development process follows a four-step method: conceptualization, operationalization, indicator generation, and validation and revision. A pressure-state-practice (PSP) model is developed as an overall framework for developing safety leading indicators. The safety level of a construction project is conceptualized as a high-level abstract construct that can be assessed by state indicators, pressure indicators, and practice indicators. Criterion validity (i.e., concurrent validity and predictive validity), practicability and cost-effectiveness of the leading indicators were qualitatively tested and supported by the empirical evidence collected from three construction projects.

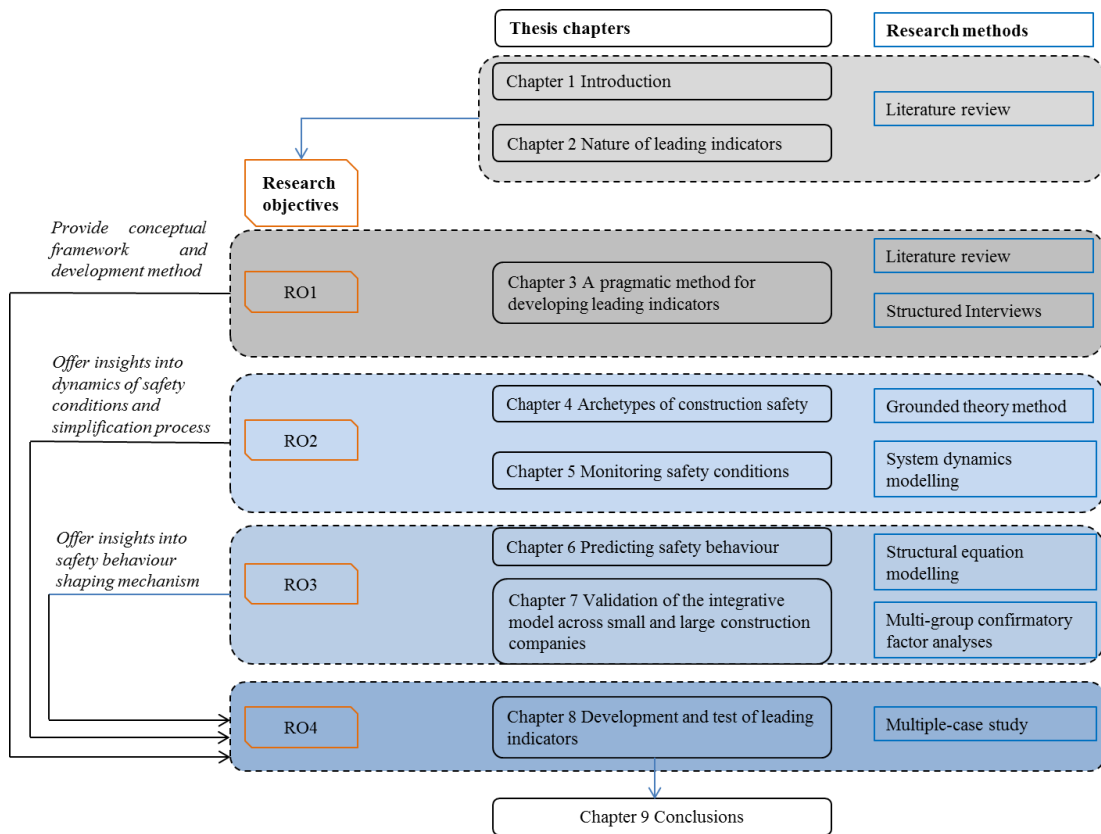


Figure 1.2 Research framework

1.6 Significance of research

This research aims to provide the New Zealand construction industry a set of leading indicators for safety performance measurement and proactive safety management. The role of leading indicators is to generate foresight, motivate people to work on safety and contribute to fix safety problems and maintain a high safety standard. Underlying the idea of leading indicators is a proactive and dynamic mindset towards safety management. The set of leading indicators provides the construction companies with an alternative to assessing safety conditions and measuring safety performance at the project level. By capturing multiple sides of safety (e.g., technical, psychosocial, and organizational), the use of leading indicators can extend traditional safety efforts

beyond hazard management and safety training. It is suggested that construction companies, particularly those that embrace the “zero harm” philosophy, integrate leading indicators in safety management systems and link the information with current safety practices and activities.

In addition, this research project advances our understanding of complexity and dynamics of safety management in the construction industry. The eight construction safety archetypes represent an effort to identify and categorize behaviour patterns that recur in construction safety management. They create a library of fundamental dynamic structures that generate counter-intuitive behaviours with which managers must cope. They can be used as a tool to facilitate a systemic analysis of construction accidents and a systemic assessment of safety conditions.

Furthermore, this research provides a four-step method for leading indicator development. The method proposed in this paper improves the process of developing leading safety indicators for the construction industry. It permits safety conditions to be conceptualized in different ways based on different safety models, and it emphasizes the importance of validating leading indicators.

1.7 Overview of the research

This PhD thesis is structured as follows:

- Chapter 1 introduces the doctoral research project. It provides the background information of construction safety. It gives a brief review of past developments of leading indicators in the construction industry and identifies the limitations and research gaps. It then presents the research objectives and an overview of

methodology used to achieve these objectives, which are followed by the significance of the research project and the structure of the thesis.

- Chapter 2 discusses the nature of leading indicators with respect to definition, function, purpose, attribute, type. It reviews applications of leading indicators in various industries, including nuclear, chemical process, oil and gas, and construction industry. Particular attention is paid on reviewing the development of leading indicators in the construction industry and discussing limitations of these leading indicators.
- Chapter 3 develops a conceptual framework that clarifies the nature of the indicators in terms of definition, purpose and attribute. It then proposes a pragmatic method for systematically identifying a set of leading indicators for construction projects. A hypothetical example is provided to illustrate the entire development process.
- Chapter 4 explores the complexity and dynamics of construction safety management. Based on the data collected by interviews, it identifies 8 system archetypes of construction safety. These archetypes represent an effort to identify and categorize behaviour patterns that recur in construction safety management. They enhance the understanding of complexity of construction safety and provides insights into the development of leading indicators.
- Chapter 5 aims to capture the dynamics of safety conditions at the project level. A system dynamics (SD) model was built to capture the key dimensions of safety conditions of a medium-sized construction project and the causal links between safety conditions and safety outcomes. Numerical, written, and mental data were collected from the project by interview, questionnaire, and documentation. The

model was validated through various tests. The results of simulation suggest that safety conditions of the project tend to change over time because of a complex web of relationships among system factors.

- Chapter 6 develops and tests an integrative model of construction workers' safety behaviour with an attempt to better understand the mechanisms by which key safety climate factors (i.e., management safety commitment, social support, and production pressure) and individual factors (i.e., safety knowledge and safety motivation) influence workers' safety behaviour. Data were collected from 215 construction workers in New Zealand using a questionnaire. Eight competing models were tested using structural equation modelling (SEM). The results showed that safety climate is a useful leading indicator of safety behaviour.
- Chapter 7 compares the level of safety climate between small and large construction companies. Data were collected using a questionnaire from 215 construction workers from large (n= 110) and small (n= 105) construction in New Zealand (NZ). This study used multi-group confirmatory factor analyses (CFA) to test the measurement equivalence (ME) of a multidimensional safety climate measure across small- and large-company groups. Results support the measurement equivalence of the safety climate measure across the two groups.
- Chapter 8 develops and validates a set of leading indicators that can be used in safety assessment and proactive safety management at the project level. The development process follows four steps: conceptualization, operationalization, indicator generation, and validation and revision. A systems framework is proposed to provide the theoretical basis for the development of leading indicators. A set of 30 leading indicators are developed to measure the safety state and safety process

of a construction project with respect to five subsystems: goals and values, structural, psychosocial, technical, and managerial. The design validity was tested by examining the scientific quality of the leading indicators. In addition, a multiple-case study was conducted to test their output validity.

- Chapter 9 integrates all parts of the thesis to reach meaningful conclusions. It reviews the research objectives and summarises how these objectives have been achieved. The original contributions to the knowledge of leading indicators and their managerial implications are highlighted. In addition, limitations of the current research are articulated and future research directions are recommended.

Chapter 2 The Nature of Leading Safety Indicators

2.1 Introduction

This chapter reviews the nature of leading indicators with respect to definition, function, attributes, and development method. By identifying various definitions of leading indicators, debates, and current practices, it establishes the context in which the research was conducted. Particular attention was paid on the development of leading indicators in the construction industry. This chapter identifies knowledge gaps in the concept of leading indicator and provides the basis for the design of the research.

2.2 Definitions of leading indicators

In the development and use of safety indicators, the first intriguing conceptual question arises: what is a safety indicator? The term “indicator” is derived from the Latin “indicare”, which means to announce, point out or indicate (Schirnding, 2002). Oxford Dictionary defines an indicator as “a sign that shows what something is like or how a situation is changing”. The Organisation for Economic Co-operation and Development (OECD) defined an indicator as “A parameter, or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/ environment/area with a significance extending beyond that directly associated with a parameter value” (OECD, 1993). In the domains of ecology and

environmental planning, *indicator* is understood as a synonym for *indicans*, i.e., a measure or component from which conclusions on the phenomenon of interest (the *indicandum*) can be inferred (Heink and Kowarik, 2010). Walz (Walz, 2000) defined an indicator as “a variable that describes the state of a system.

Various definitions of leading indicator exist in the safety literature. It may be evident that there has been a diverse set of understandings of the concept of leading indicator (Hopkins, 2009a). As shown in Table 2.1, some definitions (e.g., (Hopkins, 2009a, Hinze et al., 2013b)) specify the indicated phenomenon of interest, such as the state of the safety management system, the effectiveness of the safety process, important aspects of safety model(s), the level of accident risk, and safety levels, while some definitions (e.g., Reiman and Pietikainen (2012), Øien (2001b)) tend to be general and vague as they do not specify what should be measured. The varied understandings may be justified by the youth of the concept of leading indicator. However, they also produce confusion concerning the nature of leading indicators and may thus hinder their development and use in safety management.

Table 2.1 Definitions of leading indicator

Study	Definitions
HSE (2006)	The leading indicator identifies failings or holes in vital aspects of the risk control system, discovered during routine checks on the operation of a critical activity within the risk control system.
NOHSC (1999)	A safety indicator is a statistic or other unit of information which reflects directly or indirectly, the extent to which an anticipated outcome is achieved, or the quality of processes leading to that outcome.
Cipolla et al. (2009)	Safety indicators are measures of the effectiveness safety management tasks.
Hopkins(2009a)	An indicator should measure the state of the safety management system.
Kjellén (2009)	A safety indicator provides the metric used to measure the level of risk of accidents and how this develops over time.
Wreathall (2009)	A safety indicator is a proxy measurement for items identified as important in the underlying model(s) of safety.
Hinze et al. (2013b)	Leading indicators of safety performance consist of a set of selected measures that describe the level of effectiveness of the safety process.

Øien (2001b)	A safety indicator is a measurable/operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality.
Step Change in Safety (2014)	A safety indicator is something that provides information that helps the user respond to changing circumstances and take actions to achieve desired outcomes or avoid unwanted outcomes.
OECD (2008)	A safety performance indicator is a means for measuring the changes over time in the level of safety, as the result of actions taken.
Grabowski et al.(2007a)	Leading indicators are conditions, events or measures that precede an undesirable event and that have some value in predicting the arrival of the event, whether it is an accident, incident, near miss, or undesirable safety state.
Dyreborg (2009)	Leading indicators are proactive measures of performance before any unwanted outcomes have taken place.
Reiman and Pietikainen (2012)	A safety indicator is any measure—quantitative or qualitative — that seeks to produce information on an issue of interest.

2.3 Purpose, function, and role of leading indicators

Implicit in these definitions is the requirement that leading indicators be able to identify safety problems and facilitate remedial actions *before* an accident occurs. This is done by providing early warnings and predicting the possibility of there being an accident tomorrow (Øien et al., 2011a). Leading indicators are developed to serve the purposes of discovering weaknesses in control systems and providing ongoing assurance that risks are being adequately controlled (HSE(Health and Safety Executive), 2006). Hale (2009) suggested that leading indicators should be able to (1) monitor the level of safety in a system, (2) decide where and how to take action, (3) motivate those in a position to take the necessary action to take it. In correspondence with these purposes, leading indicators must be able to perform two specific functions: information function and decision-aid function. First, whatever they measure, they must provide simplified information that is useful and meaningful for preventing accidents and injuries. Second, the information should be linked to practical safety management so that decision makers can take timely and effective interventions and remedial actions. In contrast, Harms-Ringdahl (2009) had a wider perspective on the

purpose of leading indicators. According to him, they can be used to: (1) obtain a value, without defining the use, (2) obtain values and use them in an improvement feedback system, (3) function as a part of an economic incentive program, (4) demonstrate that enough safety is achieved, (5) demonstrate safety to the world outside the company, (6) focus either process or occupational safety, depending on the interests of different stakeholders.

In essence, leading indicators are an improvement feedback subsystem with a safety management system (Harms-Ringdahl, 2009). They play an essential element of control process, providing feedback of current safety state of the system and directing safety efforts that steer the system back to desired state. As demonstrated in Figure 2.1, they play an important role as proactive sensors ($Sensors_P$) that capture the safety state of the system and indicate deficiencies within the transforming process. When there is deviation from desired state, the controller (i.e., a decision maker) then changes the control input according to the difference between actual and desired outputs and brings actual outputs closer to the reference.

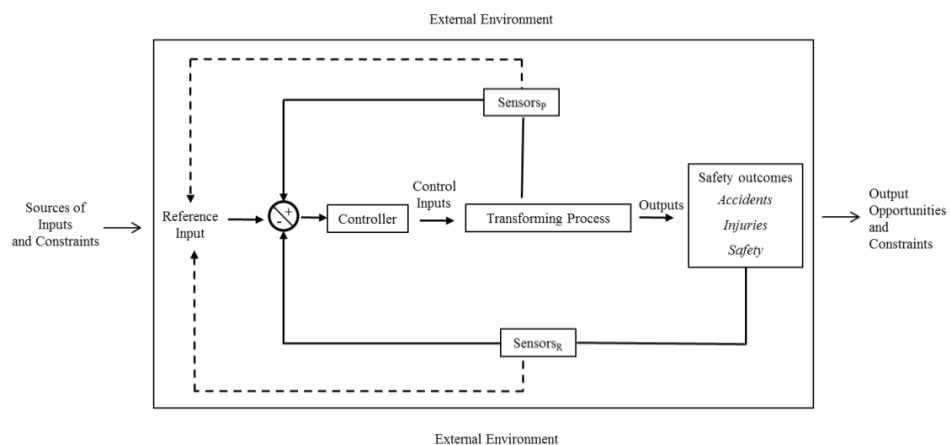


Figure 2.1 Functions of leading indicators

2.4 Essential attributes of leading indicators

Compared with the varied understandings of “what is an indicator?”, people’s views on “what should an indicator be?” are more consistent. In general, the essential attributes of leading indicators can be categorized into scientific and managerial dimensions: analytic soundness, predictability, practicability, and cost-effectiveness (Kjellén, 2000, Kjellén, 2009, Vinnem, 2010, Webb, 2009, Øien et al., 2011b).

To be scientific, leading indicators must be analytically sound. This requires that they have a strong scientific and conceptual basis and reflect the causes of accidents. In addition, they must be able to predict accidents by providing early warnings. At the same time, indicators must be compatible with practical safety management and must be cost-effective in terms of data collection (see Table 2.2).

Table 2.2 Essential attributes of leading indicators

Attributes		Description	Reference
Scientific dimension	Analytic soundness	have a strong scientific and conceptual basis; based on a safety model reflect causes of accidents	(Kjellén, 2000); (Kjellén, 2009); (Vinnem, 2010);
	Predictability	sensitive to change of safety condition.; allow for early warning by capturing changes in system state that have significant effects on safety risks	(Webb, 2009);(Øien et al., 2011b);
Managerial dimension	Practicability	compatible with practical safety management; drive appropriate behaviour not susceptible to manipulation	
	Cost-effectiveness	easily observable; cost-effective to be collected.	

2.5 Debate on leading and lagging Indicators

There has been a debate on personal vs. process safety and leading vs. lagging indicators of safety management (see Safety Science special issue 47). Hopkins (2009b) argued that the distinction between personal and process safety can be made based on the differences between involved hazards. According to him, process hazard are those arising from the processing activity in which a plant may be engaged, while

personal safety hazards affect individuals but may have little to do with the processing activity of the plant. Such a distinction is supported by most researchers who participated in this debate, although Kjellén (2009) argued that this dichotomy is too simplistic.

Despite the agreement on the distinction between personal and process safety, there is little consensus among the researchers about the difference between leading and lagging indicators. Hopkins (2009b) examined the leading/lagging distinction in the Baker report (Baker et al., 2007) and found that the usage of lagging indicators is confusing. He went on to state that the distinction becomes largely irrelevant because lagging indicators can or cannot provide information about how well safety is managed, depending on the level of zoom.

Le Coze (2009) contributed the debate by raising a taxonomy issue. He argued that the concept of leading indicator should address both observable manifestations and internal processes and that rejecting the lagging/leading distinction results in addressing only a part of the problem. Mearns (2009) pointed out that the confusion was caused by organizations' inability to establish causal relationships between warning events and potential adverse outcomes. He continued to argue that it is conceptually difficult to simplify complex safety phenomena by using leading indicators. Wreathall (2009) argued that it is of little importance to distinguish lagging from leading indicators. He pointed out that *“Therefore, when considering the selection of leading indicators, these are selected not based on whimsy or arbitrary judgements (or even intuition) but should be soundly based on an underlying model of safety and the precursor forces that lead to the failures of concern-be they personnel or process related.”* Erikson (2009) argued that depending on the performance

indicator being an input or output in relation to a certain objective, it will be either a leading or lagging indicator. He provided an example that indicators focusing on the output (e.g., the number of leads, spills, fires, and explosions) do not provide any insights into how to improve safety.

Ale (2009) hold a more conservative and prudent view that no indicator is able to be a sure sign of imminent disaster and it can only reflect accident probability. He stated that even when all indicators are in the acceptable range of values, the probability of an accident is not zero. Similarly, Hudson (Hudson, 2009) also pointed out that indicators do not appear to have a direct and observable link to performance and therefore are less likely to be implemented by many HR departments. He identified three major problems or challenges: (1) the timescale of major process incidents are often much less frequent than personal safety incidents, (2) a lack of predictive validity of proactive actions, and (3) a lack of a theoretical coherent framework of how and why accidents happen. Zwetsloot (2009) elaborated the prospects and limitations of process safety performance indicators. He questioned the ability of leading indicator to help companies to develop innovative process safety strategies. Kjellén (2009) hold a view that it is still important to distinguish leading and lagging indicators when leading indicators are defined as ones that predict future changes in the risk level.

2.6 Application and practices of leading indicators

To facilitate proactive safety assessment and management, attempts have been made in different industries to develop and implement leading indicators.

2.6.1 Nuclear power industry

Development and application of leading indicators in the nuclear power industry have started since the Three Mile Island accident in 1979 (Øien et al., 2011b). Focuses of safety assessment have been placed on (1) physical system design and performance, and (2) operational system design and performance. The World Association of Nuclear Power Plant Operators (WANO) developed 10 quantitative safety performance indicators and established guidelines to implement these indicators in the areas of nuclear power plants (NPP) safety, reliability, and efficiency (see Table 2.3). Although these indicators are positively related to safety performance, they are not believed to have predictive power at individual plants (Martorell et al., 1999).

Table 2.3 The WANO standardized performance indicators

NO.	performance indicators
1	Unit capability factor
2	Unplanned capability loss factor
3	Unplanned automatic scrams per 7000 h critical
4	Safety system performance
5	Thermal performance
6	Fuel reliability
7	Collective radiation exposure
8	Volume of low-level solid radioactive waste
9	Chemistry index
10	Lost-time accident rate

In addition, the US Electric Power Research Institute (EPRI) developed two complementary classes of indicators: workplace indicators and management and organizational indicators (EPRI, 2000). Workplace indicators, known as Proactive Assessment of Organizational & Workplace Factors (PAOWF) approach, evaluate workplace factors by obtaining ratings of potential problem areas from the frontline workers and supervisors, while management and organizational indicators, known as Leading Indicators of Organizational Health (LIOH) measure the “upstream influences” on future work conditions. In a final report, it was concluded that both PAOWF and LIOH can have a beneficial effect on the ability of all levels of the plant

staff and management to understand issues associated with human and organizational performance. They can enhance self-assessment and corrective-action processes.

The IAEA has been sponsoring research in the area of safety indicators to monitor NPP operational safety performance since the late 1980s (IAEA, 2000). IAEA developed operational safety performance indicators based on a hierarchical structure which decomposes the NPP operational safety performance into four different levels: operational safety attributes, overall indicators, strategic indicators, and specific indicators. Operational safety attributes are something that a plant requires in order to perform safely. Overall indicators measure the degree of smoothness with which the plant operates. Examples include “operating performance”, “state of SSC (structure, systems and components), and “events”. Strategic indicators were aimed at providing a bridge from overall to specific performance. Specific indicators then represent quantifiable measures of performance.

2.6.2 Chemical process industry

Process accidents can cause catastrophic consequences. To prevent such accidents, it is always desirable that early warnings of accidents can be identified and the information of how well a risk control system is working can be obtained. Health and Safety Executive (HSE) (2006) produced guidance of developing process safety indicators for chemical and major hazard industries. The guidance defines leading indicators as “a form of active monitoring focused on a few critical risk control systems to ensure their continued effectiveness” and lagging indicators as “a form of reactive monitoring requiring the reporting and investigation of specific incidents and events to discover weaknesses in that system. It uses Reasons Swiss cheese model to

illustrate the relationships between leading and lagging indicators. However, as discussed above, Hopkins (2009b) pointed out that the relationships are confusing.

In addition, Webb (2009) developed and implemented various leading indicators in different plants of Basell. He identified the following lessons learned from the implementation of leading indicators in Basell: (1) the need for a champion, (2) senior management involvement, (3) the bottom line. Does it work? and (4) leading indicators are more difficult.

2.6.3 Oil and gas industry

The need for indicators that provide objective information about the actual safety conditions has long existed in the oil and gas industry. Such a need was even emphasized because of authorities' concern (Vinnem et al., 2006). Oil and gas companies have started to develop safety indicators to monitor major hazards since 1990s. For example, Elf utilized safety indicators for monitoring risks at Frigg (Vinnem, 1998). In 1996 a list of 11 indicators was developed based on results from sensitivity analysis:

- (1) Leak of frequency
- (2) Control of hot work
- (3) Automatic gas detection
- (4) Automatic fire detection
- (5) Availability of smoke diver team
- (6) Unavailability of emergency shutdown valves
- (7) Fire water supply
- (8) Availability of deluge control valves

(9) Mustering time

(10) Emergency lights at Quarter Platform (QP)

(11) Availability of search and rescue

The quantitative risk assessments (QRAs) have mainly focused on technical issues and human errors, but efforts were made to expand the assessments to organizational aspects. For example, Øien (2001a) developed a framework for establishing organizational risk indicators. The framework addressed six organizational factors, namely, (1) individual factor, (2) training/competence, (3) procedures, JSA, guidelines, instructions, (4) planning, coordination, organization, control, (5) design, and (6) PM-program/inspection. 17 leading indicators were developed to measure these organizational risk factors. Øien (2008) proposed a number of barrier, checkpoints and corresponding indicators based on investigation of the hydraulic oil leak from the Eirik Raude drilling rig in April 2005. In addition, the “Risk Level Project” was launched with an aim to develop a method to assess risk level trends in the Norwegian offshore petroleum industry (Vinnem et al., 2006). The project established the following indicators:

- Indicators for events related to major accident risk.
- Indicators for barriers related to major accident risk.
- Indicators occupational accidents and diving accidents.
- Indicators for working environment factors
- Indicators for other “defined Situations of Hazard and Accidents” (DSHA)

2.6.4 Construction industry

In the construction industry, early attention was primarily paid on outcome indicators. For example, Laufer and Ledbetter (1986) examined the effectiveness of four safety performance measures (Lost day cases, Doctor's cases, First aid cases, and No-injury cases) in terms of four attributes including efficiency, reliability, validity and diagnostic capacity. de la Garza (2013) analysed the effects of using another four indicators (the Experience Modification Rate, the Recordable Incident Rate, the Lost Time Incident Rate, and the Workers' Compensation Claims Frequency Indicator) on safety performance. Nevertheless, the development of leading indicators is not new to the construction industry. Over the last decades, a number of sets of safety indicators have been developed. For example, the National Occupational Health & Safety Commission (NOHSC) of Australia (1999) proposed a set of positive performance indicators (PPIs) to monitor six aspects of safety: management commitment, safety management system, hazard management, auditing, training and education, communication and consultation. In addition, Cipolla et al. (2009) developed a set of safety effectiveness indicators (SEIs) to measure the effectiveness of the safety management tasks that determine safety cultural competencies. These safety management tasks were identified based on interviews, focus group, and a survey (Dingsdag et al., 2008). Recently, Site Safe New Zealand (2012a) developed a set of key performance indicators (KPIs) for the Construction Safety Charter Accreditation program, which aims to assess and recognize the safety performance of construction firms. Hallowell et al (2013) identified over 50 leading indicators on the basis of case studies, content analysis of award-winning projects, and focused discussions among construction safety experts. Table 2.4 summaries the previous developments of safety indicators in the construction industry.

Table 2.4 Developments of safety indicators in the construction industry

References	Main dimensions	Examples
NOHSC's		
Positive Performance Indicators (PPIs) (National Occupational Health & Safety, 1999)	<ul style="list-style-type: none"> • commitment by management to safety, • an effective OHS management system, • risk management and control of hazards, • auditing of both management systems and physical hazards, • training and education, • communication and consultation 	<ul style="list-style-type: none"> • Number of system audits undertaken • Number of tool box meetings held • Number of accidents/near misses investigated • Frequency of site safety meetings • Number of sub-contractor plans audited • Number of reported incidents
Toellner (2001)	<ul style="list-style-type: none"> • metrics associated with measureable system or individual behaviours linked to accident prevention 	<ul style="list-style-type: none"> • Quality of morning safety meetings • Housekeeping • Barricade performance • Safety walks
Safety Effectiveness Indicators (SEIs) (Cipolla et al., 2009)	<ul style="list-style-type: none"> • Carry out project risk assessment; • Carry out workplace and task hazard identification, risk assessments and controls; • Plan and deliver toolbox talks; • Consult on and resolve issues; • Challenge unsafe behaviour/attitude at any level when encountered; • Make site visits where a site worker is spoken to directly about OH&S in the workplace; • Recognize and reward people who have positively impacted on OH&S; • Carry out formal incident investigations; • Carry out formal inspections of workplace and work tasks; • Monitor subcontractor activities; • Understand and apply general legislative OH&S requirements; • Understand and apply general regulatory workers' compensation requirements; • Work with people to solve safety problems. 	<ul style="list-style-type: none"> • Does the project team demonstrate a clear understanding of the tools and systems needed to conduct an accurate project risk assessment? • Are monitoring and review activities for risk assessment outcomes discussed, planned, specified and allocated? • Are hazards involved with each task element identified? • Are action owners consulted by facilitator/leader before task allocation? • Is toolbox talk accurately documented and distribution process agreed? • Are project team members actively encouraged to identify and raise issues and concerns? • Is there consistent and visible leadership by management in OH&S behaviours and actions?

Site Safe's	three tiers of	Key	Performance	Indicators	(KPIs)	Site Safe, New	Zealand(2014a)	<ul style="list-style-type: none"> • Subcontractor tender documents have site specific safety activity requirements • Regular tool box talks • A training/competency register for all subcontractor employees • All management positions have safety roles and responsibilities that are clearly defined within the organization • Senior managers has monitored at least two on-site activities in the past 2 months
Hinze et	al.(2013b)	<ul style="list-style-type: none"> • Active leading indicators • Passive leading indicators 	Active leading indicators:	<ul style="list-style-type: none"> • Percent of jobsite toolbox meetings attended by jobsite supervisors/managers • Percent of jobsite pre-task planning meeting attended by jobsite supervisors/managers • Number of close calls reported per 2000,000h of workers exposure 	Passive leading indicators:	<ul style="list-style-type: none"> • Number or percent of management personnel with 10-h (or 30-h) OSHA certification cards. • Number or percent of field employees with 10-h (or 30-h) OSHA certification cards. • Number or percent of subcontractors selected, in part, on the basis of satisfying specific safety criterion prior to being awarded the subcontract. 		

2.7 Types of leading indicators

A review of applications and practices of leading indicators in different industries suggests that the measurement bases can be categorised into four types: events, barriers, safety practices, and safety constructs.

2.7.1 Event based indicators

In some industries like chemical process and offshore industry, accidents are too few to be able to draw any conclusions about trends of safety level. Thus, safety risk has been expressed by observing and utilising the precursors of accidents—unplanned events (Vinnem et al., 2006). The rationale behind this approach is that undesired events are related to major accidents. The “Risk Level Project” selected 10 unplanned events, defined as defined situations of hazard and accident (DSHA). These events mainly represent technical failures of a plant.

Vinnem et al.(2006) pointed out that event based indicators have three major limitations. First, it is still based on past/historical events and it does not provide information of how underlying conditions change over time. As such, they are lagging indicators in nature. Second, the number of events relating to a particular incident or accident is limited, which cause difficulties in drawing any conclusion about the risk level. Third, registration and reporting criteria are imprecise in some cases.

2.7.2 Barrier based leading indicators

Barriers are physical, functional, symbolic, or incorporeal systems that are aimed at preventing, or protecting against the uncontrolled transportation of mass, energy, or information (Hollnagel, 2008a). From this definition, barrier indicators measure how

effectively the barrier system works. In practice, they are developed and used as a complementary illustration of risk levels. The emphasis has been placed on a barrier system that is associated with technical failures. The purpose is to inform companies whether all barrier elements function effectively.

One of major limitations of barrier indicators is that they do not address all barrier elements and actual configuration and therefore assessment of risk levels can be imprecise. Thus, Vinnem et al.(2006) warned that one should be careful to assess risk levels solely on the basis on the barrier indicators.

2.7.3 Safety practices based leading indicators

Because of the limitations of using accidents and injuries as safety performance indicators (e.g., doing so is reactive and downstream (Choudhry et al., 2007)), together with the growing popularity of safety management systems in the industry (Gallagher et al., 2003a), there has been a shift towards measuring safety management systems (SMS). An SMS is defined as a system that includes a set of safety policies and practices with the aim of influencing employee behaviour and creating a safe and healthy workplace (Van Dooren, 2011, Argyris and Schön, 1996, Lehr and Rice, 2002). SMS indicators measure individual safety practices and activities, providing information about the SMS implementation and thus directing remedial actions. One main advantage is that they are compatible with safety management processes and that corrective actions can thus be relatively easily taken.

2.7.4 Safety constructs based leading indicators

A safety construct can be defined as a conceptual term used to describe a safety phenomenon. It is an explanatory device that safety scientists create to understand the safety world. Various measurement scales are designed to measure safety constructs (e.g., management commitment (Al-Refaie, 2013), safety motivation (Fleming, 2012b) and social support (Hsu et al., 2010)) by studying the relationships between them and testing the substantive hypotheses about these relationships. These indicators create the possibility for more rigorous scientific understanding of safety phenomena.

An advantage of safety constructs based indicators is that the link between them and safety outcomes is relatively robust and clear. For example, different dimensions of the concept of safety climate have been found (e.g., (Zohar, 1980a, Dedobbeleer and Beland, 1991, Flin et al., 2000a)), and it has been convincingly shown that safety climate is an effective leading indicator of safety performance (Zohar, 2010a). Nevertheless, these indicators are weak in certain aspects. Collecting information about abstract safety constructs often relies on qualitative interviews and surveys, which are neither cost-effective nor compatible with practical safety management.

2.7.5 Limitations of existing leading indicators in the construction industry

While those leading indicators developed for the construction industry promote a shift from outcome indicators towards proactive ones, they have the following significant limitations.

(1) Ambiguous definitions

The concept of safety indicator in the construction industry is ambiguous and confusing with regard to definition and *indicandum* (see Table 2.5). National Occupational Health & Safety Commission provided two different definitions of positive performance indicators. The first definition suggests that positive performance indicators can measure both outcomes and safety processes, while the second one addresses only the safety processes. Different sets of leading indicators tend to measure different things, including quality of safety process, positive safety actions, system, individual behaviours, the effectiveness of safety management tasks or safety process, and safety leadership.

Table 2.5 Definition of safety indicators in the construction industry

Safety indicators	Definition	Indicandum
PPIs	“a statistic or other unit of information which reflects directly or indirectly, the extent to which an anticipated outcome is achieved, or the quality of processes leading to that outcome” (National Occupational Health & Safety, 1999) (p1)	the quality of safety process
	“actions that provide good occupational health and safety (OHS) outcomes” (Department of Employment and Workplace Relations, 2005)	positive safety actions
Toellner’s four indicators (2001)	“those metrics associated with measurable system or individual behaviours linked to accident prevention” (p44)	system or individual behaviours
SEIs	measures of the effectiveness safety management tasks	the effectiveness of safety management tasks
KPIs	undefined	safety management systems safety behaviour safety leadership
Active and Passive indicators (Hinze et al., 2013b)	a set of selected measures that describe the level of effectiveness of the safety process	effectiveness of the safety process

(2) Problematic simplification process

Leading indicators simplify and quantify complex safety realities to a manageable amount of meaningful information (foresight, rather than hindsight), feed decisions, and direct remedial actions. Oversimplification may generate incorrect or incomplete information and an enormous amount of information can cause difficulties in

interpretation, which deviates from the initial purpose of leading indicators. However, the simplification process by which existing leading indicators were developed has been problematic. They monitor safety conditions and identify safety problems mainly by measuring fragmented safety practices and activities. The rationale behind the method is that safety management system (SMS) safety practices are casually linked to safety outcomes. However, in reality, the connection between the SMS and safety outcomes is ambiguous and invalid, or at least indirect (Hopkins, 2007, Gallagher et al., 2003a). There are a number of reasons for this. First, there exist knowledge gaps in the effectiveness of safety management systems (Hale, 2003); knowledge about the functioning, culture and political dimensions is still limited. For example, SMSs tend to overemphasize process and procedure but underemphasize the human element and cultural factors (Choudhry et al., 2007, Wachter and Yorio, 2014b). Therefore, the information about SMSs often cannot explain why workers did not do what they were supposed to do. Second, the SMSs used in the construction industry are generally incomplete (Perezgonzalez, 2005, Costella et al., 2009). Some contractors rely on intuition and word of mouth when designing site-specific safety practices (Hallowell and Gambatese, 2009). In consequence, leading indicators have limited analytic soundness and predictability when they measure an SMS with inherent deficiencies. Empirical evidence appears to support this stance. For example, Hopkins's (2007) analysis of the Gretley mine disaster demonstrated that the presence of an SMS is not adequate for preventing accidents.

The problematic simplification process can be in part attributed to a limited understanding of complexity of construction safety. Indeed, it is difficult to simplify complexity before we understand it. In fact, construction industry exhibits unique

characteristics such as different trades, multi-organisational project structure, constantly changing work environment, and transient workforce (Rowlinson, 2004). The industry is labour intensive, dominated by a large proportion of small businesses with low level of ability and motivation to manage safety because of resources constraints (Legg et al., 2009). Less educated workers move from one project to another, which poses barriers against the development of safety culture (Lunt et al., 2008). Various pressures (e.g., production pressure and peer pressure) that exist on site are likely to undermine site safety (Mullen, 2004, Kyle, 2013, Wilson and Koehn, 2000). The tendency towards standardized safety practices makes organisational learning less effective (Howell et al., 2002, Mitropoulos et al., 2005). In addition, multiple stakeholders (e.g., regulators, union, clients, main contractors, subcontractors and workers) play various roles in contributing site safety, which causes coordination problems (Huang and Hinze, 2006, Smith and Roth, 1991, Toole, 2002, Rowlinson et al., 2003). These unique characteristics set construction apart from many other industries and pose significant practical challenges to simplify complex safety realities. Theoretical challenges also exist. Leading indicators represent proxies that are causally linked to accident and safety. Modern accident models (e.g., Swiss cheese model) have extended the causes of accidents to organisational factors and emphasizing the interrelationships between organisational deficiencies (latent failures) and human errors (active failures) (Reason, 1997). A good understanding of the interrelationships can facilitate the simplification process. Unfortunately, the cause-effect relationship with the accident sequences is not so clear with organisational factors (Le Coze, 2005). This has led to difficulties in predicting both organizational and individual behaviour. If the complex cause-effect relationships between the

organisational, technical, and human factors are poorly defined and understood, the mechanisms by which these factors shape human behaviours at the sharp end remain unclear.

(3) A lack of development method

No development methods exist that guides the development of leading indicators for the construction industry. A closer examination of the existing leading indicators in the construction industry reveals that the development method (or process) disconnect with the ultimate purpose of leading indicators. Validity, predictability, and practicability of those previous construction leading indicators have seldom, if ever, been tested. The fundamental question “is the information obtained from indicated phenomena (such as accidents, safety practices or abstract safety constructs) adequate and useful for this purpose?” has not been fully addressed (Hopkins 2009). Indeed, leading indicators should not be picked just because they are easily available. They should be developed based upon sound theoretical basis (Wreathall, 2009) and the causal links between indicators and outcomes should be explicit (Dyreborg, 2009).

2.8 Summary

This chapter revisited the nature of leading indicators. It is concluded that the concept of leading indicator is still not clear, and the understandings of what should be measured vary widely. The debate over the distinction between leading and lagging indicators reflects a lack of understanding of accident causation process and relationships between factors at different hierarchical levels. Although causes of accident have been extended to organizational factors, “the further upstream we move

from the loss, the less certain we can be about the validity of our measures as to the risk of accidents”, as Kjellén (2009) pointed out. The varied understandings may be justified by the youth of the concept of a leading indicator. However, it may hinder the development and use leading indicators in specific industries.

This chapter reviewed developments and applications of leading indicators in various industries. Existing leading indicators can generally categorized into four types: event based, barrier based, safety practices based, and safety construct based indicators. These developments and applications added to a body of scientific knowledge of leading indicators. However, there are still a number of conceptual and practical challenges with regard to definition, simplification process, development method, and validation. Chapters 2, 3, 4, 5, 6, 7, and 8 are aimed at dealing with these challenges.

Chapter 3 A Pragmatic Method for Systematically Developing Leading Indicators

3.1 Introduction

This chapter develops a pragmatic method for systematically developing leading indicators, with an effort to fill the research gap discussed in Chapter 2. A conceptual framework is developed to provide theoretical guidance on how to develop leading indicators by connecting the definition, purpose, type, and development process. The framework defines leading indicators as a *set* of quantitative and/or qualitative measurements that can describe and monitor validly and reliably the *safety conditions* of a construction project. The conceptual framework adopts a dynamic perspective and views safety conditions as a dynamic phenomenon, created, improved and maintained by safety practices. The independence between safety practices and safety conditions highlights that leading indicators should not be randomly selected to measure existing safety practices but should be developed to describe and monitor specific safety conditions through a systematic development process.

This chapter then proposes a pragmatic method for systematically identifying a set of leading indicators for construction projects. The method consists of four steps, conceptualization, operationalization, indicator generation, validation and revision, and it emphasizes two functions of leading indicators: informative and decision-aiding.

A hypothetical example is provided to illustrate the entire development process. The conceptual framework, together with the development method, provides the construction industry with both theoretical and methodological guidance on developing leading indicators that can better serve the purpose of proactive safety management.

3.2 A conceptual framework to develop leading indicators

Jesson and Mayston (2004) identified three conditions for the successful use of performance indicators: 1) a clear conceptual framework within which the indicators are derived and the associated set of purposes that they are intended to serve, 2) a selection process to determine which indicators are to be applied and how, and 3) a specification of how the indicators fit into management and decision-making processes. Cave (1997) also claimed that performance indicators should be developed within a conceptual framework that is coherent with the definition and purpose for which they are used. Although the author's claims were not made in the safety field, they are applicable to the development of leading indicators. However, there is no conceptual framework that provides theoretical guidance on developing leading indicators in the construction industry, and safety practitioners face challenges in developing indicators that fit well in safety programs (Hinze et al., 2013b).

In developing and using leading indicators, there is a need to model the causal relationships between contributing factors and safety outcomes and, at the same time, suggest how the information provided by the indicators aids in practical safety management decision making on site. As discussed in the previous sections, there are

inherent conflicts between these two requirements. Enhancing the analytic soundness of leading indicators may result in their declining practicability. Thus, there is a need for a systematic development process that can strike a balance between these two essential attributes. In addition, because of the current knowledge gaps in the concept of early accident warnings (Woods, 2009), it is unrealistic to identify valid and reliable leading indicators using one-off practices. It is therefore important to integrate the validation, reflection, and reconceptualization of leading indicators into the development process.

Considering this, this section proposes a conceptual framework that aims to clarify the nature of leading indicators and provide theoretical and methodological guidance on developing them (Figure 3.1). This conceptual framework is based on two Rasmussen's safety models: the model of migration (Figure 3.2. left) and the socio-technical system view (STS) (Figure 3.2. right), (Rasmussen, 1997, Rasmussen et al., 2000, Le Coze, 2013a). The models adopt a dynamic and macro socio-technical view of safety. Rather than focusing on individual behaviours (e.g., human errors), they focus on the macro behaviour of socio-technical systems (Le Coze, 2013a). The central idea of the model of migration is that under workload and economic pressures, the state of safety tends to migrate closer to, and even cross, the boundary of functionally acceptable performance. The purpose of safety efforts is to prevent this slow migration towards high risk. According to the socio-technical system view (STS), many nested levels of decision-making are involved in risk management, including government, regulators, companies, and individuals.

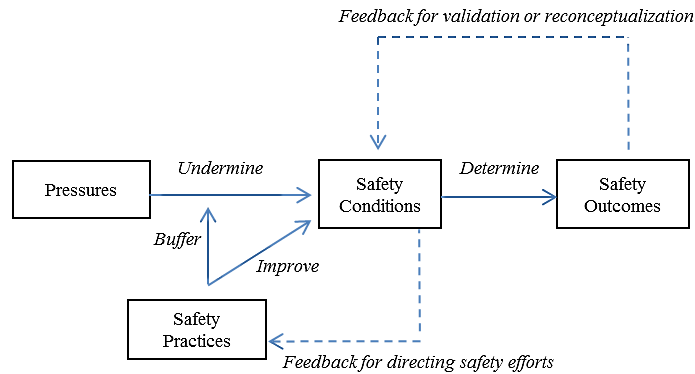


Figure 3.1 A conceptual framework for developing leading indicators

Rasmussen’s models have been widely used as tools for accident investigation (Kontogiannis, 2012, Salmon et al., 2012), and their validity has been tested (Vicente and Christoffersen, 2006, Cassano-Piche et al., 2009). These two safety models have also been successfully applied to construction safety. For example, Howell et al.(2002) reported that Rasmussen’s models offer broader and more powerful views on construction safety. Based on the models, the authors identify three zones of operation: 1) the “safe zone”, where workers’ behaviours are within the boundary, 2) the “hazard zone”, and 3) the “loss of control” zone. Similarly, Mitropoulos et al.(2005) develop a systems model of construction accident causation by adopting Rasmussen’s dynamic view on safety. Their model emphasizes the role of production pressure in undermining safety levels by pushing workers toward high risk.

Rasmussen’s two safety models offer a new perspective on safety performance measurement. They see safety as a control problem that involves decision makers at different hierarchical system levels. Rather than striving to control behaviour by eliminating deviations, these descriptive models emphasize the notion of variability and adaptation for an organization in its environment (Le Coze, 2013a). It is of particular importance to identify the control structure, i.e., controllers, performance

criteria control capability and information about the actual state of the system. This is consistent with the functions of leading indicators (informative and decision-aiding) that are aimed at motivating people in various positions and keeping the safety state distant from the boundary of acceptable performance through feedback and control (Hale, 2009, Loosemore, 1998).

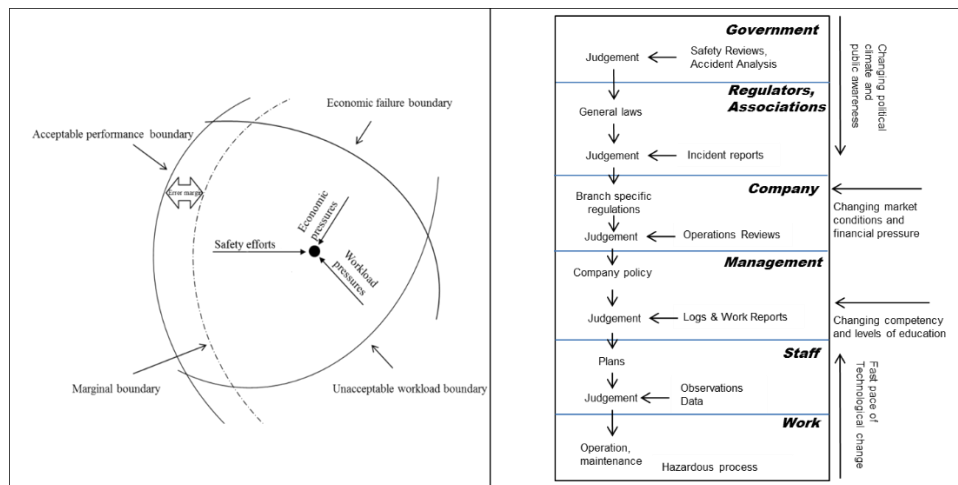


Figure 3.2 Rasmussen's two safety models

3.2.1 An overview of the proposed conceptual framework

3.2.1.1 Definition and purpose of leading indicators

This conceptual framework defines leading indicators as a *set* of quantitative and/or qualitative measurements that can describe and monitor validly and reliably *the safety conditions* of a construction project. This definition clarifies the nature of leading indicators in terms of the indicated phenomenon of interest, formation, and the level of analysis. First, the definition clearly specifies that the indicated phenomenon of interest is the *safety conditions* of a construction project. Changes in safety conditions lead to changes in safety levels and, thus, the possibility of on-site accidents. By describing and monitoring the safety conditions, leading indicators are able to reflect the possibility of accidents. This ensures that they reach the purpose of providing

foresight for proactive safety management. Second, the definition emphasizes that leading indicators should be developed and used as a functional set rather than individually. It is not possible to determine the accident risk level as a whole using fragmentary indicators. This is based on the consideration that safety phenomena are complex (Goh et al., 2012c) and that limited and discrete indicators may therefore not be adequate to capture the complexity and reflect a project's safety conditions. Third, the definition establishes the construction project as the level of analysis in developing and using leading indicators. Although it is true that most leading indicators were designed for internal company use, there is a need for indicators that can be used at the project level because site safety is dependent on a joint effort by clients, the principal contractor, and all subcontractors.

3.2.1.2 Safety conditions

The concept of safety conditions is defined herein as the state of the system with regard to its capability to produce safety. Safety conditions as a high-level construct are not directly measurable. Thus, they must be used to theorize and derive medium-level constructs that are measurable by being placed in the context of existing safety knowledge. The values of these constructs explain the current state of safety and determine the possibility of accidents. Such an explanation, however, must be based on a theoretically sound safety model that explains why accidents occur and how safety can be achieved. The reliability and validity of leading indicators is largely dependent on the appropriateness of the chosen safety model.

3.2.1.3 Safety practices

Vinodkumar and Bhasi (2013) define safety practices as “the policies, strategies, procedures and activities implemented or followed by the management of an

organization targeting safety of their employees”. In the conceptual framework, safety practices are conceptualized as positive forces that create, improve and/or maintain a system’s safety conditions. In this sense, safety practices do not determine safety outcomes in a direct manner. Instead, their effects on safety outcomes are mediated through the safety constructs (Wachter and Yorio, 2014b). It is for this reason that the effectiveness of safety practices should be assessed collectively against how well they improve safety conditions rather than individually against how well each one is performed.

3.2.1.4 Pressures

Pressures are defined as negative forces that tend to worsen a system’s safety conditions. Examples include production, cost and peer pressures (Rasmussen, 1997, Mullen, 2004). These pressures partly result from unique characteristics of the construction industry such as the temporary nature of projects, the use of subcontractors, and a transient and less educated workforce (Hallowell and Gambatese, 2009, Liao et al., 2013). These are often the sources of safety condition dynamics. Similar to safety practices, pressures indirectly affect safety outcomes by undermining safety conditions. For example, production pressure may cause managers and supervisors to invest less time and energy in safety and even encourage workers to take shortcuts to meet production schedules. As a consequence, the level of manager and supervisor safety leadership is likely to decline, which leads to the deterioration a given project’s safety conditions.

3.2.1.5 Safety outcomes

Safety outcomes in the conceptual framework include near misses, incidents, accidents, and safety (i.e., no accidents). They are outcomes of the system’s safety

conditions. They are also the most reliable and objective criteria for validating leading indicators.

3.2.1.6 The relationships among pressures, safety practices, safety conditions and safety outcomes

The conceptual framework views a system's safety conditions as a dynamic concept that is affected by both safety practices and pressures. As shown in Figure 3.3, safety conditions change over time owing to the effects of both positive (safety practices (SP)) and negative (pressures (P)) influences. In different phases, new pressures (e.g., production pressure) may emerge, and safety practices must be optimized to address these pressures. Such changes reflect the dynamics of safety conditions and in turn alter the possibility of accidents.

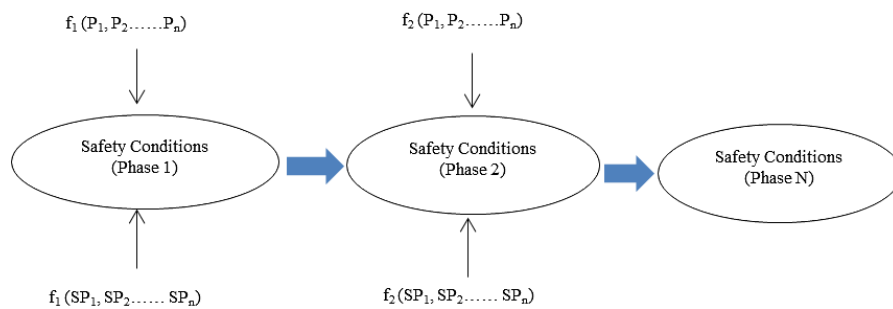


Figure 3.3 Dynamics of safety condition

This independence between safety practices from safety conditions is useful in developing leading indicators. First of all, from a methodological perspective, understanding safety practices and activities as positive forces in changing safety conditions allows for bridging the connection between scientific and managerial dimensions of the attributes of leading indicators. Second, this understanding allows leading indicators to help update and improve individual safety practices and the safety management system as a whole. In fact, according to the SMS framework developed

by Hale et al.(1997b), safety performance measurement, as an essential part of an SMS, aims to describe and recognize safety problems by comparing the current against the desired situation to improve the SMS. Measuring safety practices within the SMS without considering changing safety conditions would not be able to identify the internal deficiencies of the system itself and therefore make double-loop learning extremely difficult if not impossible.

3.3 A proposed development process

Based on the conceptual framework developed in Chapter 2, this chapter proposes a method for developing a set of leading indicators that can measure construction projects' safety conditions. To this end, the method addresses two specific issues: (1) what constitutes safety conditions and (2) how pressures and safety practices affect safety conditions. As shown in Figure. 3.4, the method consists of four steps: conceptualization, operationalization, indicator generation, and validation and revision. The method is described in details as follows.

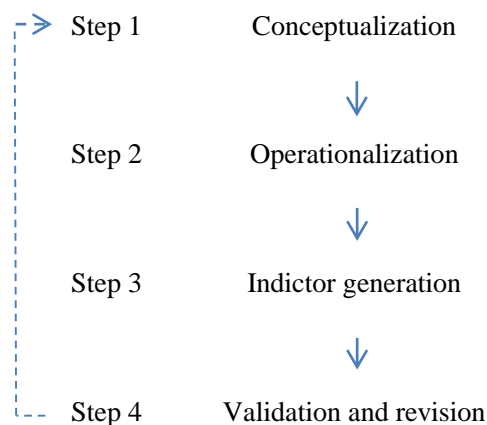


Figure 3.4 Four steps to develop leading indicators

3.3.1 Conceptualization

Step 1 aims to conceptualize the construct of safety conditions. The conceptualization process aims to describe the construct in ways that allow it to be understood and distinguished from other related constructs (Viswanathan, 2005). There are two sub-steps in conceptualization.

3.3.1.1 Conceptual definition

The concept of safety conditions was defined in the previous section as the state of the system with regard to its effectiveness in producing safety. Another issue in conceptualization is determining the level of analysis. Because the conceptual framework has determined that leading indicators should be used at the project level, safety conditions should be conceptualized at the same level.

3.3.1.2 Domain specification

This sub-step involves identifying the dimensions of the construct of safety conditions. One difficulty in this process is that the construct is underdeveloped and its dimensions have not been fully investigated. Viswanathan (2005) suggests that conceptualizing a construct requires placing it in the context of existing knowledge to understand what it is and is not. Following this suggestion, a safety model should be adopted that provides theoretical guidance on specifying the dimensions of safety conditions. This is critical because safety models not only specify key interrelated safety constructs but also provide causal links between these constructs and safety outcomes (Hovden et al., 2010).

3.3.2 Operationalization

Operationalization is a process of defining a construct that is not directly measurable in ways that can be readily and accurately measured (Soucacou and Sylva, 2010a). In this step, the safety condition dimensions are further operationalized into measurable proxies. Two requirements should be met in this process:

- 1) For leading indicators to be analytically sound and scientifically credible, measurable proxies must be causally linked with safety outcomes.
- 2) Measurable proxies must be compatible with practical safety management processes. This refers to the managerial requirements for leading indicators.

As suggested in the conceptual framework, the safety conditions of a construction project can be operationalized into measurable safety practices. Based on the mechanisms by which safety practices improve safety conditions and buffer against pressures, the safety condition dimensions indicated by different safety practices become clear, and therefore, the causal links between safety practices and safety outcomes can be bridged. The operationalization process allows for a meaningful transition from abstract safety condition dimensions (e.g., safety leadership and motivation) to tangible safety practices so that these two requirements can be met.

3.3.3 Indicator generation

The aim of this step is to design a set of indicators to measure selected safety practices. Appropriate measures should be designed to reflect the level of each safety condition dimension as accurately as possible. Typical measures include the number or frequency of safety practices (e.g., toolbox meetings, site inspection). It should be borne in mind that measures are not designed to measure a safety practice itself but

the relevant dimensions of the safety conditions behind it. Only in this way can leading indicators, as a functional set, reflect a project's safety conditions.

3.3.4 Validation and revision

Step 4 involves validating, and revising if necessary, the proposed leading indicators. Because of the complexity of safety phenomena and the possible inappropriateness of the safety models that are adopted to conceptualize the concept of safety conditions, the proposed indicators are tentative and should be validated, a necessary step in developing leading indicators. Two methods can be used for indicator validation. First, leading indicators can be validated through comparison (Bockstaller and Girardin, 2003). The information provided by leading indicators can be compared with measured data from real projects. Thus, consistencies or inconsistencies can be investigated and analysed. The second validation method is based on the judgment of experts (Mayer and Butler, 1993, Kleinert and Kearns, 1999, Taylor et al., 1993, Cloquell-Ballester et al., 2006). Leading indicators can be submitted to a panel of safety experts, and both the scientific and managerial attributes of indicators can be assessed.

Revision and refinement of leading indicators can be conducted based on the experts' judgments. In addition, if inconsistencies between leading indicators and real safety outcomes occur, the processes of conceptualization and operationalization should be reconsidered. This is important because it allows for double-loop learning (Argyris, 1999): the information that leading indicators provide must not only aid in decision making and evaluate safety processes (Young, 1996) but also reflect an existing safety

model and facilitate the construction of a new one. This refers to a re-conceptualization of the safety condition construct based on a more valid safety model.

3.4 An application of the development process

To illustrate the application of the proposed method, this section develops a set of leading indicators for a hypothetical construction project.

3.4.1 Conceptualization

Consistent with the conceptual framework, the project’s safety condition structure is determined based on a hierarchical vision of the STS. There are five system levels: inter-organizational, organizational, group, individual and working conditions. One of the weaknesses of the STS is that it does not provide information about the dimensions that should be concretely monitored, and therefore, the factors that should be included in each system level remain unclear (Le Coze, 2013a).

Thus, an extensive literature review was conducted with an attempt to identify key factors at these levels and interrelationships among these factors. Table 3.1 provides dimensions of these multidimensional constructs at each system level.

Table 3.1 Dimensions of first order safety constructs

Safety Constructs			Dimensions	References
Inter-organizational Level	Client leadership	safety	Procurement process Safety requirements Active participation	(Huang and Hinze, 2006, Hinze, 1997, Jawahar-Nesan and Price, 1997)
	Subcontractor leadership	safety	Procurement process Safety requirements Active participation	(Hinze and Figone, 1988)
Organizational Level	Principal Manager leadership	contractor safety	Value & vision clarification Safety resource support Personal involvement	(Conchie et al., 2013, Mearns and Reader, 2008, Michael et al., 2005, Choudhry et al., 2007, Hu et al., 2011)

			Empowerment & control Feedback & reward	
Group Level	Social support		Supervisor safety leadership Co-work support	(Conchie et al., 2013, Barling et al., 2002)
Individual Level	Worker competency	safety	Skills to use equipment, tools and plants Hazards information Safety rights/responsibilities	(Vroom, 1964) (Neal et al., 2000, Vinodkumar and Bhasi, 2010).
	Worker motivation	safety	Amotivation Extrinsic safety motivation Intrinsic safety motivation	(Fleming, 2012b)
Working condition Level	Physical hazard level		Housekeeping Site layout Equipment and tools Materials	(Perlman et al., 2014, Carter and Smith, 2006)

Previous studies suggest that there are four key pressures: production pressure, peer pressure, role overload, and changing working conditions (Mullen, 2004, Kyle, 2013, Carter and Smith, 2006) that tend to worsen the safety conditions. The mechanisms by which these pressures worsen safety conditions are investigated based on a literature review (Table 3.2).

Table 3.2 The mechanisms that pressures worsen the safety condition

Pressure	Mechanisms to change safety condition	Influenced constructs
Production pressure	Production pressure is caused by planning inadequacies or misjudgements, bad weather, and errors in delivery dates. (Conchie et al., 2013) Perceived production pressure results in a degradation of safety and encourages worker to take a shortcut and behave unsafely so as to reach production goals (Rundmo et al., 1998, Mitropoulos et al., 2005). Production pressure “depletes supervisors’ energy, availability and time, and consequently, their safety-related interactions with employees”. (Conchie et al., 2013, Sun et al., 2008)	Manager safety leadership Supervisor safety leadership Co-worker support Worker safety competency Worker safety motivation
Peer pressure	Workers behave unsafely in order to maintain a “tough man” image, and to avoid being teased or made fun of by co-workers(Mullen, 2004).	Co-worker support Worker safety motivation
Role overload	Safety in the construction industry has been generally considered as a separated part of job. As such, role overload tend to decrease managers’ or supervisors’	Manager safety leadership

	time on safety and “dilute the perceived importance and salience of safety, increase cognitive load, and at a more basic level, reduce the amount of time that supervisors focus on safety.” (Conchie et al., 2013)	Supervisor safety leadership
Changing working conditions	Constantly changing working environment involves unknown hazards and therefore makes it hard to control(Carter and Smith, 2006).	Physical hazards Worker safety competency

Based on Tables 3.1 and 3.2, a safety condition map of this project can be developed that specifies the project’s safety condition dimensions and the relationships among them (Figure 3.5). Eight safety constructs (client, subcontractor, and principal contractor safety leadership, social support, worker safety competency, worker safety motivation, safety behaviour and physical hazards) and four pressures (production pressure, peer pressure, role overload, and changing working conditions) are integrated into the safety condition map based on the mechanisms by which they affect safety conditions.

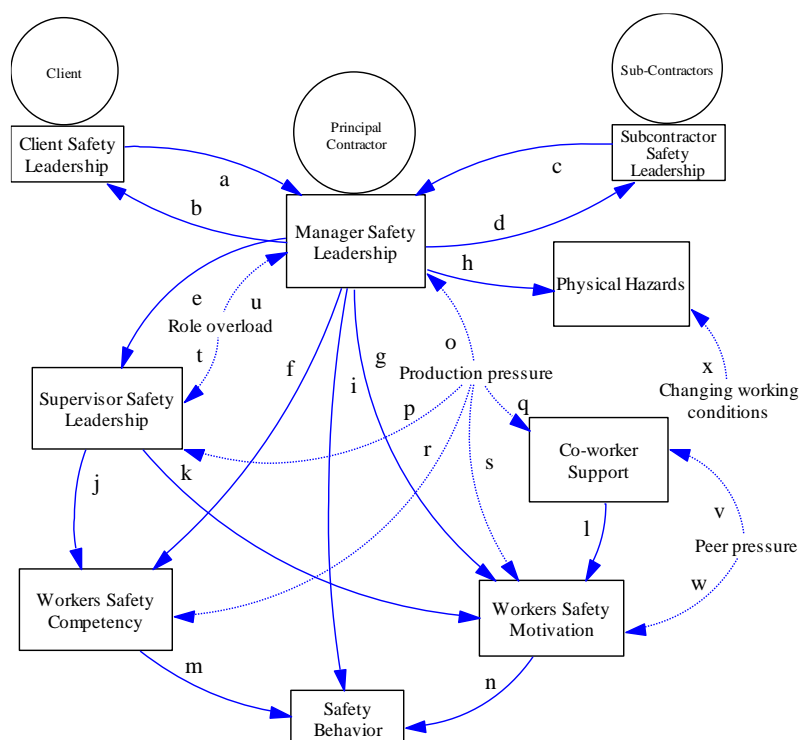


Figure 3.5 A safety condition map of a construction project

3.4.2 Operationalization

To operationalize safety condition into safety conditions, the mechanisms by which safety practices improve a project's safety conditions need to be investigated. Safety practices can be categorized into three groups according to the ways in which they improve safety conditions:

1). Safety practices as effects of a safety construct

As shown in Figure 3.6, the state of safety construct A is demonstrated through safety practices A, B, and C. Safety practices in this group can be considered outcomes, rather than causes, of the state of safety construct A. As an example, safety practices such as written safety policy, attending safety meetings, and providing safety resources that demonstrate manager safety leadership can be categorized into this group.

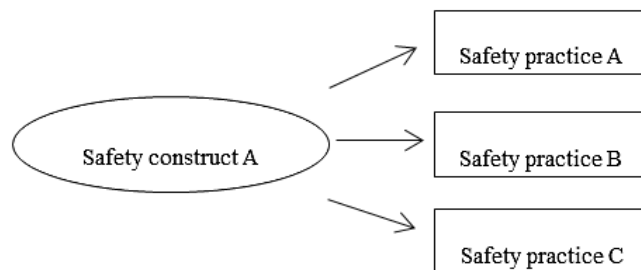


Figure 3.6 Safety practices as effects of a safety construct

2). Safety practices as causes of a safety construct

Safety practices in this group are considered causes rather than effects of safety construct A (Figure 3.7). These practices are implemented to directly or indirectly improve the state of safety construct A. For example, various safety practices (e.g.,

training, toolbox meetings) are designed and implemented to improve workers' safety knowledge.

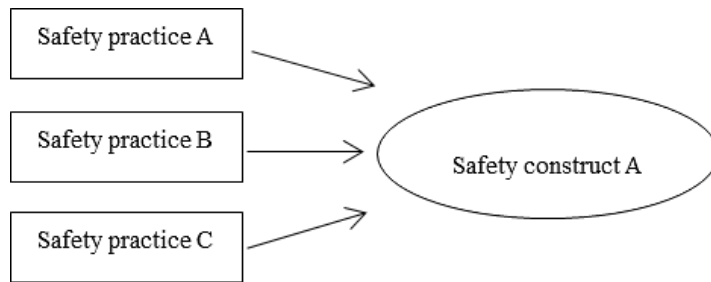


Figure 3.7 Safety practices as causes of a safety construct

3). Safety practices as buffers against pressures

Safety practices can be designed and implemented to buffer against the adverse effects of pressure A on safety construct A (Figure 3.8). For example, under production pressure, managers are likely to place production over safety, thus tending to decrease the level of manager safety commitment. To overcome this adverse effect, appropriate safety practices such as staff resource optimization and schedule management should be designed and implemented.

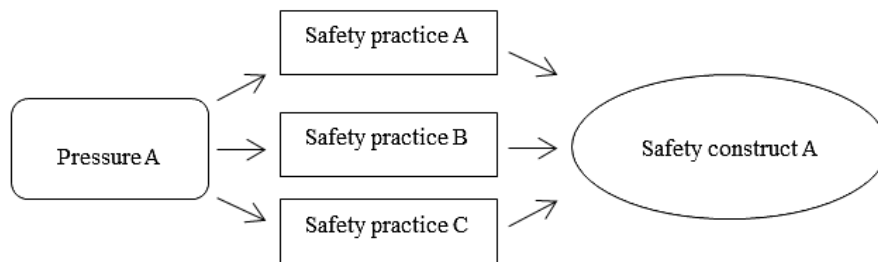


Figure 3.8 Safety practices as buffers against pressures

According to the safety condition map drawn in step 1, a set of safety practices are chosen to address all elements within the map. The mechanisms of improving project safety conditions and addressing pressures are provided in Table 3.3.

Table 3.3 Mechanisms of safety practices to change safety condition

Safety practices	Mechanisms to change safety condition	Influenced constructs
Specific safety prequalification	The Procurement procedures can raise the safety standard on individual projects. By considering safety in procurement stage, the winning tender is more likely to be the one that places emphasis on safety(Wells and Hawkins, 2014).	Safety leadership (Client, and principal contractor)
Safety meetings	Regular safety meetings provide opportunities to discuss safety problems and improve safety motivation.	Safety leadership (Personal involvement)
Written safety policy	safety policy is normally signed and dated by senior managers, which indicates safety objectives, safety responsibilities and demonstrates management commitment to safety (Hughes and Ferrett, 2012).	Safety leadership (Value & vision clarification)
Provide adequate safety resources	Providing adequate safety resources helps workers maintain safety on site.	Safety leadership (Value & vision clarification)
Safety training for workers	Training is defined as “instruction and practice for acquiring skills and knowledge of rules, concepts, or attitudes necessary to function effectively in specified task situations(Cohen and Colligan, 1998, Pellicer and Molenaar, 2009).	Safety leadership (Safety resource support) Safety competency Safety motivation
Safety training for supervisors	Senior managers support supervisors by providing their safety training. The training programs can improve supervisors’ ability and motivation to safety.	Safety leadership
Safety professionals (managers, administrators)	Safety professionals act as a communicator that understands the issues to managerial personnel and that passes on related information to these personnel(Cooper, 1998, Hale et al., 2005, Swuste and Arnoldy, 2003, Wu, 2011). Safety professionals improve safety condition by sharing following responsibilities: hazard recognition, inspections/audits, fire protection, regulatory compliance, health hazard control, ergonomics, hazardous materials management, environmental protection, training, accident and incident investigations, advising management, record keeping, evaluating, emergency response, managing safety programs, product safety, and security(Wu, 2011).	Safety leadership Worker safety motivation
Safety rules and procedures	Safety rules list the specific activities to do or avoid for competing the job effectively and safely, like rules related to the drug and alcohol (Minchin Jr et al., 2006). They represent managers’ control over safety.	Safety leadership (Empowerment & control)
Involve workers in safety-related decision making	Involving workers in safety-related decision making can facilitate worker’s participation and therefore increase worker safety motivation.	Worker safety motivation
Incentive programs	Safety incentives are reward techniques used by organizations to improve their health and safety results. It is used to motivate and/or support safety behaviours. (Haines et al., 2001, Geller, 1999)	Safety leadership (Feedback & reward) Worker safety motivation

Safety coaching	Safety coaching is an inter-personal process of one-on-one observation and feedback. Safety coaches support safety behaviours and offer useful and caring feedback regarding any risky behaviours observed(Geller et al., 2004)	Supervisor safety leadership
Minimum ratio of the number of supervisors to workers	Increasing the number of supervisors can buffer the role overload.	Role overload
Worker-to-worker observation program	Worker-to-worker observation program motivates workers to take care of co-workers' safety by cautioning their unsafe behaviours.	Co-work support
Work-hour restrictions	Work-hour restrictions can avoid or mitigate the effects of fatigue on safety.	Production pressure Worker safety competency
Toolbox meeting	“Toolbox meetings are a way for information to be provided to workers, and for workers to have their say about hazards/controls, incidents/accidents, work processes and company procedures.”(Site Safe New Zealand, 2012b)	Supervisor safety leadership Worker safety competency Safety motivation
Job safety analysis (task analysis)	Job safety analysis is implemented to identify hazards in construction activities and provide a database of accident scenario(Rozenfeld et al., 2010)	Safety competency
Housekeeping	Effective housekeeping can eliminate some workplace hazards and help get a job done safely and properly.	Physical hazards
Equipment &tools maintenance program	The primary goal of maintenance is to avoid or mitigate the consequences of failure of equipment and tools.	Physical hazards
Hazard management	Hazard management is the cornerstone of health and safety management systems – the key tool for meeting employer obligations to “take all practicable steps to prevent harm or injury” Step 1: Identification Step 2: Risk assessment Step 3: Controls Step 4: Monitor and review	1. Provide safety knowledge of physical hazards 2. Enhance workers' ability to manage physical hazards on site.
Pre-task safety planning	Hazard Controls are discussed by which hazards can be eliminated, avoided or managed, through changing task sequence, guards or the use of personal protective equipment.	Physical hazards Changing working conditions
Stop-work authority	Stop-work authority establishes the responsibility and authority of any individuals to stop work when an unsafe condition or act could result in an undesirable event.	Production pressure

3.4.3 Indicator generation

Once essential safety practices are chosen, concrete leading indicators can be developed to measure them. Table 3.4 presents a set of 32 leading indicators that describe and reflect the safety conditions of the hypothetical project.

Table 3.4 A proposed set of leading indicators

Addressed elements of safety condition map	Proposed leading indicators
Client safety leadership Links: a, b	(1) principal contractors are selected in part on the basis of satisfying historical safety performance (2) frequency that safety representatives of client visit the site (3) frequency that clients attend safety meeting on site (4) percent of subcontractors selected in part on the basis of satisfying historical safety performance
Sub-contractors manager safety leadership Links: c, d	(5) frequency that subcontractors attend safety meeting, toolbox meeting, and safety planning (6) frequency that subcontractors report safety performance to principal contractor
Principal contractor Manager safety leadership Workers safety motivation Role overload Production pressure Links: e, f, g, i, n, o, u	(7) written safety policy signed by senior managers in place (8) frequency that senior managers attend safety meeting (9) safety managers are set up on site (10) adequate safety resources (e.g., PPE) are provided on site (11) employees are provided opportunities to be involved in safety management (12) frequency that senior managers provide feedback on safety performance (13) frequency that senior managers reward good safety performance (14) frequency that supervisors discuss safety with workers (15) frequency that supervisors attend safety meetings
Supervisor safety leadership Role overload Peer pressure Links: e, t, j, k, v, w, p	(16) frequency that supervisors involved in hazard management (17) ratio of the number of supervisors to workers (18) supervisors' job is supported by senior managers (19) percent of supervisors with Site Safe Supervisor Gold Card (20) managers and supervisors emphasize safety when training new employees
Co-worker support Worker safety motivation Links: l, q	(21) worker-to-worker observation program in place (22) frequency that co-workers caution each other when they behave unsafely (23) frequency that co-workers speak up for safety (24) percent of workers with certificates to operate equipment, tools and plants (25) percent of workers of principal contractor with Site Safe training passport
Worker safety competency Production pressure Links: k, m, r, s	(26) percent of workers of subcontractors with Site Safe training passport (27) percent of workers provided with hazards information about the project (28) workers have stop-work authority (29) working hours per day

Physical hazards	(30) frequency that safety planning is conducted before performing tasks
Changing working conditions	(31) systematic hazard management program in place
Links: h, x	(32) safety rules and procedures in place

3.4.4 Validation and revision

The research findings of this study were validated with a two-phase approach as suggested by Bockstaller and Girardin (2003). This approach involves three types of validation: (1) conceptual, (2) output, and (3) end-use. The overall validation procedure is presented in Table 3.5.

Table 3.5 Validation: a two-phase approach

Phase	Types of Validation	Validation Method	Attributes
I	Conceptual	Literature review Semi-structure interviews	Analytic soundness
II	Output	Expert judgment	Analytic soundness
	End-use		Predictability Practicability Cost-effectiveness

Phase I Conceptual validation

Because the leading indicators were developed from the safety condition map (Figure 3.5), their conceptual validity will logically depend on the validity of the map. Thus, the aim of this phase is to validate the safety condition map. As discussed, the safety condition map was developed based on Rasmussen's safety models: the model of migration and the socio-technical system view (STS). The safety constructs included in the map, their dimensions, and the relationships among them were determined based on an extensive literature review. This provides a solid theoretical basis for the safety condition map and thus ensures its conceptual validity in the first place. In this phase, semi-structured interviews with 15 health and safety managers/advisors (hereafter, the

‘experts’) in the construction industry were conducted to confirm the developed safety condition map. These experts were identified using convenience and snowball sampling (Bryant and Charmaz, 2010), and the experts’ profiles are summarized in Table 3.6.

During the interviews, the conceptual validation was concerned with the question “Are the indicators scientifically founded?”, which addressed the core attribute of analytic soundness. The experts were asked how they could tell whether a site was safe from a proactive perspective, or they were asked to identify key safety factors that can reflect a construction project’s safety level. Based on the experts’ judgments, nine safety constructs emerged: (1) *management safety commitment*, (2) *subcontractor safety management*, (3) *supervision*, (4) *production pressure*, (5) *peer pressure*, (6) *safety attitude*, (7) *safety competency level*, (8) *safety knowledge*, and (9) *safety culture*.

Next, these nine constructs were compared with those on the safety condition map. The findings suggest that there is considerable overlap between the safety constructs that emerged from interviews and those included in the safety condition map. In this manner, the safety condition map was tested for conceptual validity.

Phase II Output and end-use validation

This phase involves two types of validation: output and end-use. Output validation refers to the ability of leading indicators to provide valid and reliable information about a project’s safety conditions. It is an important test that further assesses leading indicators’ analytic soundness and predictability. End-use validation addresses the practicability and cost-effectiveness of leading indicators. It is suggested that output validation be conducted by comparing the information provided by indicators with real safety outcomes (Vinnem, 2010, Øien, 2001a, Bockstaller and Girardin, 2003).

However, because the leading indicators were developed for a hypothetical scenario in this case, such a test is not possible. Nevertheless, Bockstaller and Girardin (2003) suggest that expert judgment is an alternative method to output and end-use validation. Among the 15 experts, 5 had experience developing and using leading indicators. As such they were selected to participate in this phase of validation. They were provided a questionnaire and asked to rate the indicators against the evaluation criteria (as shown in Table 3.2) with regard to four attributes: analytic soundness, predictability, practicability and cost-effectiveness. On the questionnaire, the practicability and cost-effectiveness were evaluated for each single indicator based on a five-point Likert (ranging from 1= lowest level to 5= highest level) scale, in which ratings of 1–2, 2–4, and 4–5 were considered "invalid," "indeterminate," and "highly valid," respectively. As discussed, the attributes of analytic soundness and predictability should be assessed for the full set of leading indicators. Thus, a ten-point Likert scale (ranging from 1= lowest level to 10= highest level) was used to evaluate the analytic soundness and predictability of the indicators. On this rating scale, ratings of 1–4, 4–7, and 7–10 were considered "invalid," "indeterminate," and "highly valid," respectively. In addition, experts were allowed to provide extra comments, which helped the authors revise the indicators.

All four experts completed and returned the questionnaire. The average ratings for the four attributes of leading indicators are presented in Table 3.7. For the full set of indicators, the average scores for analytic soundness and predictability were 8.0 and 7.2 (out of 10), respectively, suggesting that the leading indicators had a strong scientific and conceptual basis and could provide early warnings of accidents from the experts' perspectives. In addition, with regard to practicability, of all 32 indicators, 20

were rated highly valid, and the remaining 12 were rated indeterminate. For cost-effectiveness, 22 indicators were rated highly valid, and the remaining 10 were rated indeterminate. The results indicated that, overall, experts strongly agreed with the practicability of the leading indicators.

Minor revisions were made based on the experts' comments: The fifth indicator was changed to "(5) frequency with which site managers attend safety meetings and toolbox meetings and participate in safety planning." The 17th indicator was revised to "(17) supervisor-to-worker ratio".

Table 3.6 Experts' Profile

Experts	Position	Work experience in the field of health and safety
1	Health and safety manager	Over 25 year s
2	Senior safety consultant	Over 25 years
3	Health and safety manager, Leader of health and safety group of a construction company	Over 12 years
4	Senior health and safety advisor	Over 11 years
5	Safety consultant	Over 10 years
6	Client health and safety manager	11 years
7	Health and safety advisor	10 years
8	Group health and safety manager	Over 12 years
9	Health and safety inspector	27 years
10	Senior health and safety advisor	30 years
11	Health and safety administrator	3 years
12	Safety consultant	7 years
13	Health and safety advisor	15 years
14	Health and safety advisor	25 years (in construction industry) and 5 years (in the field of health and safety)
15	Health and safety advisor	26 years (in the construction industry) and over 5 years (in the field of health and safety)

Table 3.7 Results of experts' ratings

Proposed leading indicators	Average score of experts' ratings			
	Phase I	Phase II		
	Analytic soundness ^a	Predictability ^a	Practicability ^b	Cost-effectiveness ^b
(1) principal contractors are selected in part on the basis of satisfying historical safety performance			3.6	3.2
(2) frequency that safety representatives of client visit the site			3.6	3.0
(3) frequency that clients attend safety meeting on site			3.6	3.4
(4) percent of subcontractors selected in part on the basis of satisfying historical safety performance			3.4	3.2
(5) frequency that subcontractors attend safety meeting, toolbox meeting, and safety planning			4.4	4.6
(6) frequency that subcontractors report safety performance to principal contractor			4.2	4.0
(7) written safety policy signed by senior managers in place			4.8	4.2
(8) frequency that senior managers attend safety meeting			3.4	3.6
(9) safety managers are set up on site			3.8	3.4
(10) adequate safety resources (e.g., PPE) are provided on site			4.6	4.6
(11) employees are provided opportunities to be involved in safety management	8.0 ^c	7.2 ^c	4.4	4.2
(12) frequency that senior managers provide feedback on safety performance			4.8	4.2
(13) frequency that senior managers reward good safety performance			3.0	3.0
(14) frequency that supervisors discuss safety with workers			4.2	4.4
(15) frequency that supervisors attend safety meetings			4.2	4.4
(16) frequency that supervisors involved in hazard management			4.8	4.4
(17) ratio of the number of supervisors to workers			4.2	4.0
(18) supervisors' job is supported by senior managers			4.6	4.4
(19) percent of supervisors with Site Safe Supervisor Gold Card			4.2	4.2
(20) managers and supervisors emphasize safety when training new employees			4.4	4.8
(21) worker-to-worker observation program in place			3.6	2.8
(22) frequency that co-workers caution each other when they behave unsafely			3.8	4.2
(23) frequency that co-workers speak up for safety			3.8	4.0

(24) percent of workers with certificates to operate equipment, tools and plants	4.0	4.0
(25) percent of workers of principal contractor with Site Safe training passport	4.0	4.6
(26) percent of workers of subcontractors with Site Safe training passport	4.4	4.4
(27) percent of workers provided with hazards information about the project	4.2	4.6
(28) workers have stop-work authority	3.6	3.4
(29) working hours per day	3.6	3.0
(30) frequency that safety planning is conducted before performing tasks	4.6	4.4
(31) systematic hazard management program in place	4.6	4.0
(32) safety rules and procedures in place	4.8	4.8

^a from 1= lowest level to 10= highest level

^b from 1= lowest level to 5= highest level

^c rating was given based on the whole set of indicator

3.5 Summary

The conceptual framework developed in this chapter attempts to expand on the process of developing leading indicators in the construction industry from three aspects:

First, it clarifies the concept of a leading indicator in terms of definition, purpose and role. In specific, leading indicators are defined as a set of quantitative and/or qualitative measurements that can validly and reliably describe and monitor a construction project's safety conditions. Leading indicators must be able to provide foresight for proactive safety management. Thus, they should fit within a safety management system but extend beyond merely measuring the system itself. It is more important for them to provide useful information to direct safety actions and update the system.

Second, the conceptualization of safety conditions should be based on a safety model that is suitable for the construction industry.

Third, the conceptual framework emphasizes that leading indicators should be developed and used as a functional set. The analytic utility should be assessed within

the total constellation of a selected set of indicators. That is, leading indicators should not be regarded as independent in the overall evaluation of construction projects' safety conditions.

The proposed method improves the process of developing leading construction industry indicators. It allows for different ways to conceptualize safety conditions based on different safety models and emphasizes the importance of validating leading indicators. Consequently, a major benefit of the method is that it not only underlines the role of leading indicators in promoting proactive safety management by connecting safety practices with a project's safety conditions, addressing both scientific and managerial attributes but also highlights the importance of leading indicators in learning.

Chapter 4 Understanding Complexity of Construction Safety

4.1 Introduction

This chapter presents a study that aims to identify behaviour patterns of construction safety and improve an understanding of complexity and dynamics of construction safety. As discussed in Chapter 2, construction safety management involves complex issues (e.g. different trades, multi-organisational project structure, constantly changing work environment, and transient workforce). An investigation of complexity of construction safety is important in that it enhances the understanding of cause-consequence relationships among system factors. In the development of leading indicators, such an understanding is crucial because “a poor or improper assumption here can make leading indicator useless or even lead to a deterioration of the safety performance if it is used a decision criterion”, as Harms-Ringdahl (2009) pointed out. The results of this study can provide insights into simplifying complex safety phenomena and interpreting the information generated by leading indicators.

4.2 Construction safety management

To improve construction safety performance, continuous efforts have been made by both researchers and practitioners. In many countries, safety legislation systems have shifted toward a performance-based approach, with an aim to motivate companies

themselves to take “*all practicable steps*” to ensure health and safety of their employees (Wilson, 2012, Gribble et al., 2006). Over the last three decades, considerable research attention has been paid on identifying and designing effective safety measures and practices to reduce construction accidents (Zhou et al., 2015, Hinze et al., 2013a, Choudhry et al., 2008, Dedobbeleer and German, 1987). Practices, including but not limited to toolbox meeting, safety training, hazard management, tasks analysis, form a strong empirical basis for the development of safety management systems. A safety management system consists of policies, procedures, programs that are targeted at managing safety risks (Wachter and Yorio, 2014a). The link between safety management systems and safety performance has been supported by studies (e.g., (Hinze et al., 2013a, Aksorn and Hadikusumo, 2008a, Vinodkumar and Bhasi, 2010).

Nevertheless, such a practices-based accident prevention strategy is subject to criticism. Koh and Rowlinson (2012) argued that this approach focuses on normative compliance and error prevention. However, complex social processes and cultural factors (e.g., values, norms and behaviours) inherent in construction project settings are largely ignored (Choudhry et al., 2007, Wachter and Yorio, 2014a). The criticism seems to be valid, given the fact that collective attitudes, values, and norms are widely recognized as core preconditions and components of high safety standards in the construction industry (Törner and Pousette, 2009). In addition, construction work processes are loosely defined and workers have many degrees of freedom in how to perform their tasks (Saurin et al., 2008b). As a result, while such a normative approach emphasizes what people ought to act by establishing detailed safety procedures and rules, it is often not effective to explain why workers make mistakes on sites (Dekker

et al., 2008). Saurin et al. (2005) stated that it remains doubtful that whether the existing best practices are effective means to tackle some usual root causes, such as financial pressures, poor product design and short program time scale.

These limitations may be in part caused by a limited understanding of complex accident processes (Mitropoulos et al., 2005). Mitropoulos and Cupido (2009) pointed out that existing construction accident causation models do not take into account the mechanisms that shape human behaviour. Traditionally, accidents are viewed as the result of a sequence of linear events (unsafe conditions and unsafe behaviours). As a result, accident prevention strategies mainly focus on creating safe working conditions and eliminating unsafe behaviours (Howell et al., 2002, Shin et al., 2014). Although researchers (Fang et al., 2004, Sawacha et al., 1999, Haadir and Panuwatwanich, 2011, Ismail et al., 2011) have identified a number of significant individual and organisational factors, such as management commitment to safety, training, competency, and safety motivation, complex cause-effect relationships between the organisational, technical, and human factors are poorly defined and understood, and the mechanisms by which these factors shape human behaviours at the sharp end remain unclear.

4.3 Systems thinking in safety

Recent years, a systems thinking approach has often been used to better understand complex organisational and human processes. Systems thinking has been defined as “*the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure*” (Richmond, 1994). It has

been considered as a framework of thought that helps people to deal with complex systems in a holistic way (Flood and Carson, 1993). The rationale behind the use of systems thinking in safety research is that a holistic approach is able to provide a “big picture” of safety and therefore yield more useful insights into accident prevention strategies.

Historically, systems thinking played an important role in the development of accident theories (or models). One of the most popular systemic safety models is the Swiss Cheese Model (SCM), developed by James Reason (1997). Various accident investigation tools, like Human Factors Analysis and Classification System (HFACS), were then developed based on the SCM (Celik and Cebi, 2009, Olsen and Shorrock, 2010, Shappell and Wiegmann, 2000). The SCM, as well as related accident investigation tools, adopts a holistic view on safety, extending the causes of accidents to organisational factors and emphasizing the interactions between organisational deficiencies (latent failures) and human errors (active failures). Despite its popularity and usefulness in accident analysis, the model is not immune from criticism. For example, the model has been criticized for adopting a static perspective on complex accident causation process and thus failing to indicate how failures at different system levels (appeared as holes in the model) are likely to align (Le Coze, 2013a). Dekker (2006) argued that the layers of defence are dynamic, rather than static or constant. Reason also acknowledged that “holes” in the model should be constant flux, rather than fixed and static (Reason, 1997) (p. 9).

Rasmussen integrated the systems concepts, such as hierarchy and feedback loop, into his two safety models: the model of migration and the sociotechnical system view (STS) (Rasmussen, 1997, Rasmussen et al., 2000). Safety management in the

sociotechnical system is described in several hierarchical levels, ranging from government and regulators, via organisation and management, to staff and working condition. Vertical flow of information across these hierarchical levels forms various feedback loops, which play an essential role in safety management. In addition, the model of migration graphically describes the dynamics of the safety state of a system. The central idea of it is that under the work load and economic pressure, the state of safety tends to migrate closer to, and even cross, the boundary of functionally acceptable performance. Such a dynamic perspective was further expanded by Dekker who developed a notion of “drift into failure” (Dekker, 2011). The concept of drift was defined as *“an inexorable slide towards ever smaller margins, toward less adaptive capacity, towards a growing brittleness in the face of safety challenges that the world may throw at the organisation.”* (2011) (p.18). He claimed that traditional approaches that are based on “reductionism” and “determinism” are ineffective to deal with complexity of a system (Dekker, 2011, Dekker et al., 2011). Similar to Rasmussen’s models, Leveson’s systems-theoretic accident model and processes (STAMP) (2004), based on the control theory, focuses on complex interactions between system components and sees accidents as emergent properties of complex system. Understanding safety as a control problem, the model emphasizes the system’s control structure. However, it seems that such a control metaphor has been mainly adopted in high-tech industries, like nuclear, chemical process and oil industries (Wahlström and Rollenhagen, 2014). Its application to occupational safety research has been rather limited (Howell et al., 2002).

Systems analysis (SA) has been widely used as a problem-solving methodology to analyse accidents in various industries, with an attempt to generate deeper insights

into accident causation and prevention strategies by using different tools and models such as Accimap, Swiss Cheese model, HFACS and STAMP (Lenné et al., 2012, Underwood and Waterson, 2014, Cassano-Piche et al., 2009, Vicente and Christoffersen, 2006, Goh et al., 2010, Santos-Reyes and Beard, 2009, Patterson and Shappell, 2010, Lawton and Ward, 2005). One of common conclusions of systems analysis is that accidents were not caused by a single causal factor, but by system failures. Despite the advances, the gap between research and practice with regard to systemic accident analysis still exists and systemic accident analysis methods need considerable empirical validation before they are accepted by practitioners (Underwood and Waterson, 2013).

Dynamic complexity, as a defining characteristic of today's high-tech systems, poses challenges on safety management (Dekker et al., 2011, Carrillo, 2011). As a result, there have been calls for taking a systems view of accidents in such systems (Goh et al., 2010). System dynamics (SD), as a method founded by Forrester in MIT (Forrester, 1961) to understand and deal with complexity (Sterman, 2000), has increasingly been adopted to analyse and understand complex safety issues, such as causes of accidents (Cooke, 2003, Goh et al., 2012b, Goh et al., 2010, Tsuchiya et al., 2001, Salge and Milling, 2006), safety attitude and behaviours (Shin et al., 2014, Jiang et al., 2014), production pressure (Han et al., 2014a), organisational learning (Cooke and Rohleder, 2006b, Goh et al., 2012c), and safety conditions (Bouloiz et al., 2013). As a systems approach, SD focuses on dynamics by identifying the feedback structure in a system and addressing the behaviour patterns of the system that they generate over time (Goh and Love, 2012).

In addition, Senge (1990) proposed eight system archetypes: 1) limits to growth, 2) shifting the burden, 3) eroding goals, 4) escalation, 5) success to the successful, 6) tragedy of the commons, 7) fixes that fail, and 8) growth and underinvestment. As one of the cornerstones of qualitative system dynamics, they show common patterns of behaviour of systems (Senge, 1990, Wolstenholme, 2003). In doing so, archetypes can be used as a diagnostic tool to explain problems that recur over time. Marais et al.(2006) proposed six system safety archetypes that help to understand how and why risk level changes over time. In addition, Kontogiannis (2012) developed system dynamics models of both organisational and human processes that can be used in safety analysis by integrating organisational cybernetics models and human control models.

In summary, systems thinking is widely accepted as an effective tool to deal with complexity (Maani and Maharaj, 2004, Sterman, 2000, Checkland, 1981, Richmond, 1994) and it has provided a powerful perspective to understand the complexity and dynamics of safety management and offered systemic insights into complex safety problems (Underwood and Waterson, 2013).

4.4 Study aims

Given the complexity of safety problems in the construction industry, some researchers (Perezgonzalez, 2005, Howell et al., 2002, Mitropoulos et al., 2005) have suggested that a systems approach should be used if further significant safety improvements are to be made. Underlying the systems approach is the idea that focus should be placed on understanding the interrelationships among system components.

Rather than understanding accidents as outcomes of single component failures (e.g., frontline workers), one needs to take into account the effects of interrelationships among factors at hierarchy levels on safety. In this line of thought, it becomes important to explore and define more explicitly certain patterns of relationships between system components, if a systems approach is to advance and make contributions to safety practice.

Therefore, the aims of this chapter are to (1) better understand dynamic complexity of construction safety management by exploring archetypes of construction safety that recur at different system levels, (2) provide systemic insights into how to deal with the complexity. The rest part of the chapter is structured as follows. The Section 5 presents the methodology of this study. The findings of the studies and discussions are presented in Section 6 and 7. Finally, Section 8 presents the conclusions of this study.

4.5. Methodology

4.5.1 Development process

The use of system archetypes is one of the cornerstones of qualitative system dynamics (QSD) (Wolstenholme, 1999). QSD focuses on system description, problem identification and qualitative analysis (Boylan et al., 2008). Wolstenholme (1999) stated that “*the idea of using stand-alone causal loop diagrams was aimed at providing insight into managerial issues by inferring, rather than calculating, the behaviour over time of the system represented.*” Table 4.1 shows the two-step process (problem articulation and formulation) that qualitative system dynamics typically involves (Sterman, 2000, Coyle, 2000):

Table 4.1 Archetypes development process

	Development steps	Techniques
Step I: Problem articulation	<ul style="list-style-type: none"> • Theme identification • What is the problem? • What are the key variables? 	Interviews Ground theory method
Step II: Formulation	<ul style="list-style-type: none"> • Causal loop diagrams • System archetypes 	

Construction safety archetypes are not aimed at describing the whole system, but rather explaining specific safety problems that recur in the construction industry. The first step thus focuses on identifying common themes and problems. Key variables that are related to each theme or problem are then identified. The second step aims to generalize from the specific variables (or events) to patterns of behaviours by considering the causal relationships between them. The tool of causal loop diagrams (CLD) is used to show the causal links among these variables with arrows from a cause to an effect (Sterman, 2000). Reinforcing and balancing feedback loops and delays are basic blocks in the CLDs. Briefly, a reinforcing loop is a structure that feeds on itself to generate exponential growth and collapse, in which the growth or collapse continues at an ever-increasing rate (see Figure 4.1). If the trend is ascending, the reinforcing loop will accelerate the growth. If the trend is descending, it will accelerate the decline. In contrast, a balancing loop produces a goal seeking behaviour. As shown in Figure 4.2, it intends to reduce a gap between a current state and a desired state. It moves a present state towards a desirable target regardless whether the trend is descending or ascending. Delays represents the time that elapses between cause and effect (Marais et al., 2006).

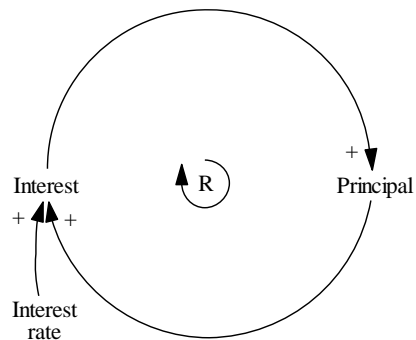


Figure 4.1 A reinforcing loop

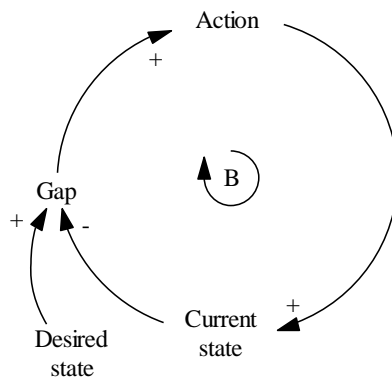


Figure 4.2 A balancing loop

4.5.2 Data collection

Considering that the archetype development is a general theory building process, the data collection and analysis procedure in this study followed the grounded theory method (GTM) formulated by Glaser and Strauss (1967). GTM “is an inductive, theory discovery methodology that allows the researcher to develop a theoretical account of the general features of a topic while simultaneously grounding the account in empirical observations or data (Martin and Turner, 1986). Based on the GTM, data collection, data analysis, and archetype development were conducted concurrently.

Three different ontological and epistemological positions are carried by the Grounded Theory Method (GTM), such as Glaser and Strauss’s post-positivist paradigm (Glaser and Strauss, 1967), Charmaz’s constructionist paradigm (Charmaz, 2006), and Corbin

and Strauss's interpretivist paradigm (Corbin and Strauss, 2008). This chapter adopted Charmaz's constructivist paradigm. The rationale behind the choice is that the constructivist paradigm is consistent with the evolution of safety theories over the last decades and matches well with the purpose of this chapter. Looking back in history, different safety theories (or accident models) were developed by scholars in different times, such as Heinrich's domino theory in 1930s, high reliable organization (HRO) in 1970s, Swiss cheese model in 1990s, and resilience engineering in 2000s. It is clear that there is not a "true" description of safety as it is and that the understanding and knowledge of safety vary with history. In addition, in order to explore the complexity and dynamics of construction safety, it is not possible to see the researchers as "objective observers" who seek objective truth. This is because the researchers are not "a blank slate", but rather are always affected by existing theories and the interactions between themselves and the phenomena under study.

4.5.2.1 Sampling strategy

Three sampling methods that pertain to GTM were used in data collection, including convenience, snowball, and theoretical sampling (Bryant and Charmaz, 2010, Morse, 2010).

Due to the exploratory nature of this study, convenience sampling was first adopted and participants at different organisational levels and positions (e.g., government, client, principal contractors, subcontractors, and independent safety consultants) were selected on the basis of accessibility. This helped the researchers to obtain an overview of construction safety management and to identify common safety problems in the construction industry. The researchers then requested introductions from the initial participants to invite their colleagues to participate in the study.

Once an initial list of common themes and problems was identified, theoretical sampling method was used. In this stage, participants were selected as indicated by these themes. For example, procurement and safety was identified as a common theme in the initial interviews. To identify key variables and patterns that describe the theme, a client project manager and a client health and safety manager were selected to seek relevant data in this regard. During this stage, the researchers collected and analysed the data simultaneously in order to decide who to sample and what data to collect next. Once variables and archetypes were initially developed, data were sought from appropriate participants in order to test, elaborate and refine these archetypes.

4.5.2.2 Participants

22 interviews were conducted with 20 participants, including 1 general manager, 1 project manager, 1 government safety inspector, 1 client health and safety manager, 1 health and safety researcher, 1 safety auditor, 4 health and safety consultants, 10 health and safety managers from construction companies. 2 health and safety managers were interviewed two times in theoretical sampling stage. Participants have rich experience in the field of construction health and safety (experience range: 3-30 years; mean experience: 15 years). Interviews ceased when all developed archetypes were “complete” and no new data emerged from interviews. The number of interviews is appropriate for grounded theory studies, as suggested by Creswell (1998) (p.65).

4.5.2.3 Interview design

Interviews in convenience sampling were mainly aimed at identifying common safety problems in the construction industry. Interviews questions were unstructured and general, covering a wide range of issues in construction safety management. In this stage, the researchers paid special attention on the safety themes (or problems) that

were raised by different participants. Interviews questions in convenience sampling were more focused, with an attempt to collect relevant data under each identified theme. The primary purpose was to elicit knowledge of participants to identify key variables and causal links among these variables that can explain each problem. In this stage, interviews questions were designed based on concurrent data analysis in order to collect most relevant data from “right” participants.

The duration of each interview was between 40 and 90 min (mean interview length: 60 min). Of 22 interviews, 1 was conducted via Skype, 2 via telephone, and the rest of 19 by face-to-face at either workplaces or Café. Interview protocols were pre-designed before each interview, which helped the interviewer take notes during the interviews. After each interview, the interviewer wrote memos in order to summarize and reflect the data collected in the interview.

4.5.3 Data analysis

To develop construction safety archetypes systematically and correspond to sampling strategies, data analysis in this study involves three stages: open coding, selective coding and theoretical coding (see Figure 4.3). First two coding procedures are also called “substantive coding” (Holton, 2010).

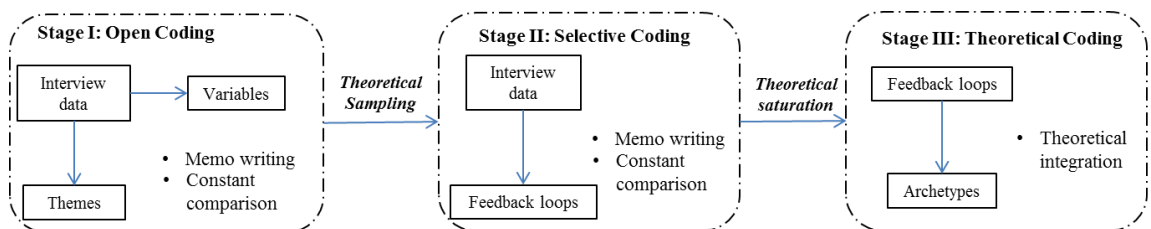


Figure 4.3 Data analysis

Stage I: open coding

The raw data collected by interviews were initially examined and coded through a process that summarizes and categorizes safety themes and problems. The purpose was to identify a list of common safety problems in the construction industry. Memos were then constantly compared, which allowed the researchers to identify recurring themes and problems.




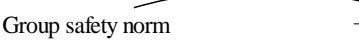
Stage II: selective coding

Selective coding began after a safety theme had been identified. The purpose was to identify behaviour patterns under each safety theme and to explore the underlying structure that can explain the patterns. In this stage, behaviour patterns (e.g., blame culture in accident investigation) were identified by analysing events and stories provided by participants. A process of constant comparison was used, which helped the researchers to see if the data support the behaviour patterns. Another significant purpose of selective coding was to explore the underlying structures (variables, causal links among variables) of all identified patterns. These structures then were mapped by using system dynamics modelling software VENSIM®. To avoid the disconnection between these causal structures with original source data, each interview and causal loop diagram were numbered. This ensures visible, traceable cohesion between a construction feedback loop and its data source (see Table 4.2 and 4.3).

Table 4.2 Coding chart example

Theme: workers unsafe behaviour						
Causal structures	Cause variable:	Schedule delay	Accident	Risk perception	Group safety norm	Peer pressure
	Effect variable:	Production pressure	Risk perception	Unsafe behaviour	Peer pressure	Unsafe behaviour
	Relationship type:	Positive	Positive	Negative	Negative	Positive
Information source: Comments and stories heard from a health and safety manager (Interview Number (IN): 10)						

Table 4.3 Example of Words-and-arrow diagrams of causal arguments

Cause	Effect	+/-	Words-and-arrow diagrams
Schedule delay	Production pressure	+	Schedule delay  + Production pressure
Accident	Risk perception	+	Accident  +Risk perception
Risk perception	Unsafe behaviour	-	Risk perception  - Unsafe behaviour
Group safety norm	Peer pressure	+	Group safety norm  + Peer pressure

Stage III: theoretical coding

Once a number of reinforcing and balancing feedback loops were developed under each theme, the researchers examined the relevance of each loop to see if it fits and works within a safety archetype under the theme. This process was in part based on existing system archetypes developed by Senge (1990). The purpose of this stage was to filter and integrate feedback loops into a generic causal loop diagram that can describe the complex behaviours within the theme. Such a coding process also guided the theoretical sampling by which data were collected to verify the structure of each archetype. The final step was to map each safety archetype by using VENSIM®. The archetypes were then converted into stock and flow diagrams. This step requires to determine the initial values of variables and quantify their relationships. It should be noted that the quantification process was aimed at only demonstrating the meaning carried by the archetypes. The “Behaviour over time” charts represented no specific cases and they should be interpreted from a general perspective.

SD modelling of safety involves soft variables, such as safety motivation, management commitment to safety, and safety knowledge. For SD analyses, the main assumption is that variables are understood as continuous in nature. This requires to define soft

variables as stock variables which accumulate over the time horizon of the study. Note that this is common practices of SD modelling in the area of safety and psychology (Levine, 2000, Han et al., 2014b, Cooke and Rohleder, 2006a, Cooke, 2003).

4.6 Results

Nine common themes and safety problems were emerged from interview data and open coding procedure, including safety regulations, incentive programs, safety in procurement, production and safety, subcontractor safety management, unsafe behaviours, accident investigation, and safety performance measurement and learning. Eight archetypes were developed to address these nine themes, including (1) safety regulations (2) Incentive programs, (3) procurement and safety, (4) safety management in small businesses (5) production and safety, (6) workers' conflicting goals, (7) blame on workers, and (8) reactive and proactive learning. Each archetype was presented and analysed as follows.

4.6.1 Safety regulations

Figure 4.4 shows an archetype of safety regulations at the government level. The central theme of the archetype is that the fixes (i.e., safety regulations) that are aimed at motivating construction companies to manage safety carry both positive and negative consequences.

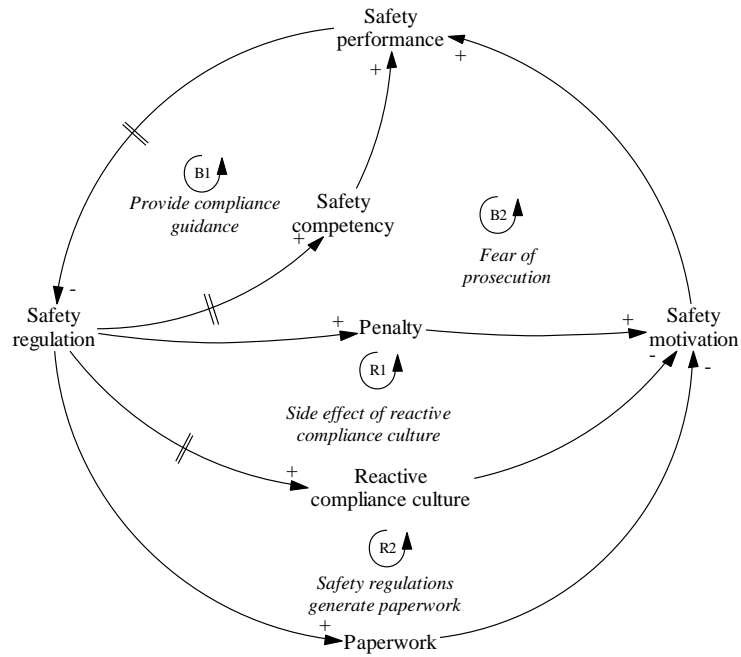


Figure 4.4 Safety regulations

4.6.1.1 Dynamic theory

The government employs a combination of “carrot and stick” approaches to motivate construction companies to manage safety on site by offering a combination of support and punishment. As suggested in the balancing loop (B1_{Provide compliance guidance}), to promote excellence in safety management, government agencies (e.g., Work Safe New Zealand) provide information and guidance to help duty holders under the health and safety legislation framework to comply safety rules, by establishing a set of safety regulations and approved codes of practice. In general, the information and guidance, together with other support services and enforcement activities (such as audits, inspections, and investigations), enhances the ability of construction companies to manage safety on site. Apart from the “carrot approach”, prosecutions and penalties would apply where serious non-compliance occurs (see B2_{Fear of prosecution}). They act as a threat to deter construction companies from offending. To avoid punishment and ensure compliance, construction companies are motivated to take “all practicable steps”

to ensure the safety of employees while at work. The government may increase penalties by developing new tiered penalty regimes, in response to historical safety performance of the industry (Ministry of Business Innovation & Employment, 2014). The rationale behind this change is that stronger penalties would result in a higher level of safety motivation.

Despite these benefits that safety regulations have brought, safety regulations do generate side-effects that tend to undermine companies' safety motivation. Although current New Zealand safety legislation system is performance-based, which establishes mandatory goals rather than enforces prescriptive standards, some construction companies, especially small ones, seem to be more comfortable with detailed prescriptions. As a safety inspector states,

“Some small companies are doing a good job. But some just wait site inspection and ask safety inspectors what should be done.”

Over time, a reactive compliance culture can be created in the construction industry. As described in the reinforcing loop (R1_{Side effect of reactive compliance culture}), the reactive compliance culture can undermine safety motivation by generating a loss of safety ownership (Hale et al., 2015) and a reactive prevention mode (Brockner et al., 2004). The culture can significantly impact companies' behaviour in safety management. They tend to do the minimum only for the sake of ensuring compliance or meeting requirements of client or main contractor. A safety advisor pointed out that:

“Some companies provide their employees with basic safety training only because they have to. Some companies book auditing service only because they just want to meet clients' requirements. ”

Another downside of current safety regulations is that compliance involves the massive volume of paperwork (R2_{Safety regulations generate paperwork}). A safety manager stated that he spent 80% of working time on safety compliance and paperwork. Documenting safety activities and writing safety reports is not necessarily counter-productive, as the documentation in a sense is a reflection of actual safety efforts made on site. However, paperwork can be divided into two types: that helps keep a safe site and that only seeks compliance (Blewett and O'Keeffe, 2011). It would be far from effective to monitor the safety level of a project if managers focus on the latter (Blewett and O'Keeffe, 2011, Maher, 2009). Pike River mine accident is a good example, where the safety manager of the mine was so busy writing policies and reports that he had no chance to go into the mine to ensure safe procedures were being followed (Royal Commission on the Pike River Coal Mine Tragedy, 2012) (p 176).

4.6.1.2 Behaviour over time

Figure 4.5 shows a typical behaviour pattern of the archetype of 'safety regulations'. Companies' safety motivation increases in initial stages, as the balancing loop (B2_{Fear of prosecution}) dominates. However, the positive effects of penalty are then undermined by increased paperwork and reactive compliance culture. As a result, safety motivation begins to decline before it levels off when positive and negative effects have reached a dynamic equilibrium.

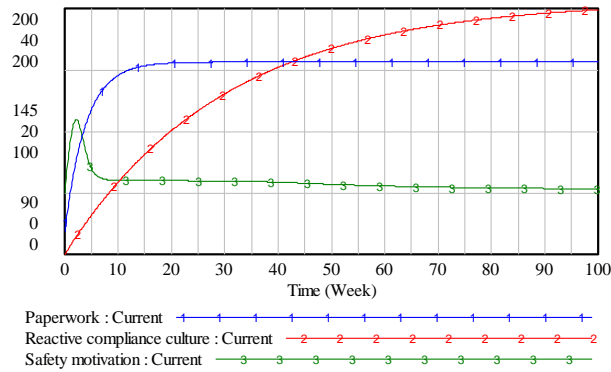


Figure 4.5 Behaviour pattern of the ‘safety regulations’ archetype

4.6.1.3 Leverage points

For the archetype of ‘safety regulations’ (see Figure 4.4), leverage lies in creating balancing loops that minimise the side effects that are produced by two reinforcing loops (R1 and R2). First, it is critical for regulators to be conscious of the effects of safety regulations on the way companies (or safety managers) manage safety on site. The possibility that detailed paperwork can lull managers into a false sense of security should be considered. In order to motivate construction companies to shift from a reactive prevention mode to a proactive promotion mode, it is important for regulators to stick to the spirit of performance-based safety regulations and encourage companies to flexibly develop their own risk management process and manage safety in a more effective and creative manner. Thus, focus should be placed on helping them, especially small construction companies, to translate generic goals into specific practices, rather than enormous compliance-oriented paperwork.

4.6.2 Incentive programs

Figure 4.6 depicts the archetype of ‘incentive programs’ at the government level. This is another special case of “Fixes that fail”. It captures a common phenomenon that

well-intentioned safety incentive programs, which are aimed at improving construction companies' safety motivation and safety performance, tend to be effective in the short term but have long-term side effects.

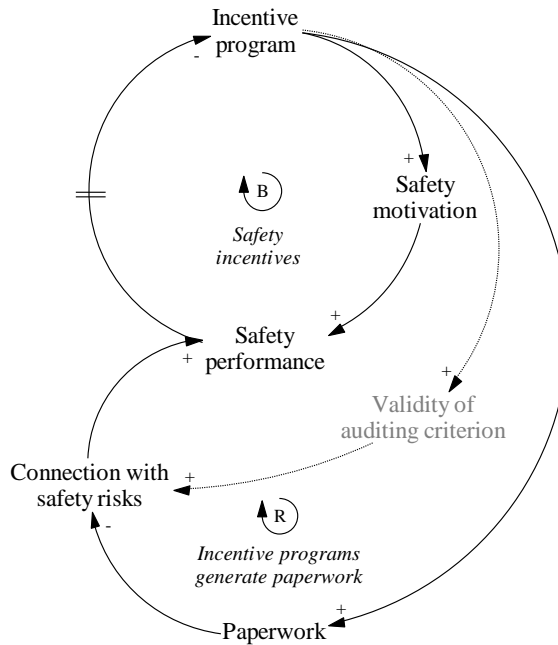


Figure 4.6 Incentive programs

4.6.2.1 Dynamic theory

As a significant part of the rehabilitation and compensation system, a set of incentives programs were designed and implemented by Accident Compensation Corporation, New Zealand (ACC). These programs include the ACC Accredited Employer (Partnership) Program, Workplace Safety Management Practices (WSMP), and Workplace Safety Discount (WSD) (The Accident Compensation Corporation, 2014). A detailed description of these programs is beyond the scope of this chapter. In general, they were designed with the intention of motivating companies to improve safety performance by offering a range of discounts (from 10% to 20%) of ACC work cover levies.

The balancing loop (B_{Safety incentives}) describes the mechanism by which these programs improve safety performance. To get the discount, companies are motivated to demonstrate safety commitment by meeting various requirements pre-set by the ACC, such as training, accident investigation, and hazard management. By implementing these safety practices, safety risks can be managed and their safety performance can be improved.

However, counter-intuitive results of these incentive programs do exist. As the application is paper-based, some companies who are oriented toward discounts take the shortest and quickest path to get them. A health and safety manager who had helped a company to achieve a second level of WSMP stated that:

“Some companies even bought documents from consultants in order to pass ACC auditing and get discount. I don’t think that ACC’s incentive programs are effective to lead to actual and effective safety practices on site. It is not effective because it is paper-based and it fails to cover how safety hazards are identified and managed at sites.”

This is highly likely to cause a missing link between the paperwork and safety practices implemented on site. ACC audit criteria and the evidence are subject to auditor’s interpretation and so-called desk auditing is not uncommon in the construction industry (Blewett and O’Keeffe, 2011). This may further encourage inconsistencies between what companies have presented on documentation and what they have done on sites. In addition, an ACC auditor stated that some companies consider the incentive programs only from a market perspective: get the discount and use it as a sales tool to win projects. While this does not necessarily diminish safety

motivation, such a reaction at the industry level has deviated from original purposes of these incentive programs. The disconnection between paperwork and safety risks in fact increases the likelihood that these safety risks remained unmanaged and therefore causes more accidents, as shown in $R_{\text{Incentive programs generate paperwork}}$. An implicit possibility is that companies who have passed incentive programs do not necessarily produce better safety performance. In fact, a statement made by a government safety inspector supports this view:

“ We prosecute the tertiary level (WSMP) companies on a regular basis.”

4.6.2.2 Behaviour over time

A typical behaviour pattern of the archetype of “incentive program” is depicted in Figure 4.7. Initially, safety motivation increases, which indicates that incentive programs work properly in the short-term. However, as the amount of paperwork increases sharply and significantly, safety motivation begins to drop down. The behaviour pattern suggests that over time the fixes (i.e., incentive programs) can no longer control the problem (i.e., a lack of safety motivation) and that the problem reappears and begins to increase in severity. From a system dynamics perspective, this occurs because the loop dominance shifts from the balancing loop $B_{\text{Safety incentives}}$ to the reinforcing loop $R_{\text{Incentive programs generate paperwork}}$.

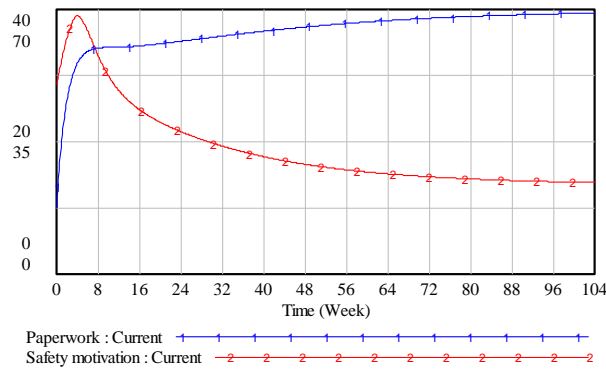


Figure 4.7 Behaviour patterns of the ‘incentive programs’ archetype

4.6.2.3 Leverage points

To minimise or eliminate the side-effects of paperwork, it is essential to bridge the connection between paperwork and safety risks that need to be managed. This requires that incentive programs should be based on a robust auditing system. Thus, an additional balancing feedback loop can be created by adding a variable “validity of auditing criterion” between incentive program and connection with safety risks (highlighted in dotted line in Figure 4.6). To do so, the focus can be shifted from paperwork that is compliance-oriented toward safety practices that are designed and implemented according to safety risks facing a company or project. As every construction project is unique in its own right, audit criterion that is one-size fits all may not be appropriate and it should be flexible and targeted (Blewett and O’Keeffe, 2011).

4.6.3 Procurement and safety

The archetype of procurement and safety consists of a reinforcing loop (R long-term effects of safety budget cut) and three balancing loops (B1 Cut safety budget, save money, B2 On-site control and B3 select safe contractors), as shown in Figure 4.8. Feedback loops B1 and R can be

considered as a special case of “Shifting the burden” archetype developed by (Senge, 1990).

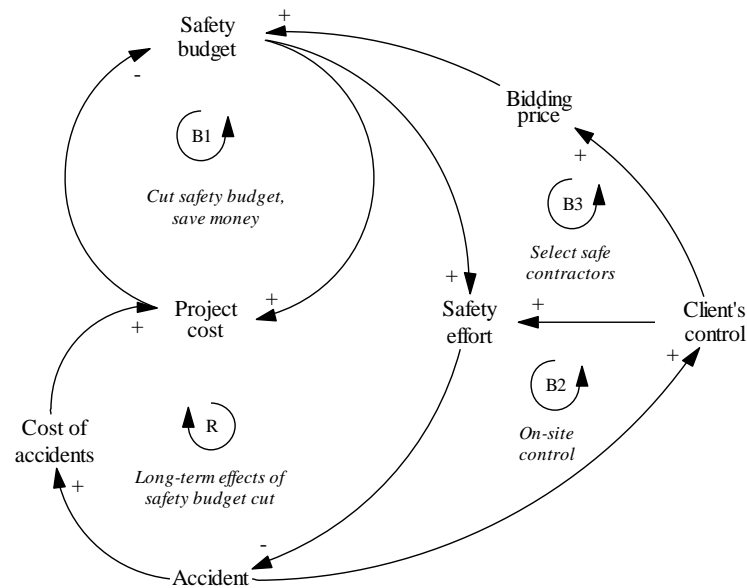


Figure 4.8 Procurement and safety

4.6.3.1 Dynamic theory

Despite the existence of performance based procurement systems like best-value method, lowest-bid has remained a very popular procurement method in the construction industry. Such a price-focused method can impact site safety management in different ways. Given the need to trim costs in order to win projects in the first place, there are few incentives for the contractors to pay attention to site safety. A lower bidding price often means lower profit margin. The possible consequence is, as a safety manager stated, “*Health and safety is the first thing thrown out of the window*”. This is especially true for small construction companies who are financially fragile and desperate for market share (Legg et al., 2009). Thus, project cost is reduced often by adopting a quick fix: cutting safety budget, as described in B1 Cut safety budget, save money. However, such a symptomatic solution carries long-term side

effects. In general, safety efforts are reduced as safety budget cuts. Such an attitude has been fuelled by clients' focus on the "initial cost" to themselves rather than the lifetime cost to the whole nation. With less efforts made on site safety, the number of accident would increase. As illustrated in the reinforcing loop R_{long-term effects of safety budget cut}, this causes considerable accident costs and therefore increases project cost. The reinforcing loop describes a vicious circle of safety budget cuts: the more safety budget cut, the more project cost. In addition, price driven procurement can stifle innovation and ignore training and development (New Zealand Construction Industry Council, 2004) (p.10). This is likely to undermine site safety indirectly.

However, safety budget and safety efforts made by contractors are governed by two balancing loops (B2_{On-site control} and B3_{select safe contractors}). Accidents are likely to result in a decline of clients' satisfaction. As a result, they are likely to take both short-term and long-term actions. In the short term, they are likely to increase involvement in site safety management and exert more safety pressure on contractors (B2_{On-site control}). In the long term, they tend to add safety management as a fundamental part of the selection process when tendering for future construction work. For example, they select contractors partly based on safety performance record and quality of safety management systems. Such requirements would be helpful to select "safe" contractors and be indicative of a "good start" in site safety management (Hinze et al., 2013b). However, an integration of safety requirements into procurement process is heavily dependent on clients' commitment to safety. In fact, during the interviews, safety managers of client and principal contractors were asked the question "Do you consider health and safety standard of potential contractors in procurement process?" The answers were mixed. A safety manager of principal contractor answered:

“theoretically yes, but practically no”. Nevertheless, there has been an increasing acceptance that excellent safety practices should be one of key determinants of the selection process (New Zealand Construction Industry Council, 2004). This was proved by a safety manager of client who stated that “When I select contractors, I require them to submit specific safety plan, not generic one.”

4.6.3.2 Behaviour over time

Figure 4.9 depicts how ‘safety budget’, ‘accident cost’ and ‘project cost’ change over time, without clients’ control (B2 and B3). Initially, project cost experiences a sharp decrease because of safety budget cut. During the period between the 5th week and 35th week, project cost remains unchanged because the amount of money saved by reducing safety budget is the same as extra accident costs. However, project cost begins to climb when safety budget is reduced to zero and accident costs continue to increase.

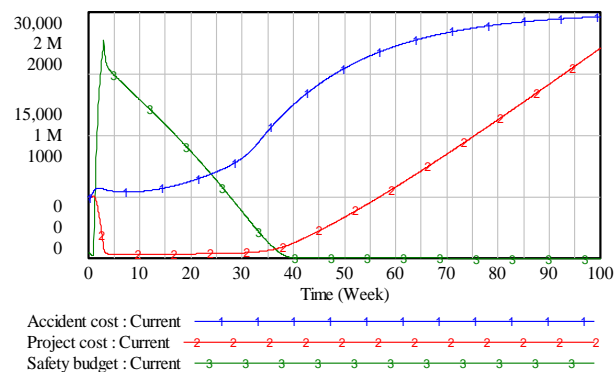


Figure 4.9 Behaviour pattern of feedback loops of R and B1

4.6.3.3 Leverage points

Clients’ on-site control and selecting a safe contractor can be considered as two high leverage points. Figure 4.10 shows the effects of clients’ on-site control (B2 On-site control). During the initial 10 weeks, average incident rate decreases gradually because

of a high level of safety effort. After the 10th week, the level of safety efforts begins to decline as a result of safety budget cut. This causes a significant increase in average incident rate, which thus leads to more on-site control by clients. The increased on-site control immediately improves the level of safety efforts made by the contractor, which is followed by a decline of average incident rate after the 60th week.

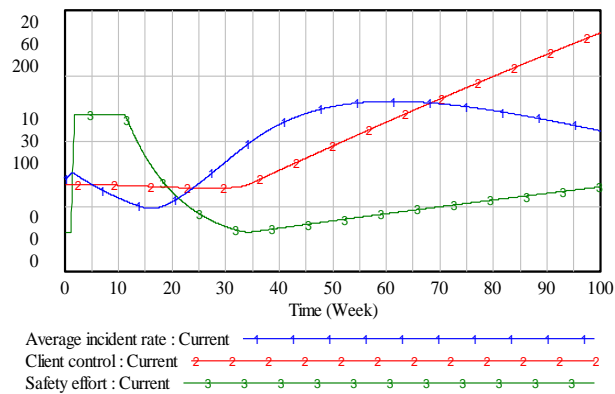


Figure 4.10 Behaviour pattern of feedback loops of R, B1 and B2

Figure 4.11 illustrates the behaviour pattern of the whole ‘procurement and safety’ archetype. The behaviour of a project that adopts a lowest-price method is shown in the first 100 weeks, while the second 100 weeks capture another project that chooses a best-value method. It is clear that the average incident rate in the second project is much lower than that of the first one because of the positive effects of best-value bidding method on both safety budget and the level of safety efforts.

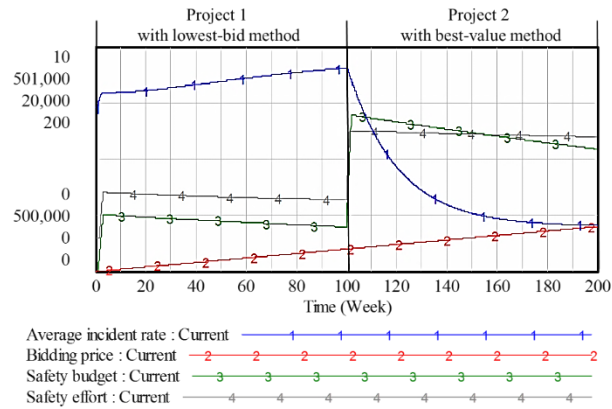


Figure 4.11 Behaviour pattern of the ‘procurement and safety’ archetype

4.6.4 Safety management in small businesses

Figure 4.12 presents an archetype of limited safety resources facing small construction companies. It is a special case of “*Limits to Growth*” (Meadows and Randers, 2004). Small businesses (with fewer than 20 employees) dominate the New Zealand construction industry. The number of small construction firms was 48557, making up over 98% of the construction industry (The Ministry of Business Innovation & Employment (MBIE), 2014). They are mainly involved in residential construction (Curtis and Page, 2014). Small construction companies face different challenges in managing safety on sites, such as tight profit margins, limited market share, limited safety knowledge, a lack of resources. As a result, they put emphasis on client satisfaction, workloads, and cash flow which are vital for business success (Curtis and Page, 2014).

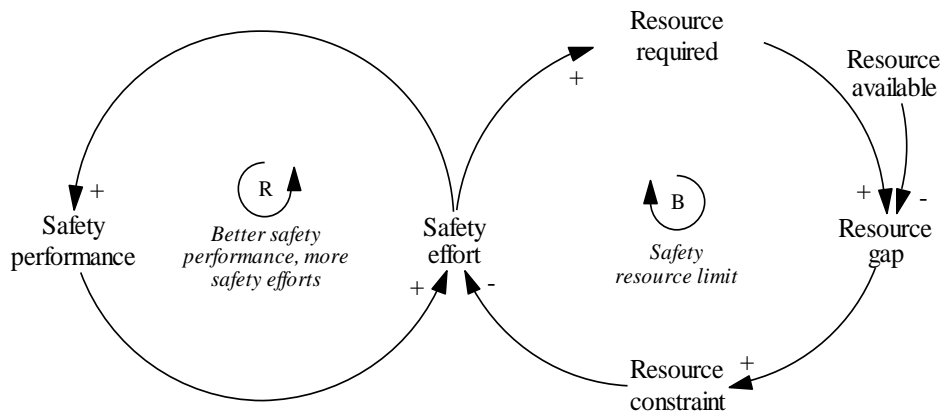


Figure 4.12 Safety management in small businesses

4.6.4.1 Dynamic theory

This archetype states that a reinforcing process of accelerating growth (R Better safety performance, more safety efforts) will encounter a balancing process (B Safety resource limit) as safety resource limit that small construction companies are approached. In specific, as shown in the reinforcing loop, more safety efforts produce better safety performance. In consequence, managers are motivated to demonstrate a higher level of safety commitment, which in turn leads to more safety efforts.

However, such a virtuous circle would be impeded by a combination of financial constraints and a lack of safety knowledge. Small construction companies may become reluctant to manage safety because they see safety as a burden, as it costs dollars to either provide workers with safety training or book external auditing services. Adapting to the resource pressure, small companies cut safety budget and reduce safety efforts. In addition, they have low safety motivation because of a lack of knowledge of their legal duties and safety practices. As a safety manager of a main contractor pointed out:

“One of major challenges is that they (sub-contractors) have no idea what their legal obligations are. And safety attitude of (subcontractors’) managers is problematic.

Some small companies ignore safety because of financial problems, some because of a lack of safety knowledge even they don't have such financial problems”.

4.6.4.2 Behaviour over time

The dynamic behaviour determined by such a “Limits to growth” structure would be that the improvement in safety performance levels off when running up against the balancing process. As shown in Figure 4.13, in initial stages, the reinforcing process of improvement (R Better safety performance, more safety efforts) operates on its own before it bumps up against resource limits facing small construction companies. When the balancing loop (B Safety resource limit) works, the improvement plateaus and then drops quickly.

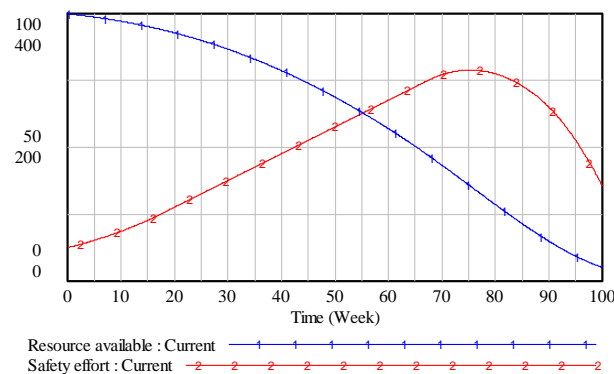


Figure 4.13 Behaviour pattern of the ‘safety management in small businesses’ archetype

4.6.4.3 Leverage points

To change the behaviour pattern of the archetype of “Limits to Growth”, it is important to identify and change the limiting factor (Senge, 1990). In this example, in order for the balancing loop to work continuously, it is necessary to postpone or eliminate the limiting processes produced by the reinforcing loop. This can be achieved by increasing the capacity of construction companies with respect to safety management.

4.6.5 Production and safety

The archetype of production and safety presents a special case of “Fixes that fail”, describing why fixes that aim to eliminate schedule delay may ultimately cause more delay and intensify the production pressure. As shown in Figure 4.14, the archetype is composed of a combination of two balancing loops (B1 *Work faster* and B2 *Work longer hours*) and two reinforcing loops (R1 *Less safety efforts, more accidents*, R2 *Effect of fatigue*).

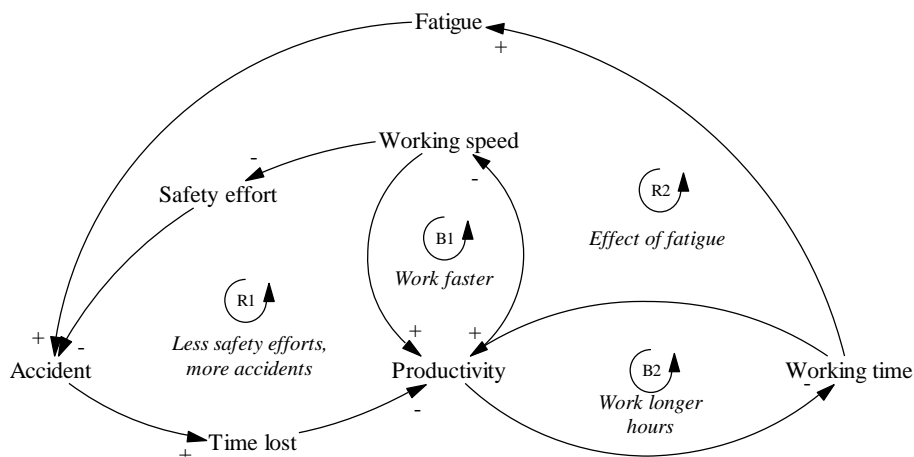


Figure 4.14 Production and safety

4.6.5.1 Dynamic theory

It is common that construction projects are under considerable production pressure because of schedule delay. At the project level, schedule delay is reduced by either spending less time on safety (e.g., hurried safety meeting) or working longer hours. However, each quick fix carries both short-term (positive) and long-term (negative) consequences. Under production pressure, production is more likely to win the “battle” against safety. As a safety manager pointed out:

“Safety tends to be marginalized when projects are under significant production pressure. Managers said safety is our top priority. But, in reality, safety is our priority until it is not.”

As suggested by B1 *work faster*, to catch up the schedule and meet expectations of clients and insurance companies, managers deemphasise the importance of safety by ignoring safety practices and increasing working speed. This, from a short-term standpoint, can increase productivity and therefore relieve production pressure somewhat. When current productivity reaches the desired level, the working speed stops increasing.

However, the long-term consequences the quick fix carries may deteriorate the productivity problem. As shown in R1 *less safety efforts, more accidents*, increasing working speed often means putting less emphasis on safety, which leads to a decline of safety level on site. In this situation, workers are “forced” to work quickly by taking shortcuts in order to satisfy their boss and complete the tasks as soon as possible. Over time, unsafe behaviours become acceptable on site. One thing for sure is that more unsafe behaviours result in more accidents and injuries, which in turn undermine productivity and lead to further delays.

In addition, working longer hours is another common way to improve productivity and eliminate the schedule delay, as described in B2 *Work longer hours*. However, another possible issue is fatigue caused by overtime work. A safety manager said:

“Right now, fatigue has been identified as an area we need to think about. Fatigue reduces alertness and this can cause errors and injuries .Some workers even work 18 hours a day. They take drugs to stay awake.”

Fatigue negatively affects workers’ ability to think clearly and act appropriately. Fatigued workers are less alert and therefore are more likely to have accidents and injuries. If it remains unmanaged, a vicious circle would emerge, as shown in R2 *effect of fatigue*. Tired workers tend to be more likely to be involved in accidents and injuries.

This would decrease productivity and worsen schedule delay. To “improve” the situation, managers tend to push even harder and working hours become even longer.

4.6.5.2 Behaviour over time

A typical behaviour pattern of the “production and safety” archetype is that initially successful fixes fail to resolve the problem due to side-effects they carry. As shown in Figure 4.15, increasing working speed and working time are successful in increasing productivity and thus reducing schedule delays in the short-term. However, as the negative effects of these two fixes manifest themselves as accidents, the schedule delay problem reappears and continues to worsen in the long run.

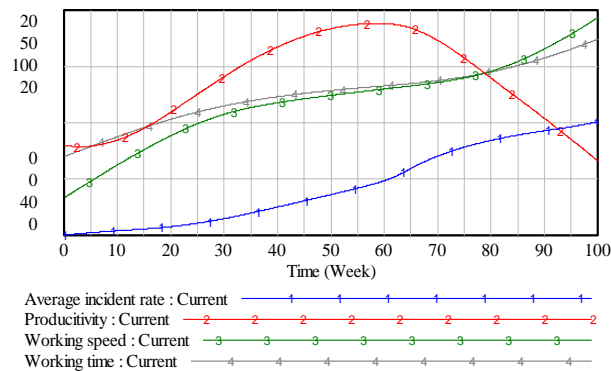


Figure 4.15 Behaviour pattern of the ‘production and safety’ archetype

4.6.5.3 Leverage points

A leverage point of this archetype lies in a direct link between schedule delay and accident. This requires managers to develop a long-term vision and challenge their “mental models” that determine not only how they make sense of the relationships between production and safety, but how they take action to solve problems that are relevant to the relationship. It is critical for them to consider the long-term consequences of decisions that are aimed at improving productivity. Once the direct connection schedule delays and accident is bridged, managers can weaken the

symptomatic fixes by balancing the time spent on production and safety and controlling working hours.

4.6.6 Workers' conflicting goals

In the interviews, the majority of participants were asked questions of “Why are unsafe behaviours so common on sites, although workers do know safety risks?” and “What are factors that affect their behaviours?” Three major factors emerged: risk perception, peer pressure, and production pressure. The archetype of workers' conflicting goals captures the dynamic effects of these three individual factors on safety behaviours, as shown in Figure 4.16. The structure shows that, at the individual level, workers' safety behaviour is mainly governed by three balancing loops (B1 Self-protection, B2 Production VS safety, and B3 Maintain a macho image).

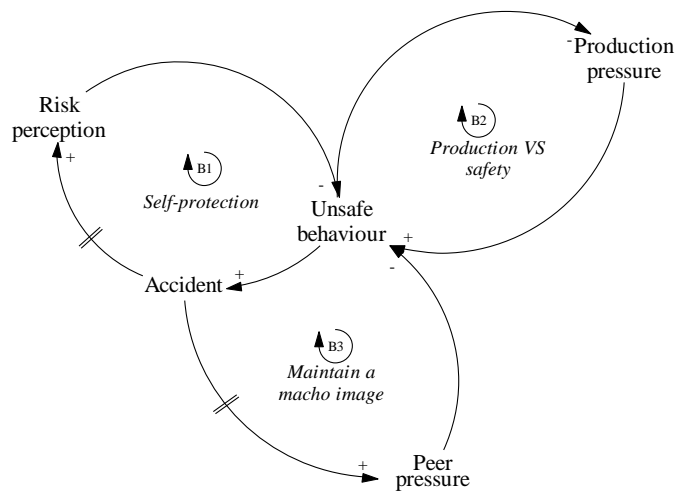


Figure 4.16 Workers' conflicting goals

4.6.6.1 Dynamic theory

The first balancing loop (B1 Self-protection) describes the dynamics of risk perception and its dynamic influences on workers' safety behaviours. Risk perception in this

archetype is the subjective judgment that workers make about the severity of hazards on sites. Most interview participants stated that as workers experience more accidents, they become more protective. As a result, workers tend to take protective behaviours from the anticipation of negative consequences (injuries and accidents).

The balancing loop (B2 Production VS safety) captures the dynamic effects of production pressure on workers at the individual level. As discussed in the archetype of production and safety, workers may be forced to take short cuts under production and time pressures. A general belief is that unsafe behaviours increase working speed and thus improve productivity. As the production pressure eases off, managers and supervisors have more energy on safety issues, which, in turn, decreases unsafe behaviours (see B2 Production VS safety).

In addition, peer pressure is another significant factor that affects workers' behaviours. Peer pressure in this archetype is defined as influence of a peer group that can change group members' safety attitude or behaviour. From a system dynamics perspective, the value of peer pressure can be either positive or negative. Positive peer pressure enhances safety attitude and therefore encourages safety behaviours, whereas workers who are under negative peer pressure tend to risk their personal safety over social conflict. As a safety consultant pointed out:

“If older workers do something wrong, young workers are not confident enough to point it out. They tend to observe them and copy them. ”

Negative peer pressure can be attributed to the machismo that has been deeply embedded in the male-dominated construction industry. As shown in the balancing loop (B3 Maintain a macho image), workers behave unsafely only because they do not want to be seen as “unmanly” or “weak” (Mullen, 2004, Kyle, 2013). The state of peer

pressure is determined by group safety norm which, in turn, is shaped by lessons learned from accidents. However, it would take a long time to develop group safety norm. This process is subject to the mobility of workforces and people's ability to learn.

4.6.6.2 Behaviour over time

In reality, social environment of a project in which workers perform their jobs is complex and dynamic. While it is true that workers have been told that safety is a priority, they may receive conflicting and inconsistent messages from co-workers, supervisors and managers. These mixed messages can cause motivational forces with different directions and magnitudes and affect workers' choice. Figure 4.17 shows the behaviour pattern of unsafe behaviour in the archetype of 'workers' conflicting goals'. From a systems dynamics view, negative feedback loops generate goal-seeking behaviour. In initial stages, unsafe behaviour increases. However, it soon levels off because three negative feedback loops have reached a dynamic equilibrium.

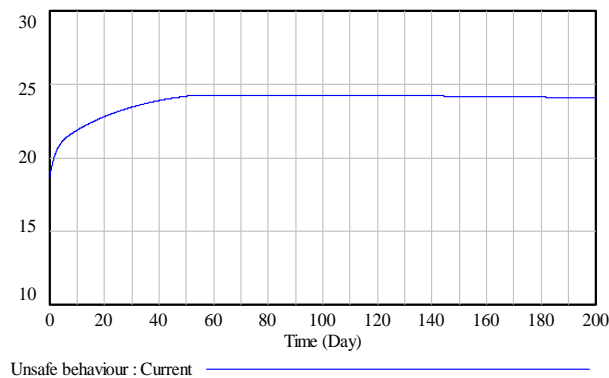


Figure 4.17 Behaviour pattern of the 'Workers' conflicting goals' archetype

4.6.6.3 Leverage points

A system containing negative feedback loops will be in equilibrium when all of its stocks (i.e. unsafe behaviour) are equal to all of its goals (i.e. improve productivity,

self-protection, and maintain a macho image) simultaneously. As shown in Figure 4.18, how unsafe behaviour changes at the beginning and which level it approaches depends on initial conditions of three feedback loops and the magnitude of effects of three factors (i.e., production pressure, risk perception and peer pressure) on unsafe behaviour. When each factor has the same magnitude of effect on unsafe behaviour (CoeR=1, CoePr=1, CoePe=1), unsafe behaviour decreases at the beginning and then remains the same at the level of about 23. In contrast, when the effect magnitude of risk perception is five times greater than the others our (CoeR=5, CoePr=1, CoePe=1), unsafe behaviour increases slightly in initial stages and remains the same at the level of about 12. Thus, leverage points of this archetype lie in its own three negative feedback loops. Setting more desirable goals, such as less production pressure, higher level of risk perception, positive peer pressure, are able to create discrepancy and thus draw the unsafe behaviour to the lower level.

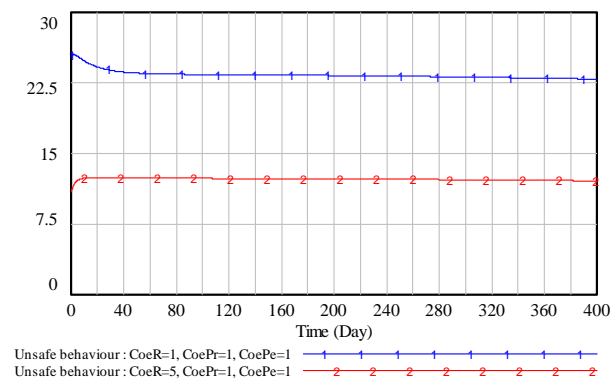


Figure 4.18 Dynamics of unsafe behaviour under different conditions

4.6.7 Blame on workers

The archetype of blame on workers captures short and long term effects of the approach used by the construction companies in accident investigation. As shown in

Figure 4.19, this archetype is a special case of “shifting the burden”. Composed of a combination of a balancing loop (B Person approach) and a reinforcing loop (R Side effect of person approach), the structure illustrates how blaming workers fails to reduce accidents.

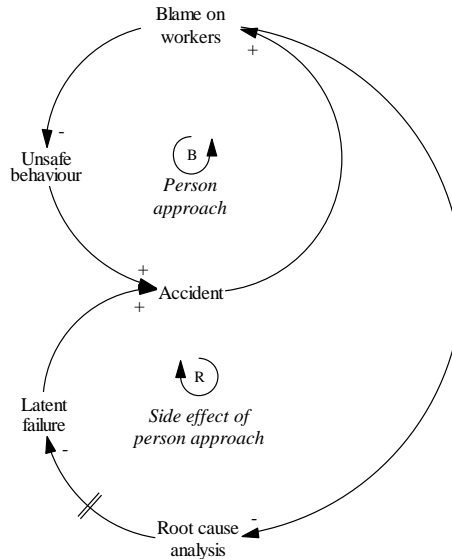


Figure 4.19 Blame on workers

4.6.7.1 Dynamic theory

A safety consultant stated that the person approach has been widely adopted by the construction firms in accident investigation and analysis:

“Blame culture is absolutely common in the industry. After accidents occur, managers tend to point the finger at workers, without addressing root causes of accidents. Workers just do the best they can. People fail to ask why unsafe acts are acceptable on site.”

The person approach sees accidents as results of workers’ unsafe behaviours and lazy attitude (Reason, 2000). In accident investigations, it is important that investigators identify root causes that lead to the accident. However, such an importance has not been widely recognized in the construction industry. It is not uncommon that construction accident investigations often ended with a conclusion that it was the

worker's faulty decision and unsafe behaviour that caused the accident. By adopting the person approach, the only reason for the accident would be unsafe behaviours at the sharp end and managers tend to assign blame on the workers who caused the accidents. By doing so, workers tend to place more attention on safety because of pressure caused by the blame. As a result, unsafe behaviours are less frequent and thus accidents decrease (B Person approach).

However, accident is a complex phenomenon, which involves a number of factors at different system levels (Dekker et al., 2011). Managers' tendency to attribute accidents to problems with workers would decrease possibility of identifying root causes. In consequence, latent failures (e.g., low level of management commitment, high production pressure, and problematic site condition) are ignored without timely correction, which create an undesirable context within which worker behave even less safely (R Side-effects of person approach).

4.6.7.2 Behaviour over time

Figure 4.20 illustrates the dynamics of the archetype of 'blame on workers'. Initially, the approach of blaming workers for their mistakes works properly to reduce accident rate. However, as managers place their attention only on workers, root cause analysis of accidents is less conducted. As a result, more latent failures are left without correction. Thus, accident rate stops to decline and reaches a plateau, even though managers continue to assign blame on workers. It is obvious that the symptomatic solution (i.e., blame workers) no longer works because the insidious reinforcing feedback loop dominates and the fundamental solution (i.e. root cause analysis) is gradually abandoned.

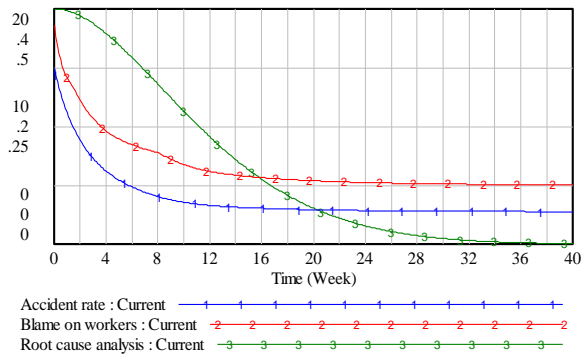


Figure 4.20 Behaviour pattern of the “blame on workers” archetype

4.6.7.3 Leverage points

Side effects of the person approach can be significantly minimised by linking accident and root causes analysis. In fact, this represents a systemic approach to understanding and analysing accidents. Figure 4.21 describes the dynamics of accident rate when a systemic approach is adopted. Side effects of the person approach remain zero, as each accident is thoroughly investigated and analysed. As a result, there is a steady decline in accident rate over time.

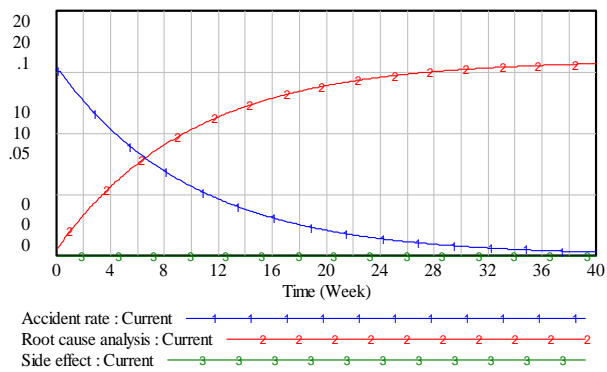


Figure 4.21 Behaviour pattern of a systemic approach

4.6.8 Reactive and proactive learning

Figure 4.22 describes an archetype of different learning strategies (reactive learning and proactive learning) adopted by the construction industry. The archetype consists of three balancing loops (B1 Reactive learning, B2 Proactive learning and B3 The effect of complacency).

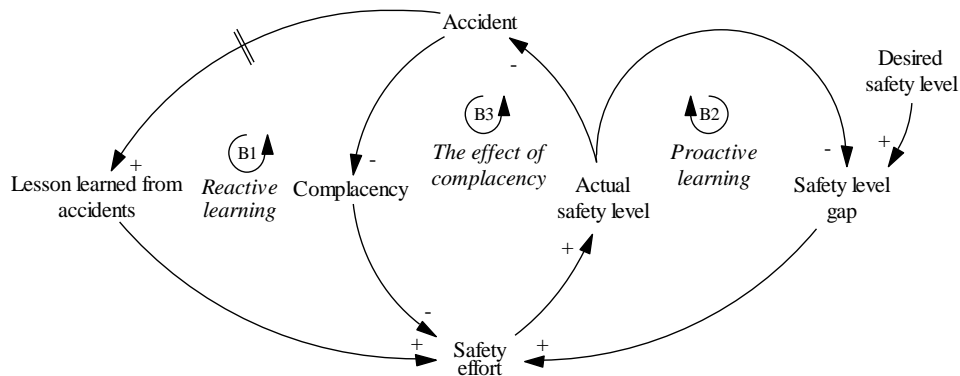


Figure 4.22 Reactive and proactive learning

4.6.8.1 Dynamic theory

In the construction industry, the safety level has been traditionally assessed by lagging indicators such as accident rates, TRIFR (Total recordable injury frequency rate), and fatality rates. Learning is largely based on accident investigation and analysis. How much is learned yet is heavily dependent on organisational ability. As a safety manager stated,

“.....It depends on the ability of companies, if they have “right” people, they can learn much from accident which helps to prevent accident. But not all companies have such “right” people.”

In general, lessons learned from accidents help companies to improve the effectiveness of safety actions and therefore improve safety level (see balancing loop B1 Reactive learning). However, one problem with such a learning style is that it is reactive in nature and thus provides only hindsight. As Rochlin argues, *“Defining an organisation as safe because it has a low rate of error or accident has the same*

limitations as defining health in terms of not being sick.”(Rochlin, 1999). Due to a long time lag between accident analysis and real situation, managers can lose an opportunity to make sense of real-time safety conditions. In addition, during the period without accidents, learning is inactive until next accident occurs. In this situation, companies are likely to become complacent about current seemingly good safety performance (see balancing loop B3 The effect of complacency). A safety manager provided an example in the interview.

“A contractor received a national level safety award because of excellent safety performance. But only a few months later, four workers were killed on site.”

This example points to a strong need for leading indicators. Despite the fact that the majority of construction companies still rely on lagging indicators, some have had designed and implemented leading indicators such as near miss reporting, scheduled safety observations, close-out of external audit findings and close-out of action items from peer reviewed investigation reports. A safety manager of a large contractor uses a number of leading indicators which, as he claimed, helped him to make sense of the “safety trend” of the project. Irrespective of the quality of leading indicators, such a proactive mind-set is encouraging. As shown in balancing loop B2 Proactive learning, leading indicators are able to identify the gap between actual and desired safety level by indicating safety problems and directing remedial actions (Mearns, 2009, Hopkins, 2009b). By doing so, safety level can be maintained and improved without lessons learned from next accident.

4.6.8.2 Behaviour over time

Figure 4.23 compares the dynamics of actual safety level in two different learning strategies. A construction project that adopts a reactive learning approach tends to

Han et al., 2014a, Jiang et al., 2014)) in terms of purpose and structure, despite the fact that there are some similarities with regard to dynamic structure, i.e. feedback loops and delays. First, the eight archetypes represent an effort to identify and categorize common behaviour patterns that recur again and again in construction safety management. Unlike those existing CLDs which were mainly derived from, and targeted at, specific cases, each of eight archetypes, grounded in data collected by 22 interviews, can be considered as a conceptualized theory that is not tied to specific construction companies or projects. They concretize lessons and management principles within general system archetypes and facilitate contextual learning in the domain of construction safety. They can play a role as templates or generic structure of construction safety modelling. Second, the eight archetypes are far simpler and more general than those existing CLDs. The focus is placed on general relationships among dynamic structure, behaviour and policy, rather than particularities.

4.7.1 Dynamics of construction safety

These eight archetypes capture the interactions between a wide range of factors within and among various hierarchical levels (government, company project and individual) and subsystems (regulation, procurement, cost, production, human resources and safety). As shown in Figure 4.24, different stakeholders (regulators, clients, main contractors, and sub-contractors) play various roles in construction safety management. These archetypes explicitly indicate that safety performance is not only determined by management activities within safety subsystem, but also by the interactions among factors of different subsystems (regulation, procurement, production, cost, and human resources) at different hierarchical levels.

The eight archetypes, as a form of systems thinking, advance the understanding of complexity and dynamics of construction safety management. They illustrate how complex feedback processes can generate problematic patterns of behaviour at different hierarchical levels. They aid in visualizing common construction safety problems and underlying structures that drive these problems.

From the systems thinking perspective, dynamic behaviours of a system are determined by its structure. The structure includes interrelationships among components of the system, the hierarchy and process flows. Each archetype is composed by a minimum number of feedback loops and delays. They are the cause of dynamics of construction safety. Reinforcing loops generate exponential growth and collapse. For example, companies' safety motivation can decrease continuously because of the R1 Side effect of reactive compliance culture R2 Safety regulations generate paperwork in Figure 4.4, R3 Incentive programs generate paperwork in Figure 4.6 and R Long-term effects of safety budget cut in Figure 4.8. But such processes are affected, stabilized and controlled by the balancing loops of safety regulations, incentive programs and client controls. Similarly, safety motivation at both company and individual levels shows a similar behaviour pattern: forces with different directions may result in a decrease or increase in the level of safety motivation. The complex combinations of both reinforcing and balancing feedback loops determine how safety level changes over time.

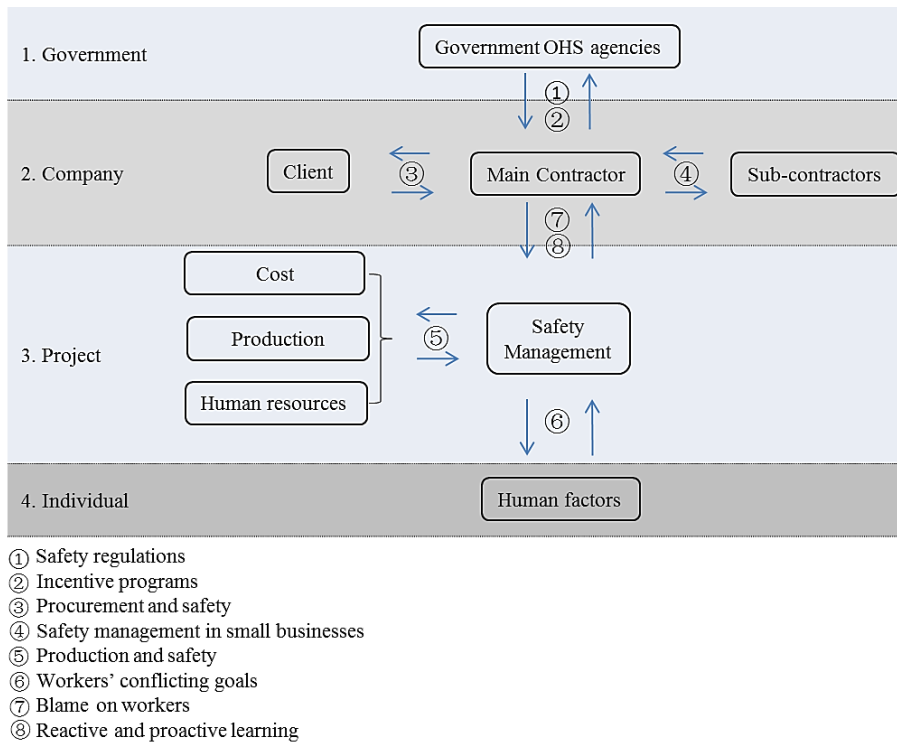


Figure 4.24 Interactions between system levels

A closer examination of system components in each archetype reveals that various pressures play significant roles in generating dynamics in safety management. Pressures can be defined negative (e.g., production pressure, negative peer pressure, and economic pressure) or positive (e.g., safety pressure from client and positive peer pressure) forces that tend to change the safety conditions of a system. For example, when pressure towards production is dominating, managers and supervisors tend to invest less time and energy on safety and even encourage workers to take shortcuts so as to meet production schedule. As a consequence, the level of management commitment to safety is likely to decline, which leads to a deterioration in safety conditions of a construction project. This dynamic view is consistent with Rasmussen's model of migration (Rasmussen, 1997). These archetypes visually portray the migrations of activities toward higher risk areas at different system levels.

However, this process of “drift into failure” is often invisible in reality, as some pressures are unconscious and managers tend to ignore the long-term effects. They tend to manifest themselves through workers’ unsafe behaviours and accidents at the sharp end.

Construction safety dynamics also have their sources from organisational learning strategies (style and effectiveness) adopted by construction companies. Archetypes of “blame on workers” and “reactive and proactive learning” depict and explain the dynamic effects of learning strategies on safety performance. Construction companies’ learning with regard to safety has been largely based on accident investigation and analysis (Hallowell, 2011). However, the approaches used in accident investigation and learning styles (reactive or proactive) have considerable influence on both organisational and individual behaviour. Using “human errors” as a convenient and cheap label to explain accidents may, in the long term, have limited effects in reducing accidents. Reactive learning based on lagging indicators may miss the link between expected and actual problems and therefore fail to maintain the safety level of construction projects. Leading indicators have potential to improve adaptive capability of construction companies. But they have not been fully brought into regular practices, because of both theoretical and practical difficulties.

4.7.2 Implications for construction safety management

Unlike chemical process industry and nuclear plants where there are in-depth defences against failures, it is much more difficult to model and describe the sufficient conditions for construction safety, due to a higher degree of uncertainty in many aspects. The uncertainties largely stem from a limited understanding of the

mechanisms by which organisational and individual factors shape workers' behaviour, as well as the dynamics of the safety conditions of an organisation.

As suggested in the archetypes, some well-intentioned safety programs carry side-effects. It is clear that causes and effects are often distant in time and space. It is therefore not effective to treat safety problems like snapshots. A dynamic view is needed in practice. This underscores a strong need for an integration of safety into other subsystems (production, cost, and human resources). Separating the safety management from other management activities may make coordination less effective. In this situation, invisible side-effects of well-intentioned decisions and actions are likely to be ignored.

The construction safety archetypes developed in this chapter also generate systemic insights into design and implementation of safety management systems. Safety management systems are mainly designed and implemented to prevent accidents by identifying and managing safety risks. Safety risks have various sources including physical hazards, safety knowledge, production pressure, and safety motivation. In general, however, they are used in a "static" manner and the combination of standard safety practices within the system does not consider the dynamics of those safety risks. For example, the safety management system may not be updated to cope with temporary production pressure as well as the emerging negative peer pressure caused by new workforce. This may cause functional misalignment between safety practices and existing safety risks and thus leave some risks unmanaged. It is therefore important for managers to adapt the safety management system to make it constantly functional in new situations.

4.8 Summary

This chapter developed eight construction safety archetypes based on general system archetypes and system dynamics. Grounded in interview data, they capture the side effects of safety regulations and incentive programs at the government level. In addition, they suggest that the interactions between clients, main contractors and subcontractors can have significant impact on safety performance at procurement and construction stage. Furthermore, they help to understand why small businesses fail to achieve desired safety standards as expected and why workers keep behaving unsafely on site.

These archetypes represent an effort to identify and categorize behaviour patterns that recur in construction safety management. They create a library of fundamental dynamic structures that generate counter-intuitive behaviours with which managers must cope. They can be used as a tool to facilitate a systemic analysis of construction accidents and a systemic assessment of safety conditions. By capturing the dynamics of safety risks, they enhance the understanding of dynamics of construction safety. They can help decision makers focus underlying systems structures that cause constant and vexing problems, rather than human errors and physical hazards. They also facilitate a broader definition of accidents that goes beyond workers unsafe behaviour and thus provide insights into accident analysis and prevention. In addition, archetypes can be used as a planning tool. They alert decision makers to future unintended consequences and encourage them to look at the “big picture” and take a systemic view. More importantly, these eight archetypes describe complex construction safety process and thus provides insights into how to simplify complex safety reality.

Chapter 5 Monitoring Safety Conditions of a Construction Project Using System Dynamics Modelling

5.1 Introduction

This chapter reports on a study that aims to investigate complexity and dynamics of construction safety at project level. When leading indicators are implemented in a specific project, it is essential that they are able to express and monitor the safety conditions of the project. Such ability is associated with their predictive validity and the purpose of providing early warnings of accidents. Thus, it is essential to model safety risk of a project and understand how it changes over time.

This chapter develops a system dynamics model that captures the key dimensions of safety conditions of a medium-sized construction project and the causal links between safety conditions and safety outcomes. The modelling process is in part based on the results of Chapter 4. Numerical, written, and mental data were collected from the project by interview, questionnaire, and documentation. The model was validated through various tests, including parameter verification testing, extreme condition testing, behaviour reproduction testing, sensitivity analysis, and statistical screening. The results of simulation suggest that safety conditions of the project tend to change over time because of a complex web of relationships among system factors. They are determined not only by the state of single factors (e.g., management commitment to safety), but also by the interrelationships among safety and other subsystems (i.e.,

regulation, production, and human resource). This chapter then discusses the implications of this study for the development of leading indicators.

5.2 Background of the study

Construction is a complex system (Baccarini, 1996, Dubois and Gadde, 2001, Fewings, 2005, Bhattacharjee et al., 2011), which involves unique characteristics such as temporary workers, subcontractors, changing work conditions, and multi-organizational project structure. It remains the main contributor of workplace accidents and injuries in many nations (e.g., USA, UK, Australia, China, and New Zealand) (Pinto et al., 2011, Shin et al., 2014, Waehrer et al., 2007, Zhou et al., 2015), although safety improvements have been made over the last decades (Howell et al., 2002). These accidents and injuries have caused huge personal, social and financial costs (Feng et al., 2015, Pinto et al., 2011).

5.2.1 Safety (risk) assessment

Safety (risk) assessment is a core element in safety management. It is always desirable that the information about the risk of accidents can be obtained so that remedial actions can be undertaken. Early risk assessment methods (e.g., Event Tree Analysis and Fault Tree Analysis) assess risk associated with a complex engineered technological entity by using probabilistic risk analysis (PRA). Risk is typically defined by two quantities: severity and probability (Bedford and Cooke, 2001). Despite the popularity in the industry, current generation of PRAs does not integrate effects of organizational

factors on safety (Mohaghegh and Mosleh, 2009a). Hence, researchers have questioned their suitability to assess organizational side of safety risk (Le Coze, 2005). As organizations are seen as the origin of accidents, various risk assessment methods, being qualitative and quantitative, have included organizational factors in evaluating safety risks of complex systems. Examples include HAZOP (Kletz, 1997), CREAM (Grimm et al., 2009), Causal Modeling of Air Safety (Roelen et al., 2003), and WPAM (Davoudian et al., 1994). A detailed description of these methods is beyond the scope of this paper (see (Mohaghegh and Mosleh, 2009a)). From the organizational perspective, safety risk is interpreted and assessed based on formal or informal organizational safety causal models. These models filter complex safety reality and give meaning to the description of safety risk. Many studies (Fang et al., 2004, Ismail et al., 2011, Sawacha et al., 1999, Haadir and Panuwatwanich, 2011, Haslam et al., 2005b, Choudhry and Fang, 2008b) have identified a number of organizational and human factors that affect safety performance of a system, such as management commitment to safety, experience, production pressure, physical hazards, safety motivation, training, and safety climate, etc. Results of these studies enrich the meaning of safety risk of a complex system. They also promote a series of studies that integrate the relationships among technical, human, and organizational factors into risk assessment frameworks. For example, Le Coze (2013b) developed a sensitizing model for industrial safety assessment. This model indicates dimensions at macro, meso, and micro levels that need to be considered. To provide foresight, this model emphasizes the importance of understanding dynamic relationships between system components that produce unwanted events. In addition, Griffin et al.(2014) proposed a fitness-to-operate (FTO) framework for safety assessment in the offshore oil and gas

industry. The framework defines “safety capability” as “the capability to maintain the safety of complex systems operating in uncertain and interdependent environments”.

Common among these studies is that they all emphasize a cross-level view on safety risk.

In addition, the evolving and changing nature of organizations has increasingly been recognized as a challenge in safety management. Several researchers (e.g., (Rasmussen, 1997, Dekker, 2011, Leveson, 2004, Mitropoulos et al., 2005, Snook, 2002)) stressed the importance of cross-time analysis of safety risk. The focus of such a dynamic perspective is on how safety risk changes over time within a complex system. Thus, interaction, circular and non-linear cause-effect relationships among system factors and a “big picture” of safety risk are emphasized. As Snook (2002) stated:

“Focus solely at any one level and you’ll miss it. A second way to miss it is to take a snapshot. As a dynamic process, it cuts across time just as surely as it does levels of analysis. Like an animal in the wild that remains hidden until it moves, drift can’t be seen at a single glance.”

5.2.2 Safety (risk) assessment in the construction industry

There have also been parallel efforts to develop safety risk assessment tools in the construction industry. For example, Jannadi and Almishari (2003) developed a model that assesses risk of various construction activities. Similarly, Gürcanli and Müngen (2009) developed a risk assessor model to determine the risk associated with a particular task. Pinto (2014) proposed the Qualitative Occupational Risk Assessment model (QRAM) to assess accident risk level on site. The model comprises four

dimensions (i.e., safety climate, severity factors, possibility factors, and safety barriers) to estimate the risk of nine accident modes (e.g., fall and contact with electricity). The QRAM, in essence, is still task-oriented, although it includes safety climate as one dimension of safety risks. There has been a great disconnection between these methods and organizational and human factors. In addition, Bayesian networks (NBs) have been used to perform probabilistic analyses of various types of accident (e.g., falls from heights, object falling, and electrocution) and to help design early and preventive safety measures (Leu and Chang, 2013).

In practice, safety risk is often assessed based on safety management system principles. Governmental agencies adopt this approach to assess safety level of construction projects by checking compliance against procedures and rules (Blewett and O’Keeffe, 2011, Le Coze, 2005). In essence, it represents a rational and structural perspective on safety risk. Implicit in the approach is an assumption that safety can be achieved as long as a safety management system (SMS) is in place. Such an illusion is often fuelled by popular safety audits that assess compliance by solely checking whether a safety management system is in place and how well safety practices are documented. This has encouraged a “paper system” approach to safety and promoted a standardization of safety practices (Gallagher et al., 2003b). The assumption has led to a common understanding that an SMS *per se* represents all dimensions of safety capability by which a company prevents injuries and accidents. However, due to knowledge gaps regarding the effectiveness of SMS (Hale, 2003), SMSs often fall short of companies’ expectation. Empirical evidence does exist showing that SMSs fail to produce safety (Hopkins, 2007). Such a failure can be in part attributed to the fact that the SMSs used in the construction industry are generally incomplete (Perezgonzalez, 2005). But the

root of the problem is a lack of understanding of the safety process and causal relationships between safety management systems and safety outcomes. Although some accident models, such as the Swiss cheese model (Reason, 1997) and the system model of construction accident causation (Mitropoulos et al., 2005), have extended the causes of accidents from technical and human factors to organizational factors, the understanding of the relationships and interactions among these factors, safety practices, and safety outcomes is far from adequate (Øien et al., 2011a).

5.3 Study aims

The challenge facing risk assessment in complex systems has been empirical, methodological, theoretical and epistemological (Le Coze, 2013b). Different perspectives understand safety risk in a different way. In recent years, complexity science and systems theory provide a promising and powerful perspective on the cause of accident and safety (Dekker et al., 2011, Carrillo, 2011, Leveson, 2012, Reiman and Rollenhagen, 2014). Due to the nature of organizations, Le Coze (2005) also suggested that complexity should be considered as a key concept for the scientific understanding of safety risk and that acknowledging and understanding complexity can help current risk assessment and auditing practices overcome limitations of traditional technical risk assessment methods. He argued that it can complement to traditional principles which are often characterized by “determinism and order”, “decomposition (analysis)”, “linear cause and effect”, and “positivism”. On the other hand, our understanding of complexity and dynamics of systems and their effects on safety is rather limited. This is especially the case for construction safety, although

several researchers (e.g., (Guo et al., 2015a, Han et al., 2014a, Shin et al., 2014, Jiang et al., 2014)) advanced an understanding of complexity of construction safety management in terms of production pressure, safety behaviour, and common behaviour patterns.

Therefore, the aim of this chapter is to better understand the dynamics of construction safety risk at the project level. To this end, a system dynamics (SD) model was built to model complex interactions and nonlinear relationships among factors at different levels of a construction project. A cross-time and cross-level analysis was conducted to examine how safety level of the project changes over time.

5.4 Research method

5.4.1 System dynamics

System dynamics (SD), which was founded by Forrester in MIT (Forrester, 1961), is a methodology that can be used to understand, analyse and model complex real-world problems. Unlike traditional approaches that are concerned with linear cause-and-effect, system dynamics is conceptually based on the feedback concept and focuses on circular, interlocking, and sometimes time-delayed relationships among system components (Sterman, 2000). An advantage of the SD methodology is that a model can represent a number of feedback loop processes simultaneously, which is closer to what happens in the real world.

The system dynamics modelling approach is adopted because it, as an aspect of systems theory, suits organizational safety issues better than a traditional scientific worldview (Le Coze, 2005). It considers all concepts in the real system as continuous

quantities interconnected in feedback loops and circular causality (Sterman, 2000). System dynamics has long been applied to the safety research field. For example, SD was adopted in studies (Cooke, 2003, Goh et al., 2012b, Goh et al., 2010, Tsuchiya et al., 2001, Salge and Milling, 2006) to model accidents by capturing feedback structure and its effects on accident causation processes. In addition, Bouloiz et al.(2013) analyse the safety conditions of a chemical storage unit by modelling interrelationships among technical, organizational and human factors and their effects on safety. Due to complex issues involved in construction safety management, SD has been increasingly used as a tool to better understand, for example, production pressure (Han et al., 2014a) and safety attitude and behaviours (Shin et al., 2014, Jiang et al., 2014).

The development of the system dynamics is an iterative process. Each iteration leads to a better and more robust model. An SD analysis typically involves the following five steps (Sterman, 2000): (1) problem articulation, (2) formulation of dynamic hypothesis, (3) formulation of a simulation model, (4) testing, and (5) policy design and evaluation. The first model-building step is to clearly identify the purpose for a model and the problem that it aims to solve. This step is concerned with specifying the problem of concern and determining appropriate scope and resolution of the model. The second stage of model building focuses on determining the structure of the model in a qualitative way. The tool of causal loop diagram (CLD) is used to map causal links among these variables with arrows from a cause to an effect (Sterman, 2000). Reinforcing and balancing feedback loops and delays are basic blocks in the CLDs. Briefly, a reinforcing loop is a structure that feeds on itself to generate exponential growth and collapse, in which the growth or collapse continues at an ever-

increasing rate (see Figure 4.1). If the trend is ascending, the reinforcing loop will accelerate the growth. If the trend is descending, it will accelerate the decline. In contrast, a balancing loop produces a goal seeking behaviour. As shown in Figure 4.2, it intends to reduce a gap between a current state and a desired state. It moves a present state towards a desirable target regardless whether the trend is descending or ascending. Delays represents the time that elapses between cause and effect (Marais et al., 2006).

Once an initial dynamic hypothesis is developed, a modeller needs to transfer the causal loop diagram into a stock and flow diagram in which the type of variables (i.e., stock or flow), equations between these them, initial conditions are determined. The stock and flow diagram provides a quantitative description of the system. As shown in Figure 5.1, stocks represent accumulation and thus characterize the state of the system, as a result of difference between inflow and outflow. After the model is built, it is necessary to build confidence in the model's ability to represent the real system. Various tests can be conducted in this stage, including dimensional consistency test, extreme conditions test, sensitivity analysis, and behaviour pattern test. Once a model is deemed to be credible it can be used for policy analysis. Modeller can assess a range of policy options by modifying different variables and even structure for specific time periods. The purpose of policy analysis is to gain better understanding of such problem behaviours and to design policies aimed at improving them.



Figure 5.1 Stock and flow

5.4.2 Subject of study

The subject of this study is a medium-sized construction project which comprises of commercial and residential apartment blocks and over 6000 square meters of recreational and garden area. During the period when this project was under study, there were 1 main contractor and 3 subcontractors working on site. About 30 workers were involved in construction operation each day. Various safety practices were implemented in this project to manage site safety on a daily basis.

5.4.3 Data collection and analysis

As suggested by Forrester (1980), three types of data should be used in model construction and testing: numerical, written, and mental data. Numerical data used in this study include time series and cross-sectional records such as the number of incidents/accident occurred each week. These data were obtained by documentation and interviews with the project manager, the health and safety manager, and workers of the project. The information enabled the modeller to determine the initial values of model parameters and to test the validity of the model by comparing the simulated and actual injury rate. Written data that were useful for this study include the safety management system, safety rules and procedure, safety policy, organizational charts, and project description. These data were collected mainly by documentation. They acted as an excellent source of information about system structure. Mental data included people's impressions, stories, their understanding of the system and how decisions are actually made (Sterman, 2000) (p 853). In this study, mental data played a significant role at all stages of the modelling process. Despite the fact that system dynamics models are mathematical representations of problems, it is recognized that most of the information available to the modeller is qualitative in nature (Luna-Reyes

and Andersen, 2003). The safety conditions model developed in this study involves the use of soft variables, such as “management commitment to safety”, “safety motivation”, and “safety competency”. Thus, the gap between the reality (i.e., actual safety motivation) and the formulations in the model may be noticeable. Mental data are a main source of information that can fill the gap. To collect these data, semi-structured interviews were conducted with the project manager, health and safety manager of the main contractor, the general manager, the safety officer, and a worker of a subcontractor. The duration of each interview was between 30 and 60 min (mean interview length: 45 min). All interviews were conducted by face-to-face at the workplace.

In addition, a questionnaire was administrated in this project every one month between May and July 2015, with an attempt to measure the level of key variables (i.e., management commitment to safety, workers’ safety motivation, workers’ safety competency, and social support) of the system dynamics model. The questionnaire consists of 25 items and all items were rated on five-point Likert scales (from 1= “strongly disagree” to 5= “strongly agree”). On average, 12 workers completed and returned the questionnaire back to the researcher in each round. A summary of data collection process is presented in Table 5.1.

Table 5.1 A summary of data collection process

Data collection technique	Participants	Data collected	Time frame	Modelling steps
Semi-structured interviews	Project manager, H&S manager General manager Safety office Worker	Mental data	Between May and August, 2015	Data were used in all five modelling steps

Questionnaire	Workers	Management commitment to safety Workers' safety motivation Workers' safety competency Social support Incident/accidents Safety management system	1 st round: May, 2015 2 nd round: June, 2015 3 rd round: July, 2015	Data were used mainly in step3: formulation of a simulation model and step 4: testing
Documentation	/	Safety rules and procedure Safety policy Organizational charts Project information	Between September 2014 and August 2015	Data were used in all five modeling steps

Numerical data were analysed and used to determine initial values of model parameters and to test the validity of the model. The analysis procedure of qualitative data adopted the grounded theory method (GTM) formulated by (Glaser and Strauss, 2009). In the second step, formulation of dynamic hypothesis, the main purpose of data analysis was to translate qualitative data into a causal loop diagram and a stock & flow diagram. To this end, three coding processes (i.e., open, selective, and theoretical coding) were used to identify key variables and to draw causal relationships among them.

5.5 Results

The model adopts a system theory perspective and sees safety as an emergent property of the organization. The purpose of the model is to examine how safety risk of the construction project changes over time. It sees the project as a multi-level system (organization, group, and individual) and thus takes into account the relationship between factors at these levels. In addition, to obtain a “big picture”, effects of other subsystems (i.e., regulation, production, and human resource system) are included.

5.5.1 Causal loop diagram

To understand the dynamics of safety conditions of the project, a causal loop diagram is developed based on the data collected from the project. As shown in Figure 5.2, the dynamics are caused by a combination of four balancing loops and two reinforcing loops. It should be noted that all loops were emerged from data collection and only represent the real situation of this project.

The balancing loop (B1 _{MC's leadership}) describes the effects of the main contractor's safety leadership on safety performance. Main contractor's management commitment to safety (MC's MCS) can affect subcontractors' and workers' behaviour through various ways (e.g., safety policy, implementing safety practices, and personal involvement). As MC's safety control increases, the levels of subcontractors' contractor's management commitment to safety (SC's MCS) and workers' safety motivation (WSM) would increase. In addition, managers with a higher level of commitment to safety are more likely to provide workers with safety training opportunities. Thus, subcontractors' management commitment to safety is causally linked with their workers' safety competency (WSC). According to on theories of job performance (Deci and Flaste, 1996, Vroom, 1964), improved WSM and WSC would lead to a decrease in unsafe behaviours. MC's MCS is also linked with work conditions through hazard management activities. In this project, a safety officer of a subcontractor stated that the site is safe because main contractor places emphasis on hazard identification and management. More unsafe behaviours and unsafe work conditions can lead to more incidents and accidents, which, in turn, increase main contractor's attention on site safety.

The balancing loop (B2 *Effect of safety pressure*) captures the effect of safety pressure on main contractor, subcontractors' behaviour. The general manager of a subcontractor stated that safety pressure mainly comes from three sources. The first source is the fear of prosecution. To avoid financial punishment, he is motivated to take "all practicable steps" to ensure the safety of workers on site. Second, he does not want to see that the reputation of his company is undermined by excessive accidents. Third, high accident rates would cause adverse effects on market share. This may be life-threatening to his company. As a result, as safety pressure increases, both MC's MCS and SC's MCS increase.

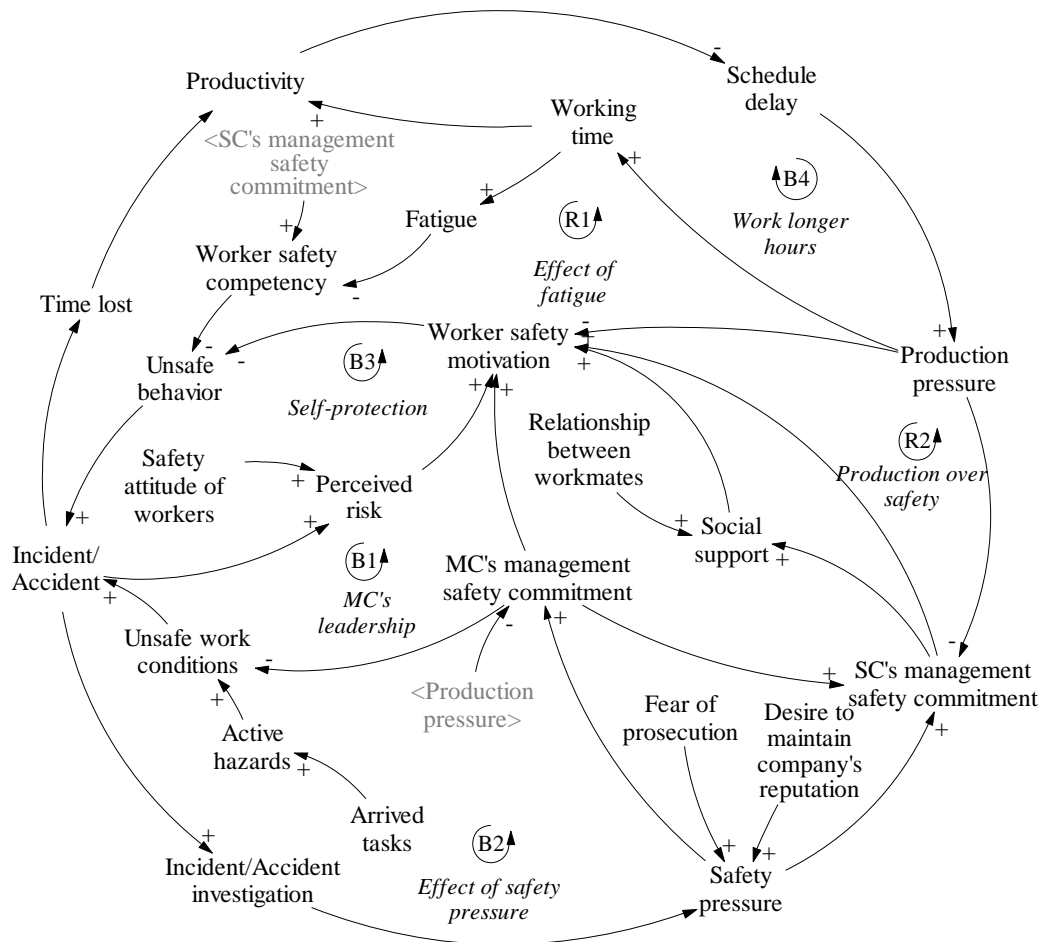


Figure 5.2 Causal loop diagram of safety conditions

The third balancing loop (B3 *Self-protection*) represents the dynamics of safety attitude at the individual level. During the interview with a worker, he stated that as workers experience more accidents, they become more protective and the level of perceived risk would go up. When an accident or incident occurs at this medium-sized project, the information about the incident or accident can be easily diffused among workers. Occurrence of accident or incident can lead to a change in risk perception of workers. The changed risk perception would make workers reassess the utility of safe behaviour and then change their safety motivation (Shin et al., 2014). Different workers may respond differently to accidents. The general manager of a subcontractor mentioned that some young workers tend to have a more positive attitude towards safety than their old peers. As such, how much workers modify their risk perception in response to accidents also depends on their safety attitude.

The fourth balancing loop (B4 *Work longer hours*) captures the way this construction project adopts to improve productivity and eliminate the schedule delay. However, as illustrated by the reinforcing loop (R1 *Effect of fatigue*), working longer hours would cause fatigue, which undermines workers' safety competency by reducing alertness.

The reinforcing loop (R2 *Production over safety*) illustrates how production pressure undermines safety performance. Due to the production pressure from both client and main contractor, subcontractors put less energy and time on safety and some of safety practices (e.g., safety meeting, toolbox meeting, and hazard management) tend to be ignored to some extent. This delivers an implicit message to workers that "production is our number one priority". As a consequence, both social support and workers' safety motivation would decline, which lead to more lost-time accidents and then further delays.

5.5.2 Stock and flow diagram

From a system dynamics view, dynamic behaviour is thought to arise due to the principle of accumulation. This is to say, all dynamic behaviour in the world occurs when flows accumulate in stocks, as shown in Figure 5.3. Thus, the third step of modelling is concerned with developing a simulation model by quantifying variables and relationships between them. To this end, some psychological variables such as safety pressure, social support, workers' safety competency and workers' safety motivation are modelled as stock variables that can either increase or decrease over the time horizon of the study. In this step, safety practices used in this construction projects are integrated into the model. In order to model psychological processes, safety practices are defined as positive forces that create, improve, and/or maintain these stock variables and pressures are considered as either negative or positive forces that tend to worsen or improve these stock variables. (Guo and Yiu, 2015). The definition is theoretically consistent with the role safety practices play in Mohaghegh and Mosleh's SoTeRiA model (2009a). Initial values of model parameters were determined based on the data collected from this project. Eight stock variables and their initial values are summarized in Table 5.2.

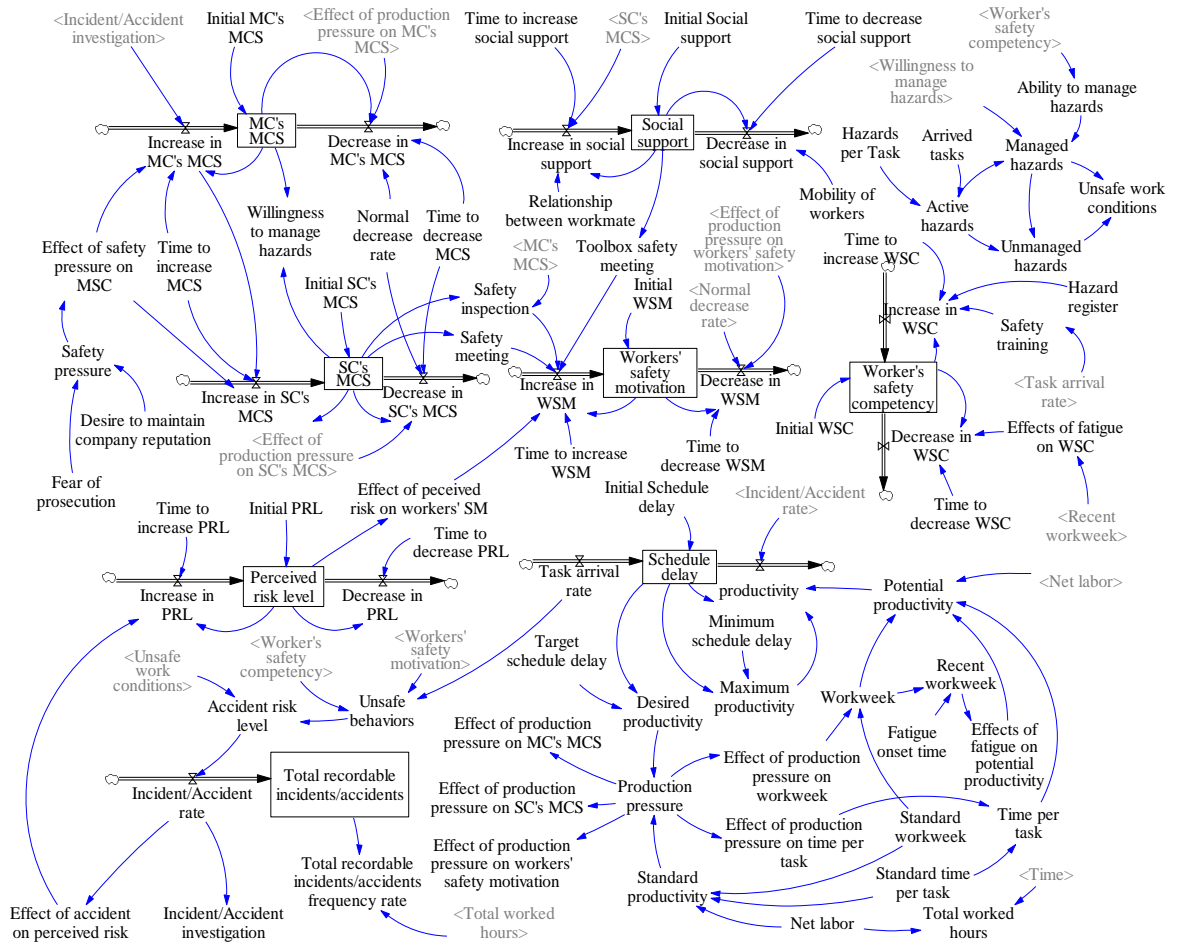


Figure 5.3 Stock and flow diagram of safety conditions

A base case was run based on the initial values presented in Table 5.2. The model equation listing of the base case is available upon request. Figure 5.4 shows the simulated behaviour of total recordable incident/accident frequency rate (TRI/AFR). TRI/AFR decreases gradually in the first 18 weeks, which is followed by a slight increase thereafter. It shows a declining trend again after the 40th week. It is evident that the behaviour of TRI/AFR tends to be damped oscillatory. The amplitude of oscillation dissipates over time. This is because TRI/AFR is largely controlled by four balancing feedback structures in which the information used to take goal-seeking action is delayed.

Table 5.2 Stock variables and initial values

Parameters	Function	Initial value
MC's MCS	Variable representing the level of main contractor's management commitment to safety	60 dmnl
SC's MCS	Variable representing the level of subcontractors' management commitment to safety	40 dmnl
Social support	Variable representing the level of social support on site	10 dmnl
WSM	Variable representing the level of workers' safety motivation	20 dmnl
WSC	Variable representing the level of workers' safety competency	50 dmnl
Perceived risk level	Variable representing the level of risk perception	10 dmnl
Schedule delay	Variable representing schedule delay	10 weeks
Total recordable incident/accidents	The number of incidents/accidents that have occurred	0

Note: Initial values of MC's MCS, SC's MCS, social support, WSM, WSC, perceived risk level were estimated

based on interviews on a scale from a baseline of zero to a maximum value of 100, as suggested by Levine (2000).

Initial values of schedule delay and total recordable incident/accidents were determined based on actual data.

dmnl=dimensionless.

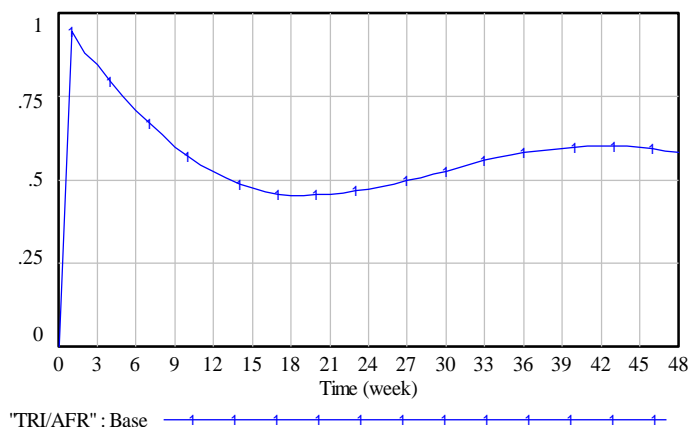


Figure 5.4 Base run of TRI/AFR

5.5.3 Model validation and testing

The model was validated by parameter verification testing, extreme condition testing, behaviour reproduction testing, sensitivity analysis, and statistical screening. Details of each testing are presented as follows.

5.5.3.1 Parameter verification tests

Model parameters (constants) were verified against data collected by interviews, survey, documentation, and site visits. The main purpose of the testing is to ensure all parameters correspond conceptually and numerically to the real construction project. The initial results of key parameters are presented in Table 5.2.

5.5.3.2 Extreme condition test

The purpose of extreme condition test is to examine whether or not the model behaves in a realistic fashion in extreme conditions. The test is important for two reasons (Senge, 1980). First, it is a powerful test to find flaws in model structure. Second, the test enhances the usefulness of a model for analysing policies that involve extreme and irregular conditions. The results for various extreme condition test are presented in Table 5.3. It is clear that behaviours of various model variables in extreme conditions are reasonable.

Table 5.3 Results of extreme condition test

Model parameter	Test	Value	Test result
Hazards per task	Zero hazards	0 hazard	Unsafe work conditions drop to zero (completely safe physical environment); Unsafe behaviours still occur because people may make mistakes even in safe environments.
Hazards per task	Maximum hazards per task	20 hazards	Unsafe work conditions increase to maximum.
Hazard register Safety training Toolbox safety meeting Safety meeting Incident investigation	No safety practices	0 practice	Compared with the “base case”, incident/accident rate increases significantly after the 15 th week, as shown in Figure 5.5.
Task arrival rate Arrived tasks	No production	0 task	Schedule delay drops to zero; Unsafe work conditions drop to zero; Unsafe behaviours drops to zero; No incidents.
MC’s MSC SC’s MSC Social support	Minimum commitment to safety	10 dmnl	Compared with the “base case”, TRI/AFR increases significantly, as shown in Figure 5.6.

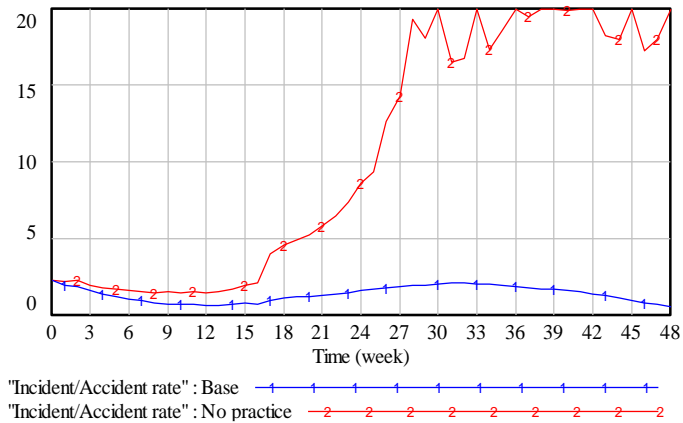


Figure 5.5 Incident/Accident rate of “base case” and “no-practice” case

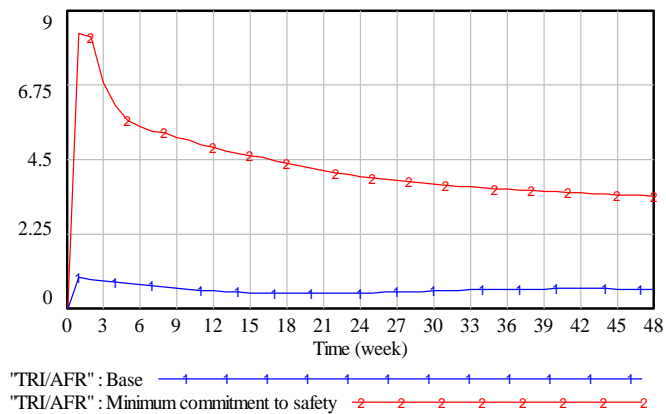


Figure 5.6 Incident/Accident rate of “base case” and “minimum commitment to safety” case

5.5.3.3 Behaviour reproduction tests

The behaviour reproduction tests aim to examine how well simulated behaviour matches observed behaviour of the real system (Senge, 1980). Figure 5.7 shows the actual and simulated behaviour of TRI/AFR.

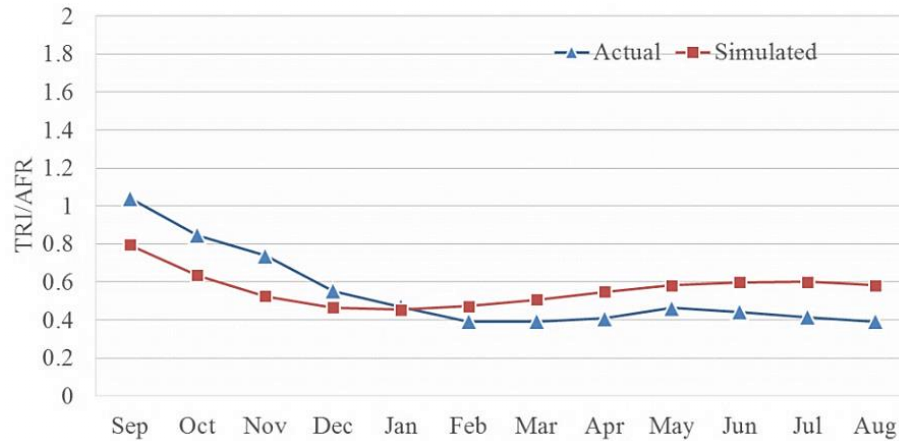


Figure 5.7 Comparison of actual and simulated TRI/AFR

To evaluate the fit, the Mean Absolute Percentage Error (MAPE) was calculated. According to Sterman (2000), MAPE is dimensionless and can be used for prediction comparisons. As suggested by Lewis (1982), the forecasting performance of the model can be evaluated in the context of the classification for MAPEs: less than 10% (highly accurate forecasting), 10-20% (good forecasting), 20-50% (reasonable forecasting), and greater than 50% (inaccurate forecasting).

Another common measure of forecast error is the mean-square-error (MSE). Theil's inequality statistics (Theil, 1966) were applied to determine the source of error by dividing the MSE into three components: bias (U^M), unequal variation (U^S), and unequal convariation (U^C). Since $U^M + U^S + U^C = 1$, Theil's inequality statistics can easily interpret the sources of error. According to Sterman (1984), a large bias (e.g., $U^M = 1$) represents a systematic difference between the model and reality. Errors because of large bias are potentially serious and usually caused by errors in parameter estimates (Sterman, 2000) (p 875). If is unequal variation is large (e.g., $U^S = 1$), it suggests that simulated data and actual data have different trends, or that the model does not capture the magnitude of a cyclical mode in the data. The unequal

convariation $U^C = 1$ indicates that the model differs from the data only point by point but captures the mean and trends in the data well.

As shown in the Table 5.4, the MAPE for actual TRI/AFR is 27.98%, indicating that the model provides reasonable prediction through simulation. In addition, the results show that the majority of error are concentrated in unequal convariation (UC =47%) and unequal variation (US=52%) and that bias is very small (UM=0.01). This suggests that the model has same mean and trends as actual data but differs from data point-by-point and that the errors are not systematic.

Table 5.4 Summary of inequality statistics

Metric	Formula	Value	Note
MAPE	$MAPE = \frac{1}{n} \sum_{t=1}^n \left \frac{S_t - A_t}{A_t} \right $	27.98%	N: number of observations (t=1, ..., n) S _t : simulated value at time t A _t : actual value at time t
MSE	$MSE = \frac{1}{n} \sum_{t=1}^n (S_t - A_t)^2$	0.02	\bar{S} : mean of S \bar{A} : mean of A
U ^C	$U^C = \frac{2(1-r)S_S S_A}{MSE}$	0.47	S _S : standard deviation of S S _A : standard deviation of A
U ^M	$U^M = \frac{(\bar{S} - \bar{A})^2}{MSE}$	0.01	r= correlation coefficient between S and A
U ^S	$U^S = \frac{(S_S - S_A)^2}{MSE}$	0.52	MAPE=mean absolute percentage error MSE=mean squares error

5.5.3.4 Sensitivity analysis

The simulation model uses a number of soft parameters whose values cannot be estimated precisely due to data availability or time constraints. This uncertainty may produce unreliable simulation results especially since the model has nonlinear and complex structures. Hence, sensitivity analysis is of particular importance to test the robustness of the model to uncertainty in assumptions. Sensitivity analysis allows an exhaustive analysis of the effects of parameter changes on model behaviour and performance to take place (Sterman, 2000). According to Moizer et al.(2001), sensitivity testing of the parameters has three uses:

“(1) It can help to narrow down those areas where more data gathering would be useful. It can be used to set a priority for data collection and the associated level of accuracy required.

(2) It can assist with improving understanding of complex problems being modelled, in particular help the modeller understand the structure-orientated behaviour of a model.

(3) It can be used to identify the pressure points in a model where the potential for improved behaviour lies.”

Since it is not possible to test all combinations of assumptions over their plausible range of uncertainty (Sterman, 2000), nine parameters that are subject to high uncertainty are included in the sensitivity analysis. The parameter values and distributions are given in Table 5.5. According to their possible values in reality, their range is plus or minus 50 percent with uniform random distribution.

As recommended by Ford and Flynn (2005), this study uses a Latin Hypercube Sampling (LHS) in Vensim’s Sensitivity Simulation Module to generate multivariate samples of the inputs and the model output Incident/Accident rate was simulated 200 times. To verify that this sample size is sufficient, we repeated the analysis with 300 runs. Results indicate that there are not differences in tolerance intervals. This suggests that the sample size of 200 is sufficiently large for the analysis. In this study, the output of interest is “TRI/AFR.

Table 5.5 Uncertain parameters

Parameters	Base values	Ranges	Distribution
Normal decrease rate	10 unit/week	(5, 15)	Uniform
Initial MC’s MCS	60	(30, 90)	Uniform
Initial social support	20	(10, 30)	Uniform
Initial WSM	20	(10, 30)	Uniform
Target schedule delay	1 week	(0.5, 1.5)	Uniform

Fear of prosecution	0.6	(0.3, 0.9)	Uniform
Initial PRL	10	(5, 15)	Uniform
Desire to maintain company reputation	0.6	(0.3, 0.9)	Uniform
Initial WSC	50	(25, 75)	Uniform

Figure 5.8 shows the sensitivity analysis results for TRI/AFR. 200 individual traces reveal that variations in the inputs change the value of TRI/AFR in the 1st week, but they do not alter its descending trend.

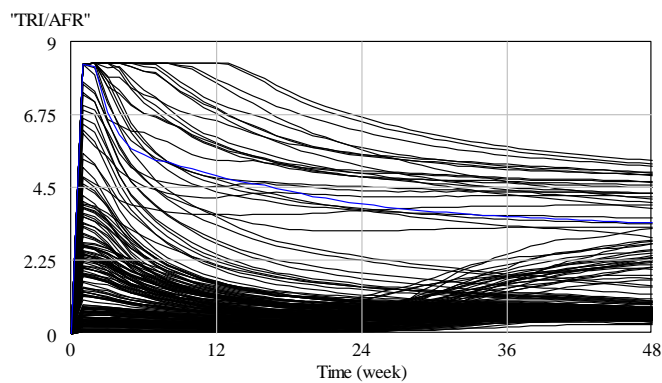


Figure 5.8 TRI/AFR from 200 runs of the simulation

Figure 5.9 shows Vensim percentile intervals for the TRI/AFR: 50 percent in light grey, 75 percent in medium grey, 95 percent in black, and 100 percent in dark grey. Results suggest that there is a 75% chance that TRI/AFR will be between around 0.2 and 2.7 in week 12. It is also suggested that the uncertainty in TRI/AFR is less during the late weeks of the simulation.

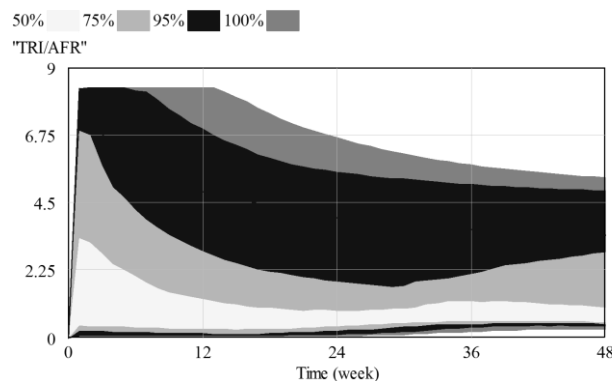


Figure 5.9 Vensim percentile intervals for TRI/AFR

In order to find key inputs that significantly affect TRI/AFR, statistical screening was used (Ford and Flynn, 2005). The relative importance of each input is indicated by calculating the simple correlation coefficient (CC) between the model's output and the values assigned to each input. The coefficient takes values within -1 and 1 range in which 1 indicates perfect positive correlation while 0 indicates no linear relationship. Parameters that have high correlation with output variable are concluded to be the high sensitivity ones.

The CC between the output and each parameter are calculated and plotted against simulation time (48 weeks), as shown in Figure 5.10. Starting in week 1, we see that initial values assigned to the WSC (CC= -0.61) and WSM (CC= -0.63) stand out as the top inputs. Despite the fact that these two parameters remain the dominant inputs throughout the whole 48 weeks of the simulation, the CCs for their initial values gradually decrease to about -0.30. These two parameters determine the value of unsafe behaviours and thus control three balancing loops: B1 MC's leadership, B2 Effect of safety pressure, and B3 Self-protection. The negative correlation for the WSC and WSM makes sense because a higher level of workers' safety motivation and competency lead to less unsafe behaviours and a lower level of incident/accident rate. The CCs for seven other parameters remain the range of ± 0.30 throughout the whole 48 weeks of the simulation. This indicates that TRI/AFR is not very sensitive to them.

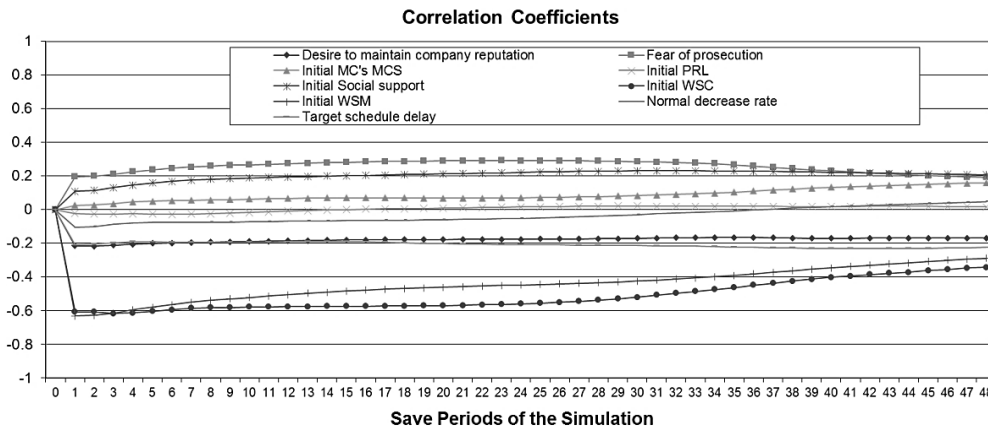


Figure 5.10 Correlation coefficients for the nine inputs to the model

5.6. Discussion

This chapter aims to examine how safety risk of a construction project changes over time. The SD model represents a systems theory and a constructivist perspective on safety risk of construction projects. Underlying the model is an idea that site safety is never an isolated phenomenon or task of safety subsystem, but rather an emergent property of the whole system which is comprised of a number of subsystems (i.e., regulation, production, cost, procurement, and human resource). Emphasis should not only be placed on practices and tools that can improve safety, but more importantly the negative effects of other subsystems that may lead to deterioration in safety. This brings about a new understanding of the role played by safety practices and safety management systems, as the model explicated the relationship between safety practices and factors at various system levels. In the SD model, the presence of safety practices is not considered as guarantee for success and human errors (i.e. unsafe acts or lazy attitude) are not a convenient label to explain failure. Unlike chemical process industry where there are in-depth defences against failures, construction safety relies heavily on “soft” control and workers’ decisions and behaviours. Any single “broken”

parts (physical environment or an under-trained worker) may lead to accidents. But a technical risk analysis of these parts is unable to deal with complex organizational safety process and thus offers little insights into how to avoid failure.

5.6.1 Multi-dimensional and dynamic risk

The model was purposefully developed to construct the complex safety reality of a construction project. The SD model integrates the psychological causes (e.g., management commitment to safety and safety motivation), organizational safety structure and practices (e.g., safety practices), physical environment (e.g., physical hazards), and regulatory environments (e.g., Worksafe's safety inspection). Results of simulation suggest that safety risk exhibits characteristics of being multi-dimensional and dynamic. It is determined not only by the state of single factors (e.g., management commitment to safety), but also by the interrelationships among safety and other subsystems (i.e., regulation, production, and human resource). Because of circular cause-effect relationships, safety risk is one of the organizational outputs that influence, and is influenced by, other outputs such as production.

At the organizational level, both main contractor's and subcontractors' safety commitment changes over time. As shown in Figure 5.11, SC's MCS has a similar behaviour mode as MC's MCS. In initial 8 weeks, both MC's and SC's MCS increase gradually, which is followed by a steady decrease between the 12th and 30th week. A closer examination of the mechanisms by which they change over time reveals that the increase in initial stages was mainly caused by the effects of constant incidents and accidents during this period. Take the MC's MCS for example. As demonstrated in Figure 5.12, even though the increase rate of MC's MCS declines in the first 8 weeks

as a result of the decreased effects of incidents and accidents, its value is greater than that of decrease rate. The decline between the 12th and 30th week is causally linked with a sharp increase of production pressure. In the final weeks, as production pressure eases off, MC's MCS begins to rise again, which is proved by an increased involvement in daily safety practices.

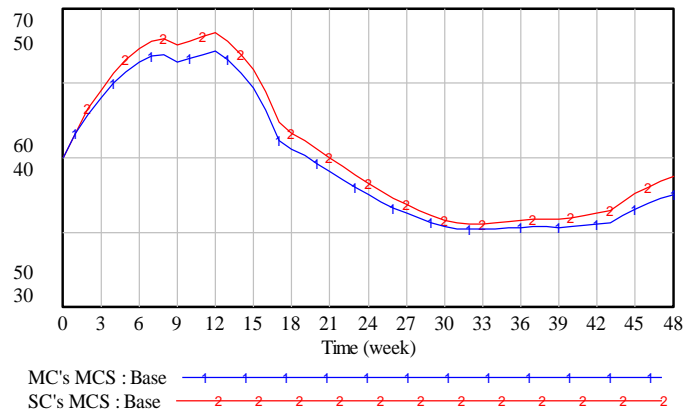


Figure 5.11 Dynamics of MC's and SC's MCS

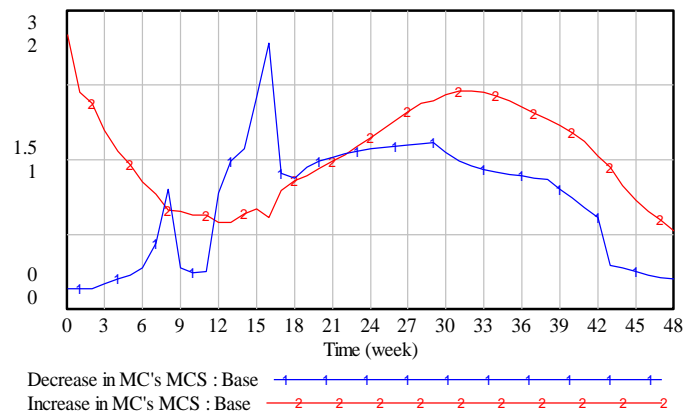
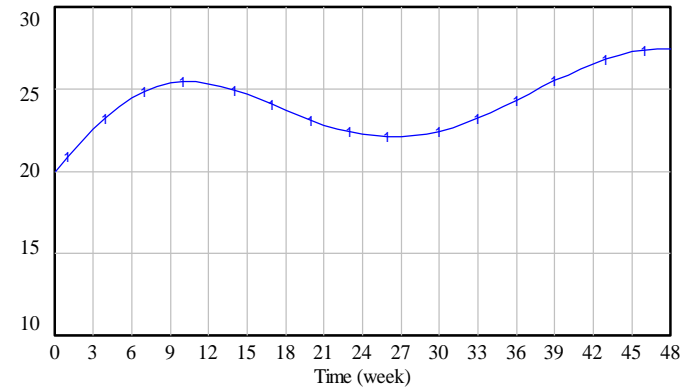


Figure 5.12 Comparison of decrease and increase in MC's MCS

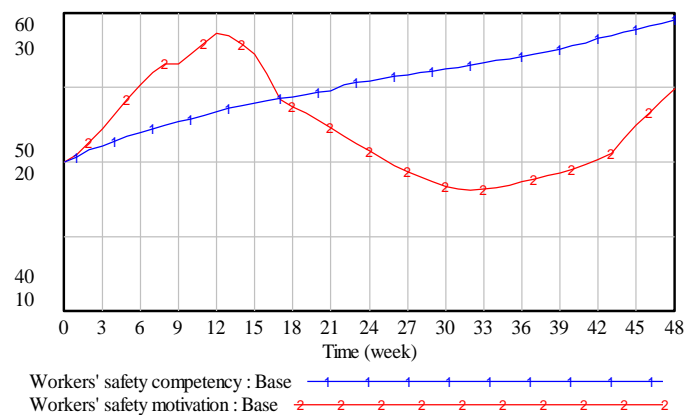
At the group level, social support plays an important role in improving workers' safety motivation. In this study, social support is modelled as a stock variable that changes with subcontractors' management commitment to safety. In reality, it takes time for workers to perceive the increase in management commitment to safety. In addition, they may not be able to perceive every random variation in the management commitment to safety. This means that transmission of the information from

management to group can be delayed. As a result, during the whole time horizon of the study, social support exhibits a sustained oscillation behaviour mode, as shown in Figure 5.13.



Social support : Base
Figure 5.13 Dynamic behaviour of social support

At the individual level lie two key factors: workers’ safety motivation and competency. Workers’ safety competency is influenced by safety practices (i.e., hazard register and training) and effects of fatigue. As the project progresses, workers become more experienced and competent in safety, as shown in Figure 5.14. Workers’ safety motivation (WSM) exhibits “ups and downs” behaviour mode in 48 weeks. This is caused a complex mechanism by which WSM is changed over time. As shown in Figure 5.15, WSM is affected by various factors such as production pressure, safety practices, and risk perception.



Workers' safety competency : Base
 Workers' safety motivation : Base
Figure 5.14 Dynamics of WSM and WSC

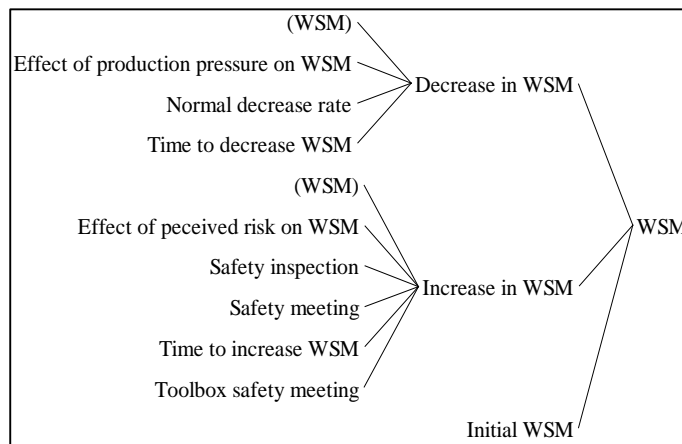


Figure 5.15 Causes tree of workers' safety motivation

5.6.2 Implications for the development of leading indicators

A quantitative simulation of the system dynamics model developed in this study provides the following systemic insights into the development of leading indicators.

First, as suggested in sensitivity analysis (see Figure 5.7 and 5.8), system performance (e.g., incident and accident rate) has sensitive dependence on initial conditions. This suggests that initial conditions are to some extent related to actual safety outcomes. It is therefore that leading indicators address initial conditions of site safety management. For example, results of simulation underscore the importance of selecting a “safe” main contractor and subcontractors at the beginning of a project. Clients and the main contractor should consider safety management as a fundamental part of the selection process when tendering for future construction work. The value lies in the fact that a “good start” in site safety management can avoid a vicious circle among accidents, schedule delay, production pressure, and management commitment to safety. Initial safety conditions will determine the safety outcomes in initial stages, which will influence both the direction and magnitude of the relationships between safety

subsystem and other subsystems. This means that selecting “safe” main contractor and subcontractors should be considered as an influence point for better safety performance in the future.

Second, the SD model is consistent with the conceptual framework (see Figure 3.1) in terms of the roles played by safety practise and pressure as well as the definition of safety conditions. Safety practices (i.e., safety training, hazard register, incident/accident investigation, safety meeting, and safety inspection) are modelled as positive forces that create, improve, and/or maintain variables of safety conditions such as workers’ safety motivation. Pressures are considered as either negative or positive forces that tend to worsen or improve these variables. The results of simulation suggest that such a framework, as well as the SD model, demonstrates ability to capture the safety process of a construction project. Results of the study also suggest that site safety is not a static phenomenon that is determined only by the presence of safety practices, but a dynamic one that is influenced by a complex web of relationships among pressures, safety practices, variables of safety conditions, and other factors of subsystems.

5.7 Summary

This chapter develops a system dynamics model of safety conditions of a construction project. As an application of systems thinking to construction safety, the model draws and quantifies the interrelationships among system factors and their effects on safety outcomes. The results of simulation illustrate the dynamics of safety risk at the project level. They suggest that site safety risk is multi-dimensional and dynamic in nature.

Improvement and deterioration of safety performance are determined by a complex web of relationships among system factors. According to the results of validity tests, the model demonstrates ability to describe the safety conditions of the project and to forecast total recordable incident/accident frequency rate.

This chapter offers systemic insights into safety risk assessment for construction projects. The system dynamics approach complements traditional risk assessment methods and draws a dynamic and more comprehensive picture of safety risk at the project level. Unlike typical linear models that see safety conditions as a sum of discrete factors, the system dynamics model captures a wider range of organizational, technical, and individual factors and their interrelationships. It addresses the balancing of multiple risk components including safety, production, human resource, and safety regulations. By doing so, this chapter provides an effective approach that enables safety practitioners to undertake systemic and dynamic safety risk analysis. In addition, this chapter also enhances the understanding of safety process at the project level. With less focus on specific tasks and activities, the system dynamics model re-conceptualizes safety as an emergent property of the system. As such, this chapter improves the understanding of complexity and dynamics of construction safety, which can contribute to further developments in safety theory (or model) for the construction industry.

Results of this study also suggest that in order to monitor safety risk of a project, leading indicators must be able to capture factors at different system levels (e.g., organizational, group, individual, and technical). Leading indicators must also be sensitive to the change of safety risk so as to provide timely information about safety level and safety problems.

Chapter 6 Predicting Workers' Safety Behaviour

6.1. Introduction

This chapter presents a study that aims to understand worker's safety behaviour at the sharp end. As discussed in Chapter 2, leading indicators were developed in other industries (e.g., nuclear, chemical process, and oil and gas industry) mainly to monitor technical risk control systems. Unlike these industries, construction safety relies heavily on administrative control and workers' behaviours. Thus, it is important to understand the mechanisms by which workers' safety behaviours are shaped. This can shed light on what should be measured in order to monitor safety risks and predict safety outcomes.

This study develops and tests an integrative model of construction workers' safety behaviour with an attempt to better understand the mechanisms by which key safety climate factors (i.e., management safety commitment, social support, and production pressure) and individual factors (i.e., safety knowledge and safety motivation) influence workers' safety behaviour. Data were collected from 215 construction workers in New Zealand using a questionnaire. Eight competing models were tested using structural equation modelling (SEM). The results showed that management safety commitment was significantly related to social support and production pressure. Production pressure was identified as a critical factor that has direct and significant effects on safety motivation, safety knowledge, safety participation and safety

compliance. Furthermore, social support was found to have the same paths to influence safety behaviour as production pressure, except that the effect on safety participation was insignificant. Safety knowledge and safety motivation were significantly and positively related to safety participation. The integrative model suggests a combination of “a safe organization”, “safe groups” and “safe workers” strategies to reduce unsafe behaviour on sites.

6.2. Background of the study

To prevent accidents, considerable attention has been paid by researchers to explore their root causes. A classic work of Heinrich’s Domino Theory (1931) understood accidents as linear outcomes of unsafe conditions and human errors. It was claimed that over 88% of preventable accidents were caused by unsafe behaviours (Heinrich, 1931). Such an understanding has led to a traditional view on human error, that is, it is a cause of accidents (Dekker, 2002). When accidents happen, workers are often blamed for forgetfulness, inattention, incompetence and lazy attitude. As such, corresponding accident prevention strategies that are based on this traditional view mainly focus on eliminating unsafe behaviours (i.e., errors and procedural violations) of frontline workers (Dekker, 2002). However, this traditional view has been criticized for over-simplifying accident causation processes and leading to a blame culture (Dekker, 2013). Subsequent research efforts shifted towards exploring the effects of organizational factors on accidents. This development has been referred to as the “third age of safety” (Hale and Hovden, 1998). In his famous Swiss Cheese Model (SCM) (Reason, 1997), Reason claimed that accidents can be traced to one or more of

four failure domains: organizational factors, supervision, preconditions and specific acts. Underpinned by the SCM is a new view on human error, that is, human error is a symptom of system failures (e.g., management deficiencies) that demands explanation (Dekker, 2002). This new view underscores the roles played by organizational factors in shaping human behaviour at the sharp end.

Awareness of the importance of organizational factors in construction safety management has driven the increased interest in safety climate in recent years. A body of work has been conducted to explore the factor structure of safety climate for the construction industry (Hon et al., 2012, Lingard et al., 2012, Dedobbeleer and Béland, 1991). There has been considerable evidence suggesting a positive link between safety climate and safety performance (Lingard et al., 2012). However, little is known about the mechanisms by which safety climate influences workforce's safety behaviour (Griffin and Neal, 2000, Neal et al., 2000, Clarke, 2006). There may be some reasons for this. First, the concept of safety climate is still ambiguous (Zohar, 2010b), which is reflected by the fact that there are no agreed safety climate scales for the industries and a wide range of variables and conceptual themes are covered by the concept (Flin et al., 2000b, Hon et al., 2012, Guldenmund, 2000). Second, the concept of safety climate, often used interchangeably with safety culture, tends to become a catch-all term for anything related to people's perception of organizational and contextual factors. Despite the solid evidence that safety climate is strongly and positively related to safety performance, a possible risk is that the concept may lose some of its analytic power when determining the mechanisms by which it influences safety behaviours and safety outcomes (Neal et al., 2000, DeJoy, 2005). Therefore, better understanding the mechanisms becomes important, since the main purpose of measuring safety

climate is to provide opportunities for improving safety performance of organizations (Cooper and Phillips, 2004). Researchers also emphasized a need for explaining how specific dimensions of safety climate influence safety behaviour (Prussia et al., 2003, Pousette et al., 2008, Wirth and Sigurdsson, 2008).

With this background, an empirical study was conducted to develop and validate an integrative model of construction workers' safety behaviour. The model was aimed at better understanding the mechanisms by which safety climate predicts safety behaviour of workforce by exploring the effects of core safety climate and individual factors on safety behaviour. The rest part of this chapter is structured as follows. It begins with a review of the safety climate studies which provide a theoretical basis for the development of the integrative model. Next, the methodology used to empirically test the model is described. The results are then presented, which is followed by a discussion of these results, limitations, and implications for the construction safety management. Finally, the conclusions of this study are presented.

6.3. Literature review

6.3.1 Safety climate

In order to prevent accidents and injuries, significant attention has been paid on improving the safety climate of a project or company. Originally developed by Zohar (1980b), safety climate has proved to be a critical construct that is causally linked to safety performance. Safety climate was defined as “*individual perceptions of the policies, procedures and practices relating to safety in the workplace*” (Neal and Griffin, 2006). A great deal of interest has been given to explore safety climate factors,

which resulted in a large number of assessment instruments (Flin et al., 2000b). However, safety climate factors are not universally stable and there are inconsistencies in factor structure of safety climate (Coyle et al., 1996). Despite the inconsistencies, safety climate has been empirically proved to be able to influence safety-related behaviours and outcomes across a variety of industries (Zohar, 1980b, Brown and Holmes, 1986, Johnson, 2007, Lingard et al., 2012, Neal et al., 2000, Gillen et al., 2002). A general conclusion is that where safety perceptions are more favourable, workers are less likely to behave unsafely and therefore accidents are less likely to occur. As a result, safety climate is often used as a leading indicator of unsafe behaviour and accident (Zohar, 2010b), although Clarke (2006) reported that the link between safety climate and accidents was weak.

Similar safety climate research patterns can be found in the construction industry. Researchers have made efforts to identify safety climate factors for the construction industry (Dedobbeleer and Béland, 1991, Glendon and Litherland, 2001, Mohamed, 2002, Choudhry et al., 2009, Fang et al., 2006, Zhou et al., 2010, Lingard et al., 2012, Hon et al., 2012). However, as shown in Table 6.1, no consistent factor structure has been established, the number of factors ranging from 2 to 10. Replicating factor structures that have emerged in previous studies has proved to be difficult. Notwithstanding the inconsistencies, there has been considerable evidence suggesting that safety climate predicts safety outcomes. For example, Mohamed (2002) reported a significant and positive relationship between safety climate and safe work behaviour. Similar conclusion was drawn by others (Fang et al., 2006, Choudhry et al., 2009, Lingard et al., 2012, Kapp, 2012), with the exception of Glendon and Litherland (2001)

who reported that no relationship was found between safety climate and safety behaviour.

Table 6.1 Safety climate factor structures for the construction industry

Studies	Factor structure	Validation
Dedobbeleer and Béland (1991)	Management safety commitment Workers' involvement	None.
Glendon and Litherland (2001)	Communication and support Adequacy of procedures Work pressure Personal protective equipment Relationships Safety rules	No relationship was found between safety climate and safety behaviour
Mohamed (2002)	Commitment Communication Safety rules and procedures Supportive environment Supervisory environment Workers' involvement Personal appreciation of risk Appraisal of hazards Work pressure Competence	Safety climate is positively related to safety behaviour
Fang et al.(2006)	Safety attitude and management commitment Safety consultation and safety training Supervisor's role and workmate's role Risk taking behaviour Safety resources Appraisal of safety procedure and work risk Improper safety procedure Worker's involvement Workmate's influence competence	Significant and positive relationship was found between safety climate and safety behaviour
Choudhry et al.(2009)	Management commitment and employee involvement Inappropriate safety procedure and work practices	The results of multiple regression analysis identified the critical safety climate factors affecting respondents' perceptions of safety performance on construction sites.
Zhou et al.(2010)	Safety regulations Safety supervision, safety training and workmate's support Management commitment Safety attitude	None
Lingard et al.(2012)	Top management commitment to safety Organizational priority placed on safety Supervisors' safety actions Supervisors' safety expectations Coworkers' actual safety response	Management commitment to safety has indirect effects on safety performance. Perceptions of top managers' commitment to safety were

	Coworkers' ideal safety response	strongly and positively correlated with perceptions of supervisors' safety actions and expectations as well as with perceptions of coworkers' ideal and actual safety.
Hon et al.(2012)	Management commitment to health and safety Application of safety rules and work practices Responsibility for health and safety	None

6.3.2 Key safety climate factors

6.3.2.1 Management safety commitment

Management safety commitment (MSC) was considered as one of the most fundamental safety climate factors (Flin et al., 2000b, Neal and Griffin, 2004). Neal and Griffin (2004) defined management safety commitment as “*the extent to which management is perceived to place a high priority on safety and communicate and act on safety issues effectively*” (p. 27). The effect of management safety commitment on safety performance has been examined in many studies and its importance has been widely recognized (e.g., (Fruhen et al., 2013, Hofmann and Morgeson, 1999, Hofmann and Stetzer, 1996, Al-Refaie, 2013, Michael et al., 2005)). The importance of MSC in safety lies in its far-reaching influences on safety management strategies, conflicts between production and safety. When upper managers are perceived as placing a high commitment to safety, supervisors and workers may want to meet upper management expectations by increasing their willingness to involve in daily safety practices. Safety climate studies suggested that these perceptions are socially transmitted to become collective norms and values within various hierarchical levels (Lingard et al., 2012). This proposition has been supported by empirical evidence in the construction industry. For example, McDonald et al.(2009) reported a cascading effect of management safety

commitment on safety performance at a large construction project. In addition, Molenaar et al. (2009) found that management safety commitment is the most influential determinant of safety performance in construction projects. Lingard et al. (2012) also reported that management safety commitment was significantly and positively related to perceptions of supervisors' safety actions and has indirect influence on safety behaviour.

6.3.2.2 Social support

Social support was defined as “*verbal and nonverbal communication between recipients and providers that reduces uncertainty about the situation, the self, the other, or the relationship, the functions to enhance a perception of personal control in one's life experience*” (Albrecht and Adelman, 1987). Putting it simply, it refers to safety-related support from supervisors and co-workers. It can be considered as a safety climate factor at the micro organizational level. Previous research indicated that front-line supervisors have significant influence on the safety behaviours of their employees (Mohamed, 2002, Hardison et al., 2014, Johnson, 2007, Zohar, 2002, Zohar and Luria, 2004). The importance of social support in construction safety management has long been realized. Lingard et al. (2012) pointed out that social support has taken on such an importance because of the fact that frontline workers are more likely to be influenced by daily interactions with supervisors and co-workers. Social support, compared to management safety commitment, has distinct roles and is perceived differently by the workforce (Flin et al., 2000b). In Haslam et al.'s ConCA model (2005a), social support is understood as a behaviour shaping factor at the group level, while management safety commitment mainly represents influences from company/project level. Past studies have proved that social support facilitates safety

communication and thus is of key importance in improving safety performance (Hsu et al., 2010, Parker et al., 2001, Gillen et al., 2002, Sampson et al., 2014b).

6.3.2.3 Production pressure

Zohar suggested that safety climate perceptions should move beyond an isolated focus on safety, toward an evaluation which incorporates the relative priorities among the various safety policies and procedures and their competing domains (e.g. production) (Zohar, 2010b). The negative effect of conflicts between production and safety has been examined by many researchers (e.g., (Choudhry and Fang, 2008a, Mullen, 2004, Seo, 2005, Flin et al., 2000b, Han et al., 2013, Mohamed, 2002). Mullen (2004) pointed out that construction workers behave unsafely not because they are not aware of the risks involved, but because of the work pressure exerted by supervisors and managers. Therefore, workers take short-cuts in order to satisfy their boss and avoid negative consequences. In such a way, production pressure tends to cause unsafe behaviours by decreasing workers' safety motivation. In addition, production pressure may make managers temporarily place production over safety and thus some safety practices (e.g., training, safety meeting) may be ignored in order to catch up schedule. Therefore, production pressure can have negative effects on workers' safety knowledge.

6.3.2.4 Safety motivation and safety knowledge

According to theories of job performance (Maier, 1955, Vroom, 1964, Campbell et al., 1993), performance is determined by an interaction of motivation and knowledge. A number of studies examined the effects of the two determinants of safety behaviour on safety performance (e.g., (Neal et al., 2000, Vinodkumar and Bhasi, 2010)). Christian et al.(2009) reported that safety performance was strongly related to safety

knowledge and safety motivation. Similarly, Brown et al.(2000) found that workers' safety attitude and safety efficacy were significantly related to safety behaviour. Neal et al.(2000) also found that safety motivation and safety knowledge predict both safety compliance and safety participation.

6.3.3 Safety behaviour

Traditionally, safety performance was primarily measured by lagging indicators such as accident rates, TRIFR (total recordable injury frequency rate), and fatality rates to monitor safety performance (Hinze et al., 2013b). However, such measures have been criticized for being reactive in nature and unable to provide early warnings of accidents (Guo and Yiu, 2013). Nevertheless, there has been a movement towards using safety behaviour to measure safety performance (Griffin and Neal, 2000, Vinodkumar and Bhasi, 2010). For example, Griffin and Neal (2000) used two factors (i.e., safety participation and safety compliance) to measure workers' safety behaviour. Safety compliance is defined as following rules in core safety activities (Griffin and Neal, 2000). This involves “adhering to safety procedures and carrying out work in a safe manner” (Neal et al., 2000). Safety participation includes behaviours that help to develop an environment to support safety. This often involves “helping co-workers, promoting the safety program within the workplace, demonstrating initiative, and putting effort into improving safety in the workplace” (Neal et al., 2000).

6.4. Research aim and hypotheses

The present study aims to better understand the mechanisms by which safety climate affects safety behaviour. To this end, this chapter develops and tests an integrative model of construction workers' safety behaviour which proposes the relationships among key safety climate factors (i.e., management safety commitment, social support, and production pressure), individual factors (i.e., safety knowledge and motivation), and safety behaviour using structural equation modelling (see Figure 6.1). This model posited sequent effects of management safety commitment at the macro organizational level on safety behaviour, via factors at the micro organizational level (i.e., social support and production pressure) and then individual factors (i.e., safety knowledge and safety motivation). This study adopted these five key safety climate factors (i.e., management commitment to safety, social support, production pressure, safety motivation, and safety knowledge) because they represent key safety climate factors identified by Flin (2000b).

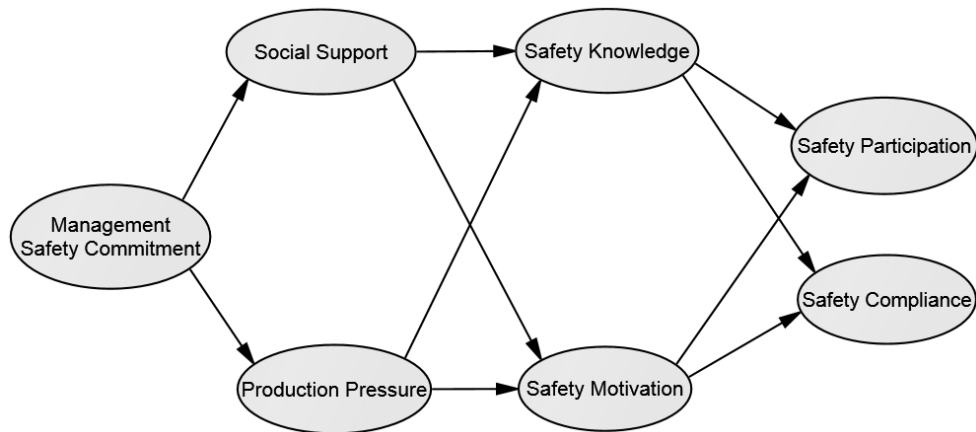


Figure 6.1 *A priori* model

Based on the current safety climate literature, the following hypotheses were formulated:

H₁: Perception of management safety commitment is positively and negatively related to social support and production pressure, respectively.

H₂: Social support is positively related to both safety knowledge and safety motivation.

H₃: Production pressure is negatively related to both safety knowledge and safety motivation.

H₄: Safety knowledge predicts both safety participation and safety compliance.

H₅: Safety motivation predicts both safety participation and safety compliance.

6.5. Methodology

6.5.1 Sample and procedure

Data were collected through sampling from workers of the New Zealand construction industry. Approximately 250 workers were randomly selected and provided questionnaires while they were attending safety training programs at three different training centres provided by a national not-for-profit organization. Anonymity was assured by providing each respondent an addressed envelope that allowed he/she returned the completed questionnaire to the researchers. In addition, another 250 questionnaires were administered to workers in four construction projects. The procedure of administration also demonstrated anonymity to respondents by having them place completed questionnaires in a sealed collection box. Of 500 questionnaires initially distributed, 215 were completed and returned. Of those, 213 were sufficiently completed to be included in data analysis, producing a usable response rate of 43%. Respondent characteristics are shown in Table 6.2. The sample size and response rate

is comparable with previous safety studies using structural equation modelling (Cui et al., 2013).

Sampling frame is construction workers who attend the safety training provided by the three training centers and workers of the four construction projects. The target population are workers. The unit of analysis is individuals (i.e., workers).As most construction projects in New Zealand require workers to have training pass from the organization, it is expected that the sample frame covered the majority of individual in the target population.

Table 6.2 Profile of respondents

Demographic variable	All (N=213)	
	Frequency	(%)
Gender		
Male	189	88.7
Female	24	11.3
Age		
<20	15	7.0
21-30	62	29.1
21-40	67	31.5
41-50	49	23.0
51-60	17	8.0
>60	3	1.4
Work experience		
1-5 years	71	33.3
6-10	54	25.4
11-20	35	16.4
Over 21	35	16.4
Unknown (respondents did not provide the information)	18	8.5

6.5.2 Survey instrument

The survey consists of three parts: (1) organizational and individual factors, (2) safety behaviour, and (3) demographic information. One of inherent disadvantages of questionnaire is that respondents may not be honest or truthful, due to social desirability bias. To avoid this problem, the following efforts were made. First of all, efforts were made to make sure that questions are clear and easy to understand and

that the sequence of questions is easy to follow. By doing so, respondents were less likely to lose their interests or focus. Secondly, all participants were informed that the questionnaire was anonymous and that confidentiality could be ensured. In addition, sensitive questions (e.g., the number of accidents) were not included in data analysis. In the pilot study, some respondents stated that they were not comfortable to provide information about accidents and near misses, but willing to answer questions about safety behaviour. Therefore, all information about accidents and near misses was not considered in subsequent data analysis.

Three safety experts reviewed the preliminary survey to maximize the content validity, as suggested by DeVellis (2003) and Seo (2005). Included were two safety advisors who both have had over 20 years of experience of construction safety management, and a construction safety researcher. Several items were further refined based on the feedback provided by them.

6.5.2.1 Organizational and individual factors

All items that measure organizational and individual factors were rated on five-point Likert scales with verbal anchors of *strongly disagree* to *strongly agree* at points of 1 to 5, respectively.

Four items were adopted from Al-Refaie (2013) to measure management safety commitment. Five items were adopted from Hsu et al. (2010) to assess social support. A scale of four items adopted from Seo (2005) was used to measure perceived production pressure. Five items were adopted from Vinodkumar and Bhasi (2010) to measure worker's perception of their own safety knowledge. A scale of six items adopted from (Fleming, 2012a) to assess workers' safety motivation.

6.5.2.2 Safety behaviour

An initial list of 15 items was developed to measure construction safety behaviour, based on construction safety studies (Haslam et al., 2005a, Choudhry et al., 2008, Choudhry et al., 2009, Fang et al., 2006, Fang et al., 2004). For these items, the respondents were asked to choose a six-point Likert scale on the frequency of safety behaviours from “never” to “always”. Because the number of responses depends on the nature of the question asked (DeVellis, 2012), six-point Likert scale is appropriate as a neutral option is not necessary in frequency scales and it increases opportunities for variability by allowing respondents more latitude in describing the frequency of safety behaviour.

6.5.2.3 Demographic information

Three types of demographic information were collected – company size, project details and individual attributes. Respondents were asked to provide the size of their companies in terms of the number of employees. In addition, the types of project (residential, commercial, civil and trade) of the respondents were working were collected. Information about individual attributes includes gender, age, and work experience (in number of years).

6.5.3 Data analysis

6.5.3.1 Treatment of data

In order to ensure the quality of data collected before starting data analysis, all the completed questionnaires (N=215) were checked against systematic response patterns and more than 5% missing items (Seo, 2005). Through this data screening process, 2 out of 215 completed questionnaires were dropped from data set. The responses with

5% or less unanswered items were retained for data analysis. Missing data points were imputed with the median of nearby points in each case.

To code responses for data analysis, the researchers identified each item as being favourable or unfavourable toward its factor to be measured, as suggested by Seo (2005). For items that measure management safety commitment, social support, safety motivation, and safety knowledge, the higher the assigned value, the more favourable these constructs were indicated. For items that measure the production pressure, the higher the assigned value the higher level of production pressure. For the safety behaviour, the higher values, the more frequent those safety behaviours were conducted.

6.5.3.2 Statistical analysis

Data were analysed with structural equation modelling (SEM) procedures (Hair, 2006). The computer program AMOS (version 22) was employed to obtain path estimates, using maximum likelihood estimation (MLE), and to evaluate the overall fit of the model tested. SEM is a comprehensive statistical method to testing hypotheses about relations among observed and latent variables (Hoyle, 1995). This study adopts SEM because it enables the researchers to examine a series of dependence relationships simultaneously (Hair, 2006), which is particularly useful in testing the theoretical model proposed in this study. In addition, SEM considerably facilitates the estimation and testing of causal sequences involving theoretical constructs rather than measured variables. Jöreskog (1993) distinguished among three situations concerning model fitting and testing in SEM: (a) the strictly confirmatory situation in which a single model is either accepted or rejected, (b) the competing models situation in which several models are formulated and one of them is selected, and (c) the model-

generating situation which involves re-specification of a target model based on misspecification revealed after initial estimation and examination of the target model. This study adopted the competing models approach and tested the hypotheses by comparing eight competing models regarding the causal relationships between latent constructs.

At present there is no consensus concerning the best index of overall fit for evaluating SEM models (Hoyle and Panter, 1995). SEM experts suggested that model fit should be assessed by multiple fit indexes that take into account the testing situation (Hu and Bentler, 1995, Hoyle and Panter, 1995). Thus, this study used different types of indexes of overall fit, including χ^2 , χ^2 /degrees of freedom ratio, the root mean square error approximation (RMSEA), comparative fit index (CFI), Tucker-Lewis Index (TLI), and the Incremental Index of Fit (IFI).

Absolute fit indexes

Absolute fit indexes typically evaluate “badness of fit”. A value of zero represent an optimal fit and increasing values indicate greater departure of the implied covariance matrix from the observed covariance matrix (Hoyle and Panter, 1995).

Chi-square (χ^2), as an absolute fit index, tests the closeness of fit between the sample covariance matrix and the fitted covariance matrix (Ullman and Bentler, 2003). If the chi-square is not significant, the hypothesized model is regarded as acceptable. Despite the popularity in testing models, the index is sensitive to sample size. When sample size is large, models tend to be evaluated as incorrect (Bentler and Bonett, 1980, Jöreskog and Sörbom, 1993). To address this limitation, an alternative fit index— χ^2 /degrees of freedom ratio—was developed (Wheaton, 1977). This fit index

is less sensitive to sample size. The model is regarded as acceptable if the value of χ^2 /degrees of freedom ratio is less than two (Ullman and Bentler, 2003).

Another commonly used absolute fit index is root mean square error of approximation (RMSEA). It is a parsimony-adjusted index in that its formula includes a built-in correction for model complexity (MacCallum, 1995). It has been considered as “one of the most informative criteria in covariance structure modelling” (Byrne, 2013). MacCallum et al. (1996) suggested that a value 0.01, 0.05, and 0.08 indicates excellent, good, and mediocre fit, respectively.

Incremental Fit Indexes

Incremental fit indexes typically evaluate “goodness of fit”: larger values indicate better fit between hypothesized model and data. Commonly used incremental fit indexes include Bentler and Bonett’s Normed Fit Index (NFI), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and the Incremental Index of Fit (IFI). NFI compares fits of two different models (the hypothesized model and the null model) to the same data set (Maruyama, 1997). However, NFI has shown a tendency to underestimate fit in small samples and has been considered as not a good indicator for evaluating model fit when sample size is small (Hu and Bentler, 1995). For this reason, Bentler (1990) revised the NFI to take sample size into account and proposed the Comparative Fit Index (CFI). Like NFI, value for the CFI range from 0.00 to 1.00 and is derived from the comparison of a hypothesized model with the null model. A value $>.95$ was considered representative of a well-fitting model (Hu and Bentler, 1999). TLI (Tucker and Lewis, 1973) is consistent with CFI, yielding values ranging from 0.00 to 1.00, with value close to .95 being indicative of good fit (Hu and Bentler,

1999). IFI, developed by Bollen (1989), is basically the same as the NFI in terms of the computation, with the exception that degrees of freedom are taken into account.

6.6 Results

6.6.1 Exploratory factor analysis

Before analysing the relationship between safety climate factors and safety behaviour, it is necessary to explore and check the dimensionality of safety behaviour items. Thus, an exploratory factor analysis was performed to identify underlying factors of the safety behaviour using SPSS 22. Maximum-likelihood (ML) and promax rotation were applied. A minimum eigenvalue of 1.0 was used as a criterion to extract the number of factors. The analysis yielded two safety behaviour factors: safety participation and safety compliance, which accounted for 60.94% of the total variance. Each of factors showed unidimensionality (Table 6.3). Item 10, 11, and 12 of safety behaviour were dropped because of low factor loadings.

Table 6.3 Exploratory factor analysis of safety behaviour

Safety behaviour (SB) items	Factor	
	1	2
SB2	.853	
SB4	.830	
SB5	.816	
SB6	.807	
SB1	.797	
SB3	.763	
SB14		.966
SB15		.869
SB7		.699
SB8		.612
SB13		.594
SB9		.560

Note: Factor 1= Safety Participation, Factor 2=Safety Compliance

6.6.2 Descriptive statistics

Correlations among all the scales are reported in Table 6.4 below. Production pressure was negatively correlated with other six variables. All variables were significantly correlated ($p < 0.01$). However, none of the correlation values exceeds the threshold value of 0.9, which suggests that the multicollinearity problem does not exist between the items (Hair, 2006) (p230).

Table 6.4 Descriptive statistics and correlations among variables

Scale	M	S.D.	MSC	SS	PP	SM	SK	SP	SC
MSC	4.22	0.72	1						
SS	4.11	0.71	.660**	1					
PP	2.76	0.76	-.489**	-.370**	1				
SM	3.97	0.76	.516**	.555**	-.445**	1			
SK	4.33	0.57	.401**	.491**	-.312**	.580**	1		
SP	4.09	1.18	.408**	.443**	-.397**	.591**	.561**	1	
SC	5.35	0.82	.505**	.517**	-.405**	.426**	.343**	.330**	1

** . Correlation is significant at the 0.01 level. MSC=Management safety commitment, SS=Social support, PP=Production pressure, SM=Safety motivation, SK=Safety knowledge, SP=Safety participation, SC=Safety compliance, M=mean, S.D.=standard deviation,

6.6.3 Testing the measurement model

In order to test the measurement model, a confirmatory factor analysis was conducted using AMOS 22.0 with the covariance matrix and ML estimation. The result of the model, including seven factors with a total of thirty one indicators, showed acceptable fit ($\chi^2=460.44$, $df=292$, $p < 0.001$, CFI=0.962, IFI=0.962, TLI=0.954, RMSEA=0.052 (90% CI=0.043; 0.061). As shown in Table 6.5, All loadings relating indicators to latent factors were statistically significant ($p < .001$). Item 2 of social support, item 4 of production pressure, item 1 of safety knowledge, item 1 and 3 of safety motivation, and item 3, 6, 9, and 13 of safety behaviour were dropped in the confirmatory factor analysis because of low factor loadings.

Table 6.5 Factor loadings of items

Construct scales	Factor loading
MSC: Management Safety Commitment	
MSC1: Management places a high priority on safety operations in company	0.96
MSC2: Management cares about the safety welfare of their employees.	0.91
MSC3: Management works to upgrade the safety of its facilities or reduce safety problems.	0.83
MSC4: Management provides resources to prevent the occurrence of safety-related incidents.	0.78
SS: Social Support	
SS1: When my supervisor and co-workers see me working at-risk, they caution me.	0.79
SS3: Supervisor makes on-going safety instruction at workplace.	0.78
SS4: Supervisor diligently reviews the safety behaviours of the employees.	0.90
SS5: Supervisor frequently moves around inspecting the workplace.	0.82
PP: Production pressure	
PP1: I take short cuts when I need to get the job done in a timely manner.	0.87
PP2: We are often in such a hurry that safety is temporarily overlooked.	0.92
PP3: Short cuts and risk taking are common due to the heavy workload.	0.79
SM: Safety Motivation	
SM2: I enjoy working safely on site.	0.76
SM4: Working safely aligns with my personal values.	0.82
SM5: I feel bad about myself when I don't work safely.	0.87
SM6: I feel guilty when I don't work safely.	0.87
SK: Safety Knowledge	
SK2: I know how to use equipment, tools and plants in a safe manner.	0.76
SK3: I know how to maintain or improve workplace health and safety.	0.92
SK4: I know how to reduce the risk of accidents and incidents in the workplace.	0.89
SK5: I know what are the hazards associated with my jobs and the necessary precautions to be taken while doing my job.	0.88
SP: Safety Participation	
SB1: How often do you assist others to make sure they perform their work safely?	0.83
SB2: How often do you speak up and encourage others to get involved in safety issues?	0.87
SB4: How often do you try to change the way the job is done to make it safer?	0.75
SB5: How often do you take action to stop safety violations in order to protect the well-being of co-workers?	0.74
SC: Safety Compliance	
SB7: How often do you wear a hard hat in designated areas?	0.74
SB8 How often do you wear eyes protection hat in designated areas?	0.71
SB14 How often do you wear proper PPE when working on or near live electricity?	0.84
SB15 How often do you wear PPE when working at heights?	0.85

Then, the convergent and discriminant validity, as well as reliability, of factors were then tested. To establish reliability, this chapter used composite reliability (CR), or rho. This score is a more accurate estimate of reliability than Cronbach's alpha because the composite reliability does not assume that the loadings or error terms of the items are equal (Raykov, 2004, Chin et al., 2003, Lowry et al., 2012). The standard minimum threshold is 0.7.

Convergent validity refers to the extent to which indicators of a specific construct converge or share a high proportion of variance in common (Hair, 2006) (p 771). Convergent validity can be estimated through factor loadings and Average Variance Extracted (AVE). As a good rule of thumb, standardized loading estimates of 0.7 or higher and AVE of 0.5 or higher suggest adequate convergence (Hair, 2006).

Discriminant validity refers to the extent that a factor is truly different from other constructs (Hair, 2006) (p 771). The requirements are that (1) the square root of AVE for a factor should be greater than inter-construct correlations, (2) AVE should be greater than Maximum Shared Variance (MSV), (3) AVE should be greater than Average Shared Variance (ASV) (Hair et al., 2010).

Against these suggested thresholds, as shown in Table 6.6, seven factors of this study do not have convergent and discriminant validity and reliability issues.

Table 6.6 The convergent and discriminant validity of factors

Factors	CR	AVE	MSV	ASV
Management Safety Commitment	0.926	0.760	0.466	0.263
Social Support	0.894	0.680	0.466	0.286
Safety Knowledge	0.919	0.739	0.411	0.221
Safety Motivation	0.899	0.691	0.366	0.279
Production Pressure	0.895	0.740	0.310	0.204
Safety Participation	0.877	0.642	0.411	0.256
Safety Compliance	0.865	0.618	0.288	0.183

6.6.4 Structural model assessment

Based on literature, eight competing models were tested in this study (see Figure 6.2).

These eight models differed in the relationships they proposed between the latent factors.

Model 1 proposed sequential effects of management safety commitment on safety behaviour, via social support, production pressure and safety knowledge and

motivation, as posited in system-person sequence model tested by Brown et al. (2000). Model 2 posited the same relationships among the latent variables as Model 1, but included the direct effects of management safety commitment on safety participation and safety compliance (Neal et al., 2000, Vinodkumar and Bhasi, 2010). Model 3 proposed the same relationships among the latent variables as Model 2, but included the direct effects of management safety commitment on safety motivation and safety knowledge. Model 4 posited the same relationships among the latent variables as Model 3, but included the direct effect of production pressure on safety knowledge. Model 5 proposed the same relationships among the latent variables as Model 3, but included the direct effect of social support on safety motivation. Model 6 posited the same relationships among the latent variables as Model 5, but included the direct effects of social support on safety compliance and safety participation. Model 7 proposed the same relationships among the latent variables as Model 6, but included the direct effects of production pressure on safety knowledge, safety participation and safety compliance. Model 8 proposed the same relationships among the latent variables as Model 7, but excluded direct effects of management safety commitment on safety knowledge, safety motivation, safety participation and safety compliance.

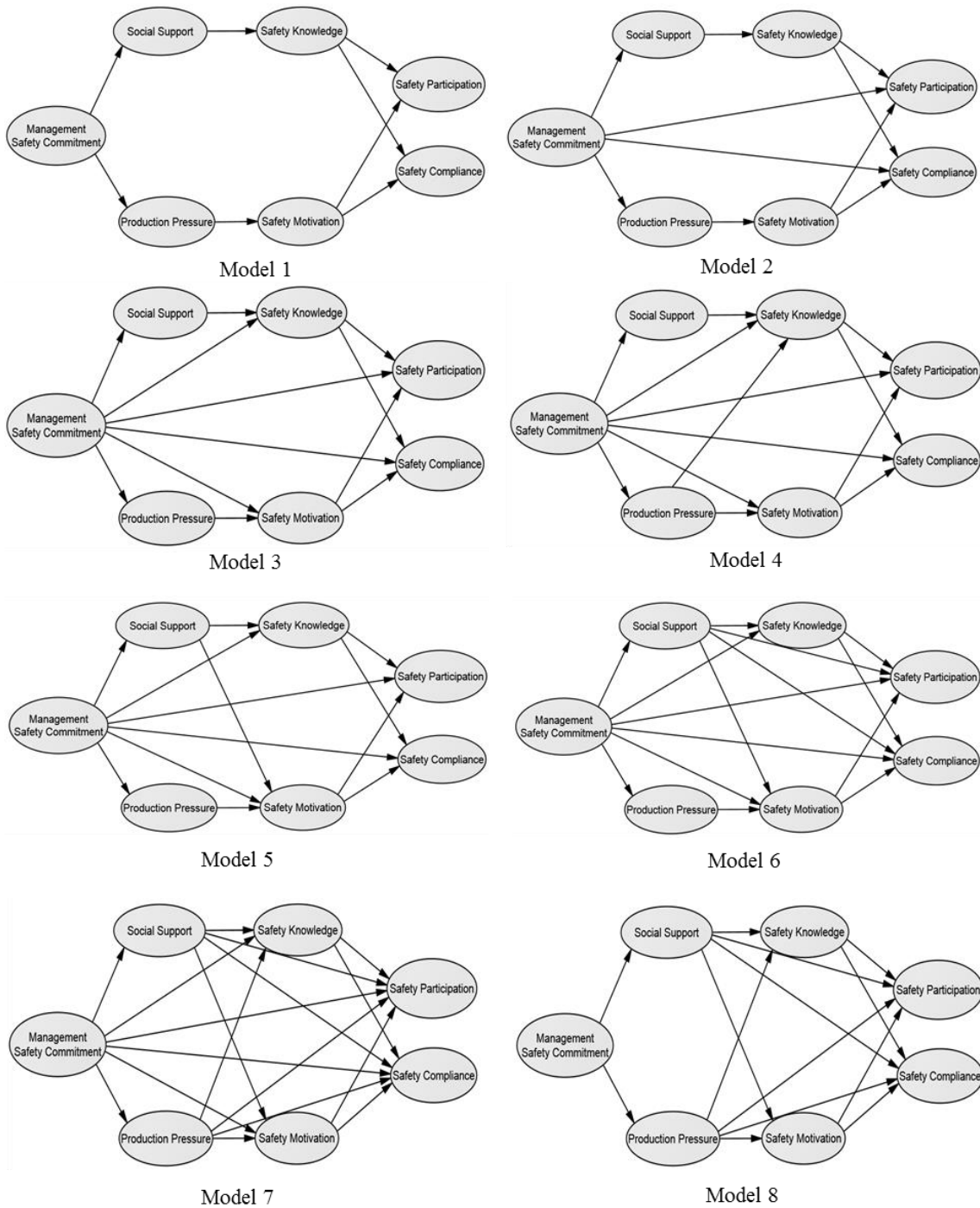


Figure 6.2 Competing models

Overall fit results were presented in Table 6.7. Model 2 showed significant χ^2 difference from Model 1, which suggests that adding the extra relationships between management safety commitment and safety participation and safety compliance would

improve the model fit significantly. Model 3 also showed significant χ^2 difference from Model 2, which suggests that adding direct effects of management safety commitment on safety knowledge and safety motivation would improve the model fit significantly. Model 4 showed no significant χ^2 difference from Model 3, which suggests adding direct effect of production pressure on safety knowledge would not improve the model fit significantly. However, adding relationship between social support and safety motivation would improve the model fit significantly, as Model 5 showed significant χ^2 difference from Model 3. Furthermore, Model 7 showed significant χ^2 difference from Model 6, which suggests that Model 7 (the least parsimonious model) is better than Model 6 in terms of model fit. Model 8 did not show significant χ^2 difference from Model 7, which suggests that the removal of direct effects of management safety commitment on safety knowledge, safety motivation, safety participation and safety compliance would not reduce the model fit significantly. However, comparing these two models, Model 8 is more parsimonious. Thus, Model 8 was concluded as the best representation of the observed relationships.

Table 6.7 Goodness-of-fit indexes for the seven competing models

Model	χ^2	DF.	χ^2/DF	CFI	IFI	TLI	RMSEA	$\Delta\chi^2$	ΔDF
1	541.922	303	1.789	0.946	0.947	0.937	0.061	-	-
2	521.415	301	1.732	0.950	0.951	0.942	0.059		
2 vs. 1 contrast								20.507***	2
3	496.677	299	1.661	0.955	0.956	0.948	0.056		
3 vs. 2 contrast								24.738***	2
4	492.965	298	1.654	0.956	0.956	0.948	0.056		
5	481.659	298	1.616	0.959	0.959	0.951	0.054		
4 vs. 3 contrast								3.712 (n.s.)	1
5 vs. 3 contrast								15.018***	1
6	471.473	296	1.593	0.960	0.961	0.953	0.053		
6 vs. 5 contrast								10.186**	2
7	460.841	293	1.573	0.962	0.963	0.955	0.052		
7 vs. 6 contrast								10.632*	3
8	463.405	297	1.560	0.962	0.963	0.956	0.051		
8 vs. 7 contrast								2.564(n.s.)	4

Note. *** $p < .001$, ** $p < .01$, * $p < .05$, n.s.($p > .05$)

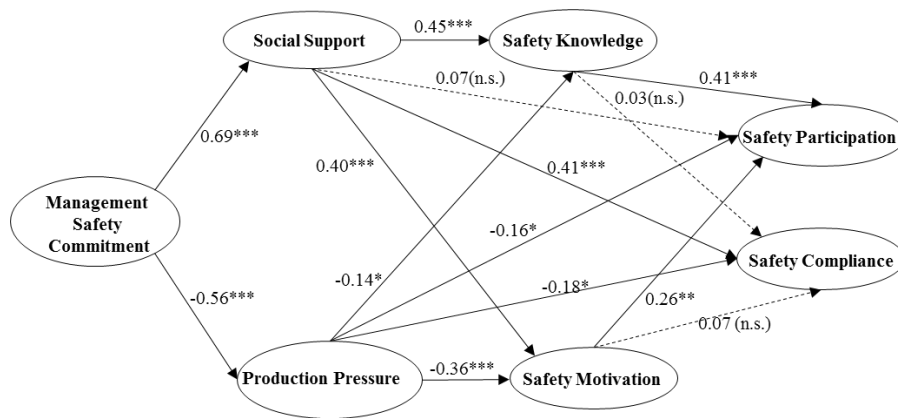


Figure 6.3 Final structural model (Model 8)

Note. *** $p < .001$, ** $p < .01$, n.s. $p > .05$; all indicators, measurement errors, and loadings were not shown for clarity

As shown in Figure 6.3, management safety commitment was positively related to social support (standardized $\beta = 0.69$, $p < .001$). The higher level of management safety commitment, the lower level of perceived production pressure (standardized $\beta = -0.56$, $p < .001$). Therefore, the hypothesis H₁ is supported. The effects of social support on safety motivation (standardized $\beta = 0.40$, $p < .001$) and safety knowledge (standardized $\beta = 0.45$, $p < .001$) were significant. Thus, the hypothesis H₂ is also supported. In addition, social support was founded to have direct effect on safety compliance (standardized $\beta = 0.41$, $p < .001$), although it was not significantly related to safety participation (standardized $\beta = 0.07$, $p > .05$). Furthermore, production pressure was negatively related to safety knowledge (standardized $\beta = -0.14$, $p < .05$) and safety motivation (standardized $\beta = -0.36$, $p < .001$), which supported the hypothesis H₃. Production pressure was also found to have direct and negative effects on both safety participation (standardized $\beta = -0.16$, $p < .05$) and safety compliance (standardized $\beta = -0.18$, $p < .05$). Both safety knowledge and safety motivation were significantly and

positively related to safety participation (standardized $\beta=0.41$, $p<.001$ and standardized $\beta=0.26$, $p<.01$, respectively). Contrary to expectations, this study did not find significant effects of safety knowledge and safety motivation on safety compliance. Thus, both hypothesis H₄ and H₅ were partially supported.

6.7. Discussion

This study aims to enhance the understanding of mechanisms by which key safety climate factors at macro (i.e., management safety commitment) and micro (i.e., social support and production pressure) organizational level and individual factors (i.e., safety knowledge and safety motivation) affect workers' safety behaviour. Perceived level of management safety commitment is significantly and positively related perception of social support. In addition, the higher level of perceived management safety commitment, the lower level of perceived production pressure. It is evident that management safety commitment had an indirect influence towards safety behaviour (safety participation and compliance), via group-level social support and perceived production pressure and individual factors (safety knowledge and safety motivation). The results underscore the importance of social support in construction safety management. The importance lies in the fact that social support has both direct and indirect effects on safety behaviour. In addition, social support fully mediates the effect of management safety commitment on safety motivation and safety knowledge and thus plays a role as a conduit through which safety value is communicated. Surprisingly, social support can predict safety compliance directly without influencing two determinants of safety performance (i.e., safety motivation and safety knowledge).

Production pressure can negatively influence workers' safety knowledge and motivation. A reasonable explanation is that, under production pressure, managers may place production over safety in order to catch up schedule. As a consequence, some safety practices may be ignored. Such ignorance tends to undermine workers' safety knowledge and motivation (Choudhry and Fang, 2008a, Mullen, 2004, Haslam et al., 2005a). A notable finding of this study was that production pressure predicted both safety participation and safety compliance directly without affecting safety knowledge and safety motivation. This finding provides further empirical support for the argument, made by Mitropoulos et al.(2005) in the system model of construction accident, that the higher level of production pressure the higher likelihood of errors. Safety motivation and safety knowledge are both strongly and positively related to safety participation. Contrary to expectations, direct effects of safety knowledge and motivation on safety compliance were not significant. Rather, safety compliance was directly influenced by social support and production pressure. Therefore, Campbell's performance theory (1993) was partially supported in this study.

6.7.1 Implications for construction safety management

The findings have significant implications for construction safety management, particularly reducing unsafe behaviours on site. It is evident that causes of human error can be traced back to management, group and individual levels. Thus, the results suggest a combination of three accident prevention strategies, namely "a safe organization", "safe groups" and "safe workers".

First, senior managers need to set the tone and tempo for safety management by demonstrating leadership in consistent ways. On-going and consistent efforts should

be made to ensure safety is priority over production. Such a consistency is critical for developing safety climate on site. As Zohar (2010b) pointed out, *“Obviously, how organizational leaders trade-off production-related policies and procedures when situations arise where some policies are in direct conflict with safety will provide the clearest message to employees regarding which is most important.”* This may sound obvious, but it is not uncommon to see the inconsistencies between “what managers say” and “what managers do” in site safety management.

Senior managers play a significant role in facilitating adequate supervision and teamwork on sites. This emphasizes the importance of creating the alignment between senior managers and supervisors in terms of safety. Such an importance stems from the fact that social support from supervisors and workmates is a critical factor in promoting safety behaviour. The “safe groups” strategy becomes necessary also because of the fact that construction is highly decentralized and the effects of senior managers are hard to maintain on site and that workers are mainly influenced by the daily interactions with their supervisors and co-workers (Lingard et al., 2012). The results of this study have shown that a lack of social support can be the breeding ground for unsafe actions. It is therefore important for supervisors and co-workers to provide guidance, oversight, and training and track workers’ qualifications and safety performance.

Finally, despite the fact that workers are believed to develop shared perceptions of the safety response of senior managers, supervisors, and co-workers (Meliá et al., 2008), equipping workers with adequate knowledge and skills and improving their safety awareness and attitude are still essential in construction safety management. Threats that can undermine workers’ safety knowledge and motivation come from various

sources. From a human resource perspective, frontline workers are typically less educated than other industries (Dainty and Loosemore, 2013), which highlight the need for on-going safety education. In addition, safety knowledge is partly composed of the information of specific hazards on site. Constant changing working environments cause difficulties in providing complete and reliable information in this regard. As such, supervisors and safety managers need to improve the effectiveness of hazard management and make sure that identified hazard information is effectively communicated to workers. This may also sound obvious since hazard management is one of most common practices used in the industry. However, what is important for supervisors and safety managers is to create an effective connection between hazard management and safety knowledge of workers. Once such a connection is created, ineffective paperwork could be avoided (Blewett and O'Keeffe, 2011). Indeed, construction work is highly dynamic and workers have many degrees of freedom when they perform their tasks (Saurin et al., 2008a). At the sharp end, site safety is heavily dependent on their adaptive behaviours. Providing adequate safety knowledge and skills and lifting safety motivation by training, hazard information and toolbox meeting are often the prerequisite for them to make “right” judgments and decisions.

6.8 Summary

This chapter examined the effects of key safety climate factors at the macro and micro organizational level and individual factors on safety behaviour. The final model suggests that safety behaviour is influenced by management safety commitment, social support, production pressure and individual factors including safety knowledge

and safety motivation. The model demonstrates that the perception of management safety commitment influences safety behaviour through its effects on social support and production pressure. Direct effects of social support and production pressure on safety behaviour were also identified. The utility of the model lies in its ability to enhance the understanding of the how key safety climate factors affect construction workers' safety behaviour. To reduce unsafe behaviours and accidents on sites, attention should be paid to creating a supportive environment in which workers are motivated to work safely and improving their ability to do so.

Chapter 7 Validation of the Integrative Model across Small and Large Construction Companies

7.1 Introduction

Chapter 6 examined the effects of key safety climate factors on safety behaviour using the data collected from 215 workers. One of limitations of this study is that it does not consider the difference between workers from small and large companies. It was assumed that safety climate measures are operating in exactly the same way in small and large companies and that the underlying safety climate construct has the same theoretical structure for these two groups. As evidenced from literature reviews, however, these two critically important assumptions are rarely, if ever, tested statistically. This implies that research findings involving one group may not be wholly transferable to the other, due to possible differences between groups.

The aim of this chapter is twofold. First, it aims to test the ME of the safety climate measure used in the Chapter 6 across workers from small and large companies. Second, it aims to validate the integrative model developed in the Chapter 6 (see Fig. 6.3) across small and large construction companies, with an attempt to examine whether there are differences in the mechanisms by which safety climate improves safety performance. Data were collected using a questionnaire from 253 construction workers from large (n= 123) and small (n= 130) construction in New Zealand (NZ).

This chapter tests the measurement equivalence of a safety climate by using MGCFA. Results provide evidence that workers from small and large construction companies had the same standing on the construct underlying the safety climate measure. In general, large companies demonstrated a higher level of safety climate than small ones, despite the fact that differences in safety knowledge and production pressure were not statistically significant. Results also suggest that there are not significant differences between small and large companies with regard to the mechanisms by which core safety climate factors affect safety behavior.

7.2 Background

Small businesses (often defined as those that employ 20 or fewer employees (Legg et al., 2009)) dominate the construction industry in many nations, such as Australia (Lingard and Holmes, 2001), US (U.S. Census Bureau, 2011), and New Zealand (The Ministry of Business Innovation & Employment (MBIE), 2014). Compared to large construction companies, smaller ones face distinct challenges and barriers in managing safety. For example, from an economic point of view, they are more fragile financially, with tight profit margins and limited market share (Lamm, 1999). As a result, they are less willing to invest time and economic resources on health and safety (Masi and Cagno, 2015, Champoux and Brun, 2003, Lamm, 1999). Poor health and safety performance can also be attributed to small companies' limited management ability. (Rubenowitz, 1997, Smith and Carayon, 2009, Champoux and Brun, 2003). In addition, construction is a labour intensive activity. Workers' safety motivation constitutes one of essential factors that contribute safety performance. However, as

managers of small companies often place productivity as the number one priority, workers tend to have low levels of safety motivation. Another critical issue is that construction industry has less educated labours than other industries (e.g., percent with no or only school qualification: general labourer (81%), builder's labourer (67%), and builder (51%) (Ministry of Business Innovation & Employment, 2013). Due to the financial constraints, small companies are less motivated to invest in improving the numeracy and literacy of their workforce.

Because of these challenges and barriers, it has been widely recognized that accident risks in small companies are higher than in large ones (Jeong, 1998, Chen and Fosbroke, 1998, McVittie et al., 1997). Hasle and Limborg (2006) conducted a literature review of health and safety in small businesses and found that strong evidence exists indicating that exposure to physical and chemical hazards are larger in small enterprises.

Previous safety climate studies in the construction industry primarily focused on either large companies or the industry as a whole, while little is known about whether workers from small and large companies understand and respond to a safety climate measure in an equivalent manner and whether the two groups have the same mechanism by which safety climate improves safety performance. Sørensen et al. (2007) reviewed sixteen scientific articles studying differences in risk between small and large enterprises and founded that the differences are mainly measured in relation to the rate of lost workdays, injuries, fatalities or the quality of the organization health and safety management system. At first glance, it would appear that the level of safety climate in small companies be lower than in large ones since small companies tend to have poorer safety performance. However, Baek et al (2008) stated that the level of

safety climate was not different by company size. This statement is supported by Rodrigues, who suggested that the level of safety climate is not dependent on company size (Rodrigues et al., 2015) (p 422). In fact, Legg et al. (2015) pointed out that the psychosocial work environment of small enterprises is not necessarily lower than that of large ones. Several researchers (Sørensen et al., 2007, Hasle and Limborg, 2006) even claimed that psychosocial work environment in small enterprises is better than larger ones. This implies that safety climate of small construction companies is not necessarily lower than larger ones since safety climate is conceptually linked with psychosocial factors of an organization.

The knowledge gap is in contrast to the number of small businesses in the construction industry. Small businesses (often defined as those that employ 20 or fewer employees (Legg et al., 2009)) dominate the construction industry in many nations, such as Australia (Lingard and Holmes, 2001), US (U.S. Census Bureau, 2011), and New Zealand (The Ministry of Business Innovation & Employment (MBIE), 2014). The scale of small firms' activity in construction projects is considerable (Sexton and Barrett, 2003). There is an underlying assumption that organizational culture and climate that characterize large companies apply to the same extent in small ones (Stroppa and Spieß, 2010). However, some researchers argued that it is inappropriate to treat a small firm as a microcosm of a large company (Ghobadian and Galleary, 1997, Wyer and Mason, 1999). Differences between small and large companies exist in terms of organizational structure, responses to the environment, managerial styles, and the ways in which they compete with other firms (Man et al., 2002, Guo et al., 2015c). For example, small companies are not able (or not willing) to establish health and safety professionals on site because of a lack of resources. The small-company

literature often suggests that management in small firms is typically informal and that the success of small firms is generally attributed to the managerial skills, training and education. In addition, peculiarities of small firms, such as simplified organizational structures, lower complexity, facilitated communication thanks to informal relationships, and higher flexibility in the use of the workforce, are often used to explain good performance (Cagliano et al., 2001). Compared to large construction companies, small firms face distinct challenges and barriers in managing safety. For example, from an economic point of view, they are more financially fragile, with tight profit margins and limited market share (Lamm, 1999). As a result, they are less willing to invest time and economic resources on health and safety (Masi and Cagno, 2015, Champoux and Brun, 2003, Lamm, 1999). In any competitive economies, the first priority for small firms is survival. Due to the financial constraints, they are less motivated to invest in safety. The differences in organizational structure and safety management processes may lead to divergent views of safety climate. If different groups hold qualitatively different views of safety climate, then combining or comparing the responses to a safety climate measure from different groups would be inappropriate (Cigularov et al., 2013). Adopting safety climate practices from large companies may not be effective due to the fact that what holds for large companies may not apply to small ones.

A safety climate measure is invariant when respondents of different populations (e.g., small and large companies) who have the same standing on the construct being measured receive the same observed score on the test. Common statistical tools, such as ANOVA and *t*-test, are often used to compare specific differences of safety climate between various groups (Ma and Yuan, 2009, Vinodkumar and Bhasi, 2009, Idris et

al., 2012, Lu and Shang, 2005, Cooper and Phillips, 2004). However, these studies failed to provide ample evidence that the meaning and measurement of safety climate are equivalent across the groups. In fact, safety climate can be examined on the manifest level, that is, the level of observed or measured variables. However, safety climate research hypotheses often allude to latent factors that have to be deduced from observed variables. Before the comparison of safety climate between various groups, there must be strong evidence that the meaning and measurement of safety climate are equivalent across the groups. This requires that the relations between latent safety climate factors and their manifest indicators (or items) be equivalent. Equivalence of these relations across groups has been labeled measurement equivalence (ME), the similarity in the conceptualization of a given construct across groups (Vandenberg and Lance, 2000, Meredith, 1993).

Testing ME of a safety climate measure across groups is important because of the fact that the fragmented and transient nature of construction raises the question of whether workgroups are sufficiently established and homogeneous to yield reliable safety climate measures (Hecker and Goldenhar, 2014) (p 9). The establishment of ME is a logical prerequisite to conducting substantive cross-group comparisons. When there is a lack of ME, comparisons of the different measurement situations regarding the target constructs are similar to the comparison of ‘sandwiches’ to ‘apples’ (Vandenberg and Lance, 2000) (p.40). As such, conclusions based on a safety climate measure may be arguable, and, at best, ambiguous. This can also result in miscommunication between researchers and practitioners and ineffective interventions to companies where the target safety climate determinants of the interventions are not very meaningful (Lee et al., 2015).

7.3 Method

7.3.1 Sample and procedure

This study was supported by a health and safety training provider that is approved by the Minister of Labor of New Zealand. With the support, data were collected through sampling from workers of the New Zealand (NZ) construction industry. Approximately 250 workers were randomly selected and provided with questionnaires when they were attending safety training programs at three different training centers in NZ. Anonymity was assured by providing each respondent an addressed envelope that allowed he/she returned the completed questionnaire directly to the researchers. In addition, another 300 questionnaires were administered to workers in six construction projects in NZ. The procedure of administration also demonstrated anonymity to respondents by having them place completed questionnaires in a sealed collection box.

Of the 550 questionnaires initially distributed, 255 were completed and returned. Of those, 253 were sufficiently completed to be included in data analysis, producing a usable response rate of 46%. In order to ensure the quality of data collected before starting data analysis, all the completed questionnaires (N=253) were checked against systematic response patterns and more than 5% missing items (Seo, 2005). Through this data screening process, 2 out of 255 completed questionnaires were dropped from the dataset. The responses with 5% or less unanswered items were retained for data analysis. Missing data points were imputed with the median of nearby points in each case.

In this study, the definition of small firms by the Ministry of Businesses, Innovation & Employment (2014) was adopted for this study. Small construction companies were defined as those employing 20 or fewer employees; large companies were those employing more than 20 employees. Out of total 253 valid completed questionnaires, 130 (51.4%) were from small construction companies and 123 (48.6%) were from large ones.

7.3.2 Measures

As mentioned earlier, this study adopted the safety climate measure tested in the Chapter 6. The survey consists of three main parts: core safety climate factors, safety behavior, and demographic information. Core safety climate factors include management commitment to safety, social support, production pressure, safety motivation, and safety knowledge.

7.3.3 Statistical analysis

ME was performed within the framework of multi-group confirmatory factor analysis (MGCFA). To achieve this, AMOS 22 was employed to conduct multi-group analysis, generating the overall fit of the model tested. It involves a series of nested CFA models in which increasingly stringent equality constraints are posited on the items' parameters. The strategy used in this study to test ME is the one suggested by Byrne (2009). According to Byrne, the process of testing equivalence of measurement and structural parameters across two groups (small and large companies) involves the

testing of a series of increasingly restrictive hypotheses. The testing strategy consists of a series of following hierarchical steps:

Step 1: configural invariance

The initial step was to test configural invariance, a basic level of ME. This is a test of the null hypothesis that the a priori pattern of free and fixed factor loadings imposed on the items is invariant across groups (Vandenberg and Lance, 2000). In testing configural invariance, interest focused on the extent to which the number of safety climate factors and pattern of their structure were similar across workers from small and large companies. Specifically, it explores whether a safety climate factor has the same meaning and basic factorial structure in these two different groups. The configural invariance model can be considered as a baseline model against which further tests of ME are evaluated. At this level, we ask the research question: Do workers from small and large companies use the same frame of reference with respect to the same number of factors and the same pattern of factor loadings when responding to the safety climate questionnaire's items?

Step 2: metric invariance

Subsequent to the configural model is the testing of metric invariance, which is effected by constraining the factor of items to be equal across groups. This is a more stringent test of factorial invariance than is the test of configural invariance because, in addition to specifying an invariant factor pattern, loadings of items within that pattern are now constrained to be equal (Vandenberg and Lance, 2000). This hypothesis tests that the regression slopes, that is, factor loadings for items relating to their corresponding latent variables are equal across the two groups. At this level, we

ask the research question: are factor loadings the same across the two groups (small and large companies)?

Step 3: scalar invariance

To compare means of latent safety climate factors between two groups, scalar invariance (i.e., equality of items' factor loadings and intercepts) needs to be tested. This test has been interpreted as a test for systematic response bias differences between the groups for comparisons, in which latent mean group differences are not otherwise expected (Bollen, 1989). Scalar invariance hypothesizes that the model linking safety climate factors to their items (i.e., observed variables) is equal across two groups. It can be examined by constraining both the factor loadings and the observed variable intercepts equal across two groups. At this stringent level, we ask the research question: Do workers from small and large companies with the same score on the latent variable demonstrate the same score on the observed variables?

Once scalar invariance across these two groups is satisfied, latent mean differences of five safety climate factors can be tested. To estimate the difference between small- and large-company group means on a safety climate factor, one of the groups is chosen to serve as a reference group and its mean on the construct is fixed to zero, while the mean of the other group is freely estimated (Byrne, 2004, Byrne, 2013). In this study small-company group was chosen as the reference group. The comparison between latent means was based on the critical ratio (CR) index. CR represents the parameter estimate divided by its standard error and it operates as a z-statistic to determine if the estimate is statistically different from zero. The test statistic needs to be greater than 1.96 or less than -1.96 before the hypothesis that the estimate equals 0.0 can be rejected.

After the ME testing, the integrative model developed and validated by Guo et al.(2016) was cross-validated to test for an invariant pattern of causal structure across small and large construction companies samples. The computer program AMOS (version 22) was employed to conduct multi-group analysis, obtain path estimates, using maximum likelihood (MLE) estimation, and to evaluate the overall fit of the model tested.

To examine model fit, this study adopted two most often cited goodness-of-fit indices as recommended in the literature (Jöreskog, 1971, Byrne, 2013, MacCallum, 1995): comparative fit index (CFI) and root mean square error of approximation (RMSEA). Value for the CFI range from 0.00 to 1.00 and is derived from the comparison of a hypothesized model with the null model. A value >0.95 is considered representative of a well-fitting model (Hu and Bentler, 1999). RMSEA is a parsimony-adjusted index in that its formula includes a built-in correction for model complexity (MacCallum, 1995). It has been considered as “one of the most informative criteria in covariance structure modeling” (Byrne, 2013). MacCallum et al. (1996) suggested that a value 0.01, 0.05, and 0.08 indicates excellent, good, and mediocre fit, respectively.

The most frequently used tool for testing the difference between models is the chi-square difference test. Evidence of non-invariances is claimed if the $\Delta\chi^2$ value is statistically significant. The justification to do so is typically attributed to Steiger et al. (1985) who demonstrated that incremental chi-square values are asymptotically independent test statistics. In addition to the chi-square test, the difference in the comparative fit index (Δ CFI) was also examined. Cheung and Rensvold (2000) proposed that a CFI difference larger than 0.01 would indicate a significant change in model fit.

7.4 Results

7.4.1 Observed variable characteristics

Observed means, standard deviations, and correlations among the scales were reported in Table 7.1. Workers from large companies exhibited higher means than those from small companies on management commitment to safety, social support, safety motivation, and safety knowledge, while workers from small companies have higher perceptions of production pressure.

Table 7.1 Means, standard deviations, alpha coefficients, and correlations for the safety climate scales in large companies (n=123) and small companies (n=130).

Latent factor	Large companies		Small companies		Correlations				
	Mean	SD	Mean	SD	1	2	3	4	5
1. Management commitment to safety	4.35	0.58	4.09	0.83	-				
2. Social support	4.25	0.65	4.01	0.77	0.66	-			
3. Production pressure	2.55	0.93	2.68	0.91	-0.49	-0.37	-		
4. Safety motivation	4.00	0.73	3.72	0.79	0.52	0.56	-0.45	-	
5. Safety knowledge	4.36	0.55	4.30	0.60	0.40	0.49	-0.31	0.58	-

Note: all correlations are significant at $p < .001$.

7.4.2 Testing for ME

Testing for ME consists of three hierarchical steps: configural invariance, metric invariance, and scalar Invariance. Table 7.2 summarizes the goodness of fit indices of three ME models.

Configural Invariance (Model 1)

The factor loadings, factor variances, means, and measurement errors (unique variances) were freely estimated by the model. The baseline model established above was tenable when tested simultaneously on both groups without imposing any constraints on any parameters. The same number of factors and the same pattern of

factor loadings was confirmed across the two groups (CFI=0.943, RESEA=0.057).

Model 1 is acceptable and shows the first level of measurement invariance.

Measurement Invariance (Model 2)

The additional constraint that specifies equal factor loadings on all items was then imposed on Model 1 to define Model 2, by constraining factor loadings (regression coefficients) to be equal across two groups. Model 2 shows a relatively good fit (CFI=0.941, RMSEA=0.056). As no significant difference in CFI (Δ CFI=0.001), there was no significant decrease in the model's fit. These results indicate that the factor loadings for all items across two groups are equivalent, demonstrating metric equivalence.

Scalar Invariance (Model 3)

In testing scalar invariance, the vector of item intercepts is assumed to be invariant across two groups. The results show that the scalar invariance constraints did not significantly alter the goodness of fit statistics, compared to Model 1. The model shows a good fit (CFI=0.936, RMSEA=0.057) and the model still fitted the data remarkably well, as evidenced by a small Δ CFI of 0.007. The non-significant difference $\Delta\chi^2$ and the very small change in CFI between Model 1 and 3 give additional support to the idea that the intercept constraints imposed by Model 3 did not significantly worsen model fit as compared to Model 1, thus supporting the scalar invariance.

Table 7.2 Goodness of fit indices of ME models

Model	χ^2	df	CFI	RMSEA	RMSEA 90% CI	Model comparison	Δ CFI
Model 1: Configural invariance	496.333	274	0.943	0.057	0.049,0.065	-	-
Model 2: Metric invariance	515.652	288	0.941	0.056	0.048, 0.064	2 vs. 1	0.002

Model 3: Scalar invariance	542.662	307	0.936	0.057	0.049,0.064	3 vs. 1	0.007
----------------------------	---------	-----	-------	-------	-------------	---------	-------

Note: 90% CI= 90% Confidence Interval

7.4.4 Testing for latent mean differences

Given that support for ME was tested, latent means of safety climate factors could be reliably and meaningfully compared across the two groups. Table 7.3 presents latent mean differences between workers from large and small companies. The results showed that large companies had higher scores than small companies in management commitment to safety (CR=3.07), social support (CR=2.32), and safety motivation (CR=2.30). Although workers from small companies tended to perceive more production pressure than those from large companies, the difference was not statistically significant (CR= -0.96). The difference in safety knowledge across the two groups was either not statistically significant (CR= 0.98).

Table 7.3 Latent means and variances

Factors	Small-company (n=130)		Large-company (n=123)	
	Mean	Variance	Mean	Variance
Management commitment to safety	.00	.793 (.122)	.329 (.107) **	.337 (.053)
Social support	.00	.723 (.115)	.260 (.112) *	.491 (.082)
Production pressure	.00	.760 (.120)	-.123 (.128)	.821 (.134)
Safety motivation	.00	.587 (.113)	.254 (.106) *	.401 (.073)
Safety knowledge	.00	.454 (.071)	.135 (.092)	.378 (.054)

Note: Maximum likelihood estimates, standard errors in parentheses, latent mean parameters were fixed to .00 for the small-company group.

**p<.01, *p<.05

7.4.5 Testing validity of the integrative model

The integrative model acted as a multi-group baseline model against which we could compare a subsequent model in which equality constraints were specified. To cross-

validate the integrative model, constraints on factor loadings (derived from metric invariance model) were maintained by using AMOS.

Table 7.4 presents the results from the full SEM test of the integrative model. We can determine that goodness of fit of the model for the two groups in combination and with no equality constraints imposed is good (CFI=0.936; RMSEA=0.049). Having constrained the structural paths to be equal across groups, the goodness-of-fit results are still good (CFI=0.934; RMSEA=0.049). The difference in CFI is 0.002, which is not significant. In sum, based on these results, we can conclude that causal structure related to the integrative model is equivalent across the small and large construction companies.

Table 7.4 Goodness of fit indices of multiple groups tested

Model	χ^2	df	CMIN/DF	CFI	RMSEA	90% CI
Unconstraint conceptual model	952.848	594	1.604	0.936	0.049	0.043,0.055
Constrained conceptual model	979.717	614	1.596	0.934	0.049	0.043,0.055

Fig. 7-1 shows the differences in the relationships of constructs between small and large construction companies. As can be seen, there are not significant differences between small and large companies with regard to the relationships of safety climate factors and safety behavior. Interestingly, impacts of management commitment to safety, social support, and production pressure were stronger in the large companies than in the small ones. The relationships between social support and safety participation, safety knowledge and safety compliance, safety motivation and safety compliance are both statistically insignificant in both groups.

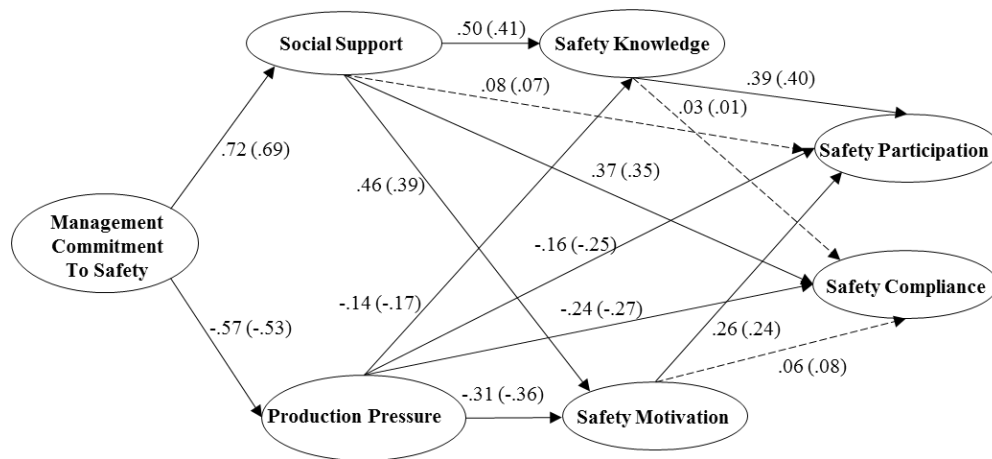


Figure 7.1 Final structural model

Note: The large company coefficients are inside parentheses; the small company coefficients are outside the parentheses

7.5 Discussion

This study aims to investigate the measurement equivalence of a safety climate measure across workers from large and small construction companies. Although small companies outnumber large ones by a wide margin in the construction industry, little is known about the psychometric properties of safety climate measures and mean levels of safety climate perceptions across these two groups. This paper is the first to systematically examine the ME and compare the difference of safety climate between small and large companies.

The series of multiple-group CFA models provided evidence that workers from these two groups used the same latent dimensions when responding to the safety climate survey. Results of ME tests indicated that three ME levels were fully supported. Specifically, the results suggested that workers from small and large companies (1) used an identical cognitive framework when responding to all items of the safety climate (as indicated by configural invariance), (2) used the Likert response scale in

an identical manner (as indicated proved by measurement invariance), and (3) responded to all items without bias (as shown by scalar invariance). These results suggested that despite differences in safety management across small and large companies, workers of these two groups share the same fundamental view of safety climate as measured by the current measure.

As ME was supported, a valid and meaningful comparison of safety climate between small and large companies was made. Findings suggested that workers from large companies perceived a significantly higher level of management commitment to safety than their small-company counterpart (mean: large-company=4.35, small-company=4.09). This is quite understandable since large companies, as discussed earlier, tend to invest more resources in safety and demonstrate a higher level of commitment to safety. As a result, a general belief among workers would be shaped that management places safety as a priority. It is also within expectation that workers from large construction company perceived more favorably with regard to social support (mean: large-company=4.25, small-company=4.01). This is not surprising because of the link between upper and middle-level management. Empirical evidence does exist that social support at the group level is positively related to management commitment to safety at the organizational level (Lingard et al., 2012, Hsu et al., 2010, Guo et al., 2016). Management commitment to safety promotes the supervisory practices (e.g., supervision, task instruction, and safety coach).

As expected, the level of safety motivation in large companies is significantly higher than that of small ones. (mean: large-company=4.00, small-company=3.72). This can be explained by the fact that workers are more willing to be involved in safety management in a supportive environment (e.g., management, supervision, and

teammate support) (Hsu et al., 2010). As large companies are more likely to implement practices like hazard management, housekeeping, and environmental control to manage hazards on site, it is not very surprising that workers of this group are more motivated to participate in safety practices. Against the expectation, the latent mean difference in production pressure between large and small companies is not statistically significant, although large-company workers suffered less production pressure than their small-company counterpart (mean: large companies=2.55, small companies=2.68). An explanation for this is that although perceived production pressure tends to be in part affected by other safety climate factors such as management commitment to safety and social support (Seo, 2005, Brown et al., 2000), it is largely influenced by factors (e.g., production planning) in the production system. When schedule delay happens in construction projects, effects of a high level of management commitment to safety and social support are often weakened or even diminished. Results also suggested no significant difference in safety knowledge. This is consistent with findings of Edwards and Holt's study (Edwards and Holt, 2008). A plausible explanation for this is that most questionnaires were collected at three training centers where trainees' perceptions of their knowledge of safety were positively affected by the training course.

The second aim is to examine whether small and large construction companies have the same mechanisms by which safety climate affects safety behavior. Results suggested that the casual structure of the integrative model is the same across the two groups. Safety climate factors have similar impacts on safety behavior. In other words, all the path coefficients in the integrative model were invariant across the two groups. However, influences of management commitment to safety, social support, and

production pressure were stronger in the large companies than in the small companies. This indicates that the management of large construction companies plays more influential roles in enhancing social support and reducing production pressure and that workers of small companies are more likely to be influenced by social support and production pressure. These differences can be in part attributed to the differences in organizational structure and safety management processes between these two groups. As discussed before, managers of small construction companies are often reluctant to demonstrate a commitment to safety due to a lack of resources and ability. In contrast, large companies are more likely to implement safety management systems which can involve people at different levels (e.g., management, supervisor, and worker). This can strength workers' perceptions of the roles played by managers and supervisors in creating a safe environment and developing safety climate.

This study has significant implications for safety climate research and construction safety management. First, the problem with the validity of safety climate measures across small and large companies has significant implications because of the fact that small businesses dominate the construction industry in many countries and that safety management in small businesses has been a global issue (Arocena and Núñez, 2010, Champoux and Brun, 2003, Masi and Cagno, 2015, Ozmec et al., 2015, Guo et al., 2015c). The unique characteristics of the construction industry (e.g., multi-party nature and a large proportion of small businesses) have generated the need to use safety climate instruments with populations in different groups. The size difference in the populations being measured necessitates an examination of the degree to which the safety climate instrument measures the same construct across these groups. In addition, empirical studies have suggested solutions with regard to how to improve

safety climate based on the comparisons between them and large ones (Ma and Yuan, 2009). However, unless measurement equivalence (ME) is established, conducting cross-group comparisons of mean differences is meaningless (Vandenberg and Lance, 2000). This paper emphasizes the importance of establishing ME of a safety climate measure before making comparisons among different groups. In addition, from a methodological perspective, testing for ME provides useful information for the refinement of existing and widely used instruments. Thus, the assumption of universal applicability of instruments can be challenged and tested.

From a practical perspective, results of ME tests indicated that workers from small and large companies understood and responded to the safety climate measure in a similar manner. These results might be of particular interest for those who are willing to benchmark their safety climate level against other companies in various sizes in the industry. In recent years, users of safety climate tools (e.g., HSE's Safety Climate Tool (HSE, 2002)) show increasing interest in benchmarking safety climate level against others. A benchmarking approach can be used to determine relative weaknesses for developing safety climate. Our results suggest that statistical and substantive differences in latent factors of safety climate cannot be attributed to item bias or other measurement non-invariance issues. In addition, subcontracting is another common phenomenon in the construction industry (Fang and Wu, 2013, Guo and Yiu, 2016). A typical construction project often involves different parties at different stages, including large and small contractors and trades. Since the factors structure of the safety climate measure is the same for the two groups of respondents, safety climate interventions and practices designed to target at core factors (i.e., management commitment to safety, social support, production pressure, safety knowledge, and

safety motivation) could be implemented at the project level where large and small firms work together.

The results of the current study may be of particular interest for those small construction companies who strive to improve safety performance by developing safety climate. As there are no significant differences in the mechanisms by which safety climate factors affect safety behavior, lessons could be transferred from both large and small companies with successful experience. Similar strategies (e.g., a safe organization, safe groups, and safe workers (Guo et al., 2016)) for developing safety climate and improving safety performance could be used across small and large companies. Relevant safety practices (e.g., supervisory practices) could be adopted and implemented at company or project level.

7.6 Summary

This chapter tests the measurement equivalence of a safety climate by using MGCFA. Results provide evidence that workers from small and large construction companies had the same standing on the construct underlying the safety climate measure. In general, large companies demonstrated a higher level of safety climate than small ones, despite the fact that differences in safety knowledge and production pressure were not statistically significant. Results of this study also suggest that there are not significant differences between small and large companies with regard to the mechanisms by which core safety climate factors affect safety behavior.

The current study represents the first explicit test of measurement equivalence of a safety climate measure between small and large construction companies. The main

contribution of this paper is that it demonstrates the ME of a safety climate measure across small and large construction companies, which has important research and managerial implications. First, the results of rigorous ME tests provide strong support for the utility of the safety climate measure across construction companies in different sizes. This is important because the fragmented and transient nature of most construction work raises the question of whether different groups are homogeneous to yield reliable safety climate measures (Hecker and Goldenhar, 2014). In safety research, safety climate surveys are often used to assess safety climate perceptions in projects where large and small construction companies work together. The results of this study suggest that the safety climate measure does not need to be tailored to each group and that meaningful data can be collected by utilizing the safety climate measure from construction projects where small and large companies work together.

Another contribution of this study is that it adds to the scientific knowledge of difference of safety climate between construction companies in different sizes. The results of our rigorous ME tests and multi-group confirmatory factor analytic approach provided strong support for the meaningful use of the safety climate measure in construction companies in different sizes. As safety climate has widely been recognized as a leading indicator of safety, a meaningful comparison between large and small companies can offer early warnings and foresight for preventing accidents and injuries.

Chapter 8 Development and Test of Leading Indicators

8.1 Introduction

The objectives of this chapter are to: (1) develop a theoretical model which conceptualizes the safety level and facilitate the design of leading indicators, (2) develop a set of leading indicators based on the theoretical model, and (3) obtain initial evidence of criterion validity, practicability, and cost-effectiveness of the leading indicators. The development process follows four steps: conceptualization, operationalization, indicator generation, and validation and revision. Chapter 3 developed a conceptual framework that guides the development of leading indicators. However, it remains an open question what constitute safety conditions of a construction project. Therefore, this chapter developed a theoretical framework of safety conditions in part based on results of previous chapters.

A pressure-state-practice (PSP) model was developed as an overall framework for developing leading indicators. A set of leading indicators were developed to measure safety level at the project level. The multiple-case study provided the qualitative evidence that the safety leading indicators have ability to indicate the weaknesses and strengths of safety state and correspond to actual safety outcomes.

8.2 Methodology

The development process of leading indicators in this chapter follows the method developed in Chapter 3. The method consists of four steps: conceptualization, operationalization, indicator generation, validation and revision (see Figure 3-4). The method was chosen because it permits safety conditions to be conceptualized in different ways based on different safety models, and it emphasizes the importance of validating leading indicators. In addition, a major benefit of the method is that it not only underlines the role of leading indicators in promoting proactive safety management by connecting safety practices with a project's safety conditions, addressing both scientific and managerial attributes.

8.2.1 Conceptualization

In essence, conceptualization aims to determine “what to measure” with consideration of the purpose of leading indicators and the level of analysis. In this paper, leading indicators are aimed at describing and monitoring safety level at the project level. Thus, a theoretical framework is needed to conceptualize safety level and specify indicated phenomena of interest. This step is important for two reasons. First, the theoretical framework not only acts as a starting point to develop leading indicators, it is also a framework for interpreting the information generated by leading indicators. Second, it provides strong evidence of the construct validity of leading indicators.

To conceptualize safety level, this paper developed a theoretical model by drawing upon concepts and models from systems theory. The validity of the model was established by seeking scientific knowledge from safety literature.

8.2.2 Operationalization and indicator generation

Operationalization is a process of defining a construct that is not directly measurable in ways that can be readily and accurately measured. This step focuses on a meaningful transition from abstract dimensions of safety conditions to specific safety constructs. Indicator generation is concerned with designing a set of indicators to measure these constructs. In developing leading indicators, these two steps can be undertaken simultaneously.

8.2.3 Validation and revision

Validation and revision are concerned with whether leading indicators can provide valid, meaningful, and reliable information on the safety level. In essence, a set of leading indicators can be considered as an instrument to measure safety level of a unit (either a project or a company). It is therefore important to establish validity (i.e. construct validity, concurrent validity, and predictive validity) of leading indicators, and test their practicability and cost-effectiveness.

Construct validity is concerned with the extent to which a particular test measures what it claims to be measuring. Scientific knowledge was sought from safety literature to support the construct validity of constructs that were selected to measure dimensions of safety level. In order to test indicators' concurrent and predictive validity, data were collected from three construction projects by interviews, questionnaire survey, and documentation. The value of each indicator was determined based on the data. Concurrent validity can thus be demonstrated by correlating scores of seven safety level constructs with safety outcome (i.e., TRIFR) of the three projects at approximately the same point in time. In contrast, predictive validity was tested by establishing correspondence between leading indicators and TRIFR at different time

points. Practicability and cost-effectiveness were evaluated based on expert judgement, as suggested by Bockstaller and Girardin (2003).

8.3 Results

8.3.1 Step 1: Conceptualization

A pressure-state-practice (PSP) model of safety level was developed to provide the theoretical basis for developing leading indicators (see Fig. 8-1). The model conceptualizes safety level of a construction project as a dynamic phenomenon that is characterized by the interrelationships among safety state, safety practices, and pressures (Guo and Yiu, 2016).

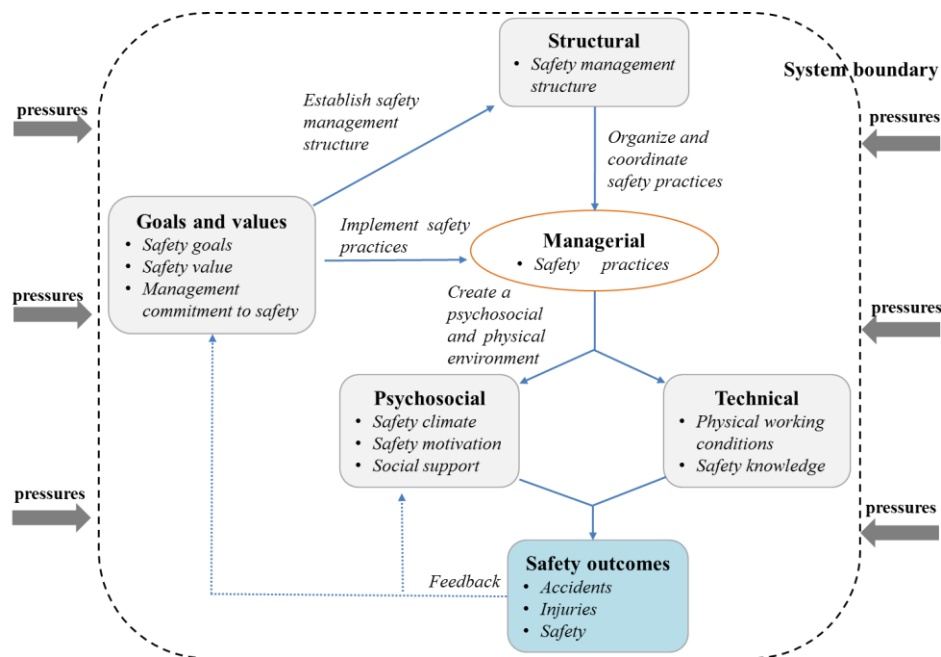


Figure 8.1 A pressure-state-practice model of safety level

The dynamic perspective is partly based on Kast and Rosenzweig's a systems model of organization (1979) (p. 19). Kast and Rosenzweig's systems view of organizations and management defines an organization as an open system that is composed of goals

and values, technical, structural, psychosocial, and managerial dimension. The PSP model considers safety as one of subsystems of the organization. All safety activities and practices within the safety subsystem can be seen as an identifiable but permeable boundary line to distinguish it from other subsystems (e.g., production, human resource, procurement, and regulation subsystems) of a construction project. These subsystems constitute the outside environments in which safety is managed at the project level. The safety subsystem is open in nature, since it receives inputs (money, people, and other resources) across the boundary, transforms them, and returns outputs (accidents, injuries, or safety). The process can be exemplified by the interactions between safety and production (Goh et al., 2012a).

The PSP model defines safety state as the state of the system with regard to its capability for producing safety. The safety capability consists of four broad dimensions: goals and values, structural, psychosocial, and technical. Goals and values are an internal subsystem of every organization. Organizational goals are defined as “statements that establish the desired future state an organization is attempting to achieve (Hodge, 1996). Safety goals can be defined as statements that establish the desired future safety state an organization aims to achieve. Safety values form a basis for organizational perceptions about what is good or bad, right or wrong with respect to safety. The structural dimension describes the sum total of the ways in which safety practices and activities are organized and coordinated. It can be seen as one of the dimensions of organizational structure which defines how activities such as task allocation, coordination, and supervision are directed toward the achievement of organizational aims (Pugh and Weber, 1971). The technical dimension refers to the knowledge required for the performance of tasks, including the techniques used in the

transformation of inputs into outputs. It is determined by the task requirements and shaped by the specialization of knowledge and skills required. The psychosocial dimension is composed of individuals and groups in interaction (Kast and Rosenzweig, 1979). This subsystem comprises individual characteristics and interpersonal relations. As an important subsystem of safety, it consists of individual behavior and motivation, status and role relationships, and group dynamics.

The managerial dimension refers to a set of safety practices that can be conceptualized as positive forces that create, improve, and/or maintain a system's safety capability. The PSP model distinguishes the managerial dimension from four dimensions of safety state because it is based on a conceptual idea that safety practices do not determine safety outcomes in a direct manner. Instead, their influence is mediated through the safety state (Wachter and Yorio, 2014c, Guo and Yiu, 2016).

Pressures can be considered as environmental forces, being negative or positive, that tend to change safety state. They represent the products of the interactions between the "inside" of safety subsystem and its outside environments. Different pressures may emerge in different phases of a construction project and they tend to pose new threats to safety. For example, schedule delays may cause production pressure which is likely to decrease the management commitment to safety (Goh et al., 2012a, Han et al., 2014b). Temporary labor forces may bring about "macho" culture and peer pressure which can motivate unsafe behavior (Mullen, 2004).

Safety state descriptions characterize the safety reality as sensed, while safety practices characterize the safety reality as acted upon. In reality, safety state, safety practices, and pressures do not exist in isolation but interact with each other. As shown in Fig.8-1, the safety goals and values dimension shapes other dimensions. It is

connected with the managerial dimension by influencing implementation of safety practices by changing the level of workers' safety engagement (Wachter and Yorio, 2014c). Furthermore, it plays a decisive role in determining how safety responsibility and authority are assigned (Guo et al., 2015c). The managerial dimension, in the form of safety practices, spans the entire safety subsystem by demonstrating safety values, directing resource and organizing people. Safety practices, being formal or informal, deliver managers' safety message and thus affect workers' perceptions of safety (Chen and Chen, 2014, Kapp, 2012, Vinodkumar and Bhasi, 2010). In addition, they improve people's competency to manage safety on site and improve work conditions by managing physical hazards. For example, providing workers with safety training opportunities would be able to improve their safety knowledge and skills. In turn, the psychosocial dimension can affect the level of workers participation in safety practices and activities. The structural subsystem affects the psychosocial subsystem by determining the communication channels by which safety information within the system is communicated, shared, stored and used. It sets a framework for the psychosocial subsystem, as it establishes the pattern of relationships among people within the system. For example, an established safety manager position in a project represents a communication channel through which subcontractors and workers report safety problems and accidents. In addition, safety coach and induction provided by supervisors are beneficial to increase workers' motivation and knowledge (Lingard et al., 2011). The structural subsystem also influences the managerial subsystem by determining the ways in which safety practices and activities are organized and coordinated. Safety outcomes (i.e., accidents and safety) are considered as emergent products of the interactions among safety state, safety practices, and pressures.

8.3.2 Step 2: Operationalization

Operationalization is a process of specifying the constructs of each dimension (i.e., safety state, safety practice, and pressure) and defining a construct that is not directly measurable in ways that can be readily and accurately measured (Soucacou and Sylva, 2010b). This step is concerned with determining specific variables of five safety dimensions and types of pressure that pertain to construction projects. One of the significant requirements is that the selection of constructs, as well as the causal relationships between the constructs, must be supported by scientific knowledge and/or empirical evidence.

Following the definition of each dimension, key constructs of those five dimensions and pressures were selected based on the safety literature (see Table 8.1). Note that such a selection process is knowledge-driven and primarily serves a descriptive, rather than a normative, purpose of describing the safety state. As such, they are tentative in nature and therefore should not be used as evaluative reference until their predictive validity is tested by empirical data. The conservativeness is necessary, considering a lack of knowledge that scientifically defines “what is safety?” and “how can safety be achieved?”

Table 8.1 Core constructs

Dimensions	Constructs	References
Goals and values	Management commitment to safety	(Hofmann and Morgeson, 1999, Michael et al., 2005, Neal and Griffin, 2004)
Structural	Safety management structure	(Gould and Joyce, 2002, Hughes and Ferrett, 2011, Hechanova-Alampay and Beehr, 2001)
	Physical working conditions	(Carter and Smith, 2006, Suraji et al., 2001, Chi et al., 2013)
Technical	Safety knowledge	(Christian et al., 2009, Neal et al., 2000)
	Safety motivation	(Neal and Griffin, 2006, Christian et al., 2009, Vinodkumar and Bhasi, 2010, Andriessen, 1978)

	Social support	(Albrecht and Adelman, 1987, Lingard et al., 2012) (Hsu et al., 2010, Parker et al., 2001, Gillen et al., 2002, Sampson et al., 2014b)
	Safety climate	(Zohar, 1980b, Brown and Holmes, 1986, Johnson, 2007, Lingard et al., 2012, Neal et al., 2000, Gillen et al., 2002)
Managerial	Safety practices	(Hale et al., 1997a, Wachter and Yorio, 2014c)
	Peer pressure	(Mullen, 2004)
Pressures	Production pressure	(Goh et al., 2012a, Han et al., 2014b)
	Safety pressure	(Guo et al., 2015b)

Classifying leading indicators into various groups can cause difficulties and confusion

in interpreting the information generated by them. Therefore, a framework is proposed to serve the purpose of providing guidance on how to derive meaningful and useful information on current and future safety level of a construction project (see Fig. 8-2).

The framework bases itself on open systems theory which assumes that system can adapt successfully according to every sensed and recorded change in the environment.

The open systems perspective is characterized by key concepts like “best fit” and “contingency” (Moorkamp et al., 2014, Morgan, 1997).

As suggested in Fig. 8-2, state indicators indicate the project’s capability for producing safety. Practices indicators are analyzed to see how internal safety efforts fit into dimensions of safety state and how safety practices cope with pressures. Pressure indicators can help decision makers predict the change of safety level and take proactive actions.

When one assesses the information generated by state indicators, he/she could ask the following questions: (1) What is the safety level?, (2) What are the weaknesses?, and (3) What are the strengths?, Safety level represents a concept that quantifies the project’s capability for producing safety. Different schemes can be designed to measure safety level, such as a three-level scheme (high, medium, and low). Due to a lack of scientific knowledge of reference point, such a quantification may be subjective in nature and thus requires further testing. Despite this, one can identify

weaknesses and strengths of the project with respect to safety state. For example, an assessor may consider management commitment to safety as a weak point when senior managers fail to demonstrate commitment to safety. When state and practices indicators are assessed together, another two questions that can be asked are: (1) How well safety practices fit into dimensions of safety state, individually and collectively?, and (2) Can current safety state justify the implementation of safety practices? The terms *fit* and *justify* carry a contingency view on management (Delery and Doty, 1996). Its fundamental assumption is that the effectiveness of safety practices to improve safety performance is posited to be contingent on safety state. From this perspective, safety practices are *fit* when the configuration of safety practices matches well with multiple dimensions of safety state.

Despite the fact that it may not be difficult to arrive at the conclusion, the information itself is unable to predict the future, as it does not capture the dynamics of safety. In other words, it is difficult to predict how safety level changes over time with the information. To draw a dynamic picture, practice indicators and pressure indicators should be included in the analysis. According to Guo and Yiu (2016), safety practices can be categorized into three groups according to the ways in which they improve safety state: (1) safety practices as effects of a safety construct, (2) safety practices as causes of a safety construct, and (3) safety practices as buffers against pressures.

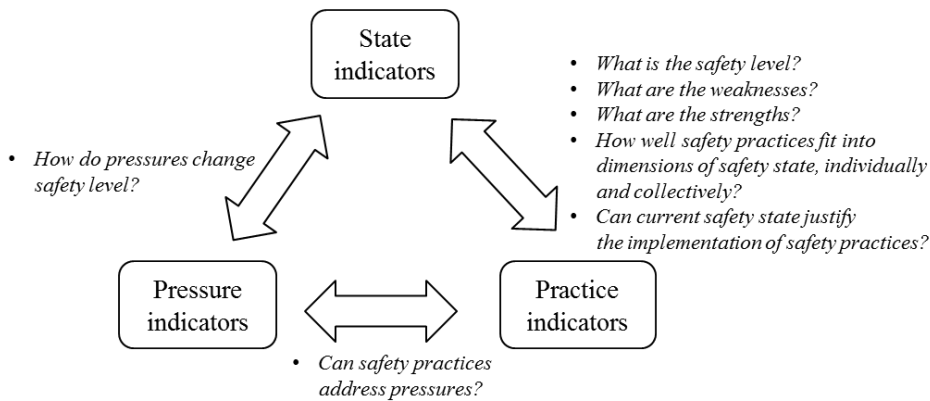


Figure 8.2 A framework for interpreting leading indicators

8.3.3 Step 3: Indicator generation

8.3.3.1 Measurement methods

Mohaghegh and Mosleh (2009b) suggested that safety constructs can be measured using subjective, objective, or hybrid methods, depending on the sources of information and measurement instruments. Table 8.2 summarizes the measurement methods adopted to measure the selected constructs.

Table 8.2 Measurement methods

Variables	Measurement methods	Sources of information
Management commitment to safety	Hybrid	Relevant safety practices Workers' perceptions
Safety management structure	Objective	Examination of written records and databases Interviews
Physical working conditions	Objective	Auditing, Checklists
Safety knowledge	Hybrid	Age and experience Relevant safety practices Workers' perceptions
Safety climate	Subjective	Workers' perceptions
Safety motivation	Subjective	Workers' perceptions Expert judgment
Social support	Subjective	Workers' perceptions
Safety practices	Objective	Design and implementation of safety practices
Production pressure	Hybrid	Schedule delay days Managers' and workers' perceptions
Peer pressure	Subjective	Workers' perceptions
Safety pressure	Subjective	Managers' perceptions

8.3.3.2 State indicators

Table 8.3 presents objective and subjective leading indicators that capture the state of the selected constructs. Among them, there are two aggregate indices: project hazard index (PHI) and Safety climate index (SCI). The project hazard index (PHI) is adopted from Imriyas et al.(2007) to measure physical working conditions. A reliable and valid safety climate measurement (e.g.,(Neal et al., 2000)) can be used to measure safety climate and the level of safety climate can be aggregated into a safety climate index (SCI).

Table 8.3 State indicators

State variables	Leading indicators	
	Objective	Subjective
Management commitment to safety	MCS1: Senior managers have specific safety goals. MCS2: the number of safety walkthroughs inspections performed by top managers per month MCS3: Frequency that senior managers attend safety meeting MCS4: percent of subcontractors selected in part on the basis of satisfying historical safety performance	MCS5: Management places a high priority on safety operations in the company. MCS6: Management cares about the safety welfare of their employees. MCS7: Management works to upgrade the safety of its facilities or reduce safety problems. MCS8: Management gets personally involved in safety programs.
Safety management structure	SMS1: Written safety policy signed by senior managers in place. SMS2: A health and safety manager is set up on site. SMS3: There is a clear assignment of safety responsibilities and authorities.	/
Physical working conditions	PWC1: project hazard index (PHI)	/
Safety knowledge	SK1: Average construction experience of workers SK2: percent of workers with certificates to operate equipment, tools, and plants SK3: percent of workers with Site Safe training passport	SK4: I received adequate training to perform my job safely. SK5: I am skilled at avoiding the dangers of workplace hazards. SK6: I am capable of identifying potentially hazardous situations.
Safety motivation	/	SM1: Everyone aims to achieve high levels of safety performance. SM2: Everyone plays an active role in identifying site hazards. SM3: Everyone reports accidents, incidents, and potentially hazardous situations. SM4: Supervisors' or managers' evaluation
Social support	/	SS1: When my supervisor and coworkers see me working at-risk, they caution me. SS2: Supervisor reports cases or shares safety-related experiences in the workplace. SS3: Supervisor makes on-going safety instruction at the workplace. SS4: Supervisor diligently reviews the safety behaviors of the employees.
Safety climate	/	SCI: Safety climate index (SCI)

8.3.3.3 Pressure indicators

Pressure indicators are designed to measure external forces on safety state and safety practices. They partly result from the unique characteristics of the construction projects. Such characteristics are often the source of dynamics of safety level (Guo and Yiu, 2016). It should be noted that pressures are context-dependent in nature. All pressures do not necessarily exist simultaneously in a construction project. Different pressures may emerge at different time points because of the fact that external environment is dynamic and uncertain. Table 8.4 presents some examples of pressure indicators.

Table 8.4 Pressure indicators

Pressures	Leading indicators	
	Objective	Subjective
Production pressure	PP1: schedule delay days	PP2: Shortcuts and risk taking are common due to the heavy workload. PP3: There is a lot of pressure to complete jobs quickly. PP4: Shortcuts and risk taking are common due to the heavy workload.
Peer pressure /		PE1: I do not want to be seen as “unmanly” or “weak” being overly safe. PE2: I work unsafely to avoid being teased or made fun of by my co-workers. SP1: Project managers are motivated to improve safety in order to avoid prosecutions and penalties. SP2: Project managers are motivated to improve safety in order to maintain the reputation of their company. SP3: Project managers are motivated to improve safety in order to meet top managers’ expectations.
Safety pressure /		

Practice indicators

In general, practice indicators are aimed at measuring the managerial subsystem of the PSP model by measuring safety practices that are implemented in a system. As

suggested by previous experience, safety practices can be measured by two general indicators: (1) What safety practices are being used? (2) How often are they conducted?

8.3.4 Step 4: Validation and revision

8.3.4.1 Criterion validity

A multiple-case study was conducted to seek qualitative evidence of criterion validity (i.e., concurrent validity and predictive validity) of the proposed leading indicators. The idea is that leading indicators are validated by examining the consistency between scores of leading indicators and actual safety outcomes, as suggested by Alteren (1999) and HSE (2006).

Sampling

Purposive sampling was adopted in this study to select construction projects where the leading indicators were implemented. Purposive sampling was used because of the fact that the sampling strategy allows identifying information-rich cases for the most effective use of limited resources (Patton, 2002). Three commercial construction projects were deliberately chosen as the subjects of the multiple-case study. Such a selection maximizes the congruence among the three projects and minimizes the influences of project type on the validation process. Detailed information about these three projects is presented in Table 8.5.

Table 8.5 Details of three projects

Projects	Project description
Project A	Project A is a medium-sized construction project which comprises of commercial and residential apartment blocks and over 6000 square meters of recreational and garden area. During the period when this project was under study, there were 1 main contractor and 3 subcontractors working on-site. About 30 workers were involved in construction operation each day.
Project B	Project B is a large-sized (about \$140 million) commercial construction project. The project involves demolishing the existing podium and link tower and constructing a new 11-floor South Tower. In total, it comprises of over 20,000 square meters of building area.

Project C	Project C (about \$300 million) includes over 30 buildings comprising accommodation, industry training, health facilities, administration, kitchen, laundry and visitor buildings. The construction site is a very busy one, where typically there are over 100 people working on site each day across multiple buildings and work-faces.
-----------	---

Data collection

In order to determine the value of each leading indicator, multiple sources of evidence were sought via interview, survey, and documentation. Such an application of data triangulation can help improve the validity and reliability of the validation process (Yin, 2003).

First, nine in-depth semi-structured interviews were conducted with six participants of project A, including one project manager, one general manager of a subcontractor, two safety officers, and two workers. The general manager and two safety officers were interviewed two times. Four in-depth semi-structured interviews with three participants of project B, including two senior safety advisors, health and safety manager of the main contractor. The health and safety manager was interviewed twice. In addition, three in-depth semi-structured interviews with three participants of project C, including two senior safety advisors, health and safety manager of the main contractor. The number of interviews was decided based on the consideration that as long as data collected from interviews were adequate to determine the values of leading indicators, together with the data collected by survey and documentation, the researchers could stop interviewing other people. However, this consideration requires researchers to delve deeply into different dimensions of safety level and to address different dimensions with different participants. Therefore, interviews questions were designed to collect information from participants in different positions. For example, interviews with project managers focused mainly on aspects, such as project

information, management commitment to safety, safety management structure, safety pressure, production pressure, and safety outcomes. Interviews with health and safety officers, managers and advisors were concerned with management commitment to safety, safety management structure, the safety management system, production pressure, safety pressure, and the implementation of safety practices. In addition, they were asked to evaluate workers' safety motivation. Workers were asked to share their perceptions of safety management, including managers' and supervisors' support, their ability and motivation to work safely, and peer pressure. There was some overlap among these questions so as to ensure data source triangulation and improve data reliability and validity. The duration of each interview was between 45 and 75 min (mean interview length: 60 min). All interviews were conducted by face-to-face at the workplaces. In addition, a safety climate survey, which was adopted from Guo et al.(2016), was administrated to workers of the three projects. The purpose of the survey was to measure workers' perceptions of safety management, including management commitment to safety, safety knowledge, safety motivation, social support, and pressures. The collected information was used to determine the values of subjective leading indicators. The procedure of administration demonstrated anonymity to respondents by having them place completed questionnaires in a sealed collection box. The response rates for project A, B, and C are 66.7% (20 completed questionnaires), 76% (76 completed questionnaires), and 42% (21 completed questionnaires), respectively.

Moreover, the researcher reviewed existing documents of safety management (e.g., safety management system, accident investigation reports, toolbox meeting, and hazard register records) of each project. The information helped the researcher to

determine the values of some leading indicators such as “percent of workers with Site Safe training passport”, “hazard register”, “toolbox meeting records”, “incident/accident investigation and reports”, and “written safety policy signed by senior managers in place”.

Second, the leading indicators were implemented three times (May, June, and July of 2015) in project A, in order to test the predictive validity. Scores of the proposed leading indicators were calculated based on the data collected in each round. One month after each round, TRIFR of the project was collected as the criterion measure.

Data analysis

In order to compare the developed leading indicators of three construction projects, a scoring system is designed as follows (see Table 8.6). The scoring system explicates how the value of each state variable and safety outcomes were determined. The scoring system does not distinguish the importance of each construct in achieving safety, as it assigns equal weight to each construct. By doing so, it only serves the purpose of cross-sectional and longitudinal comparisons among three projects. It was not aimed at providing a framework for interpreting leading indicators for individual projects. Obtaining 100 points in, for example, safety management structure does not necessarily mean it is the best in all situations.

Table 8.6 Scoring system of leading and lagging indicators

State variables	Leading indicators	Weight	Calculating Formula
Management commitment to safety (MSC)	MCS1: yes=20, no=0	20	MSC=MCS1+MCS2 +
	MCS2: 0 times=0; 1-5times=5; 6-10 times=8; 11-15 times=10; 16-20 times= 12; 21-25 times= 15; 26-30 times=20	20	MCS3+MCS4+MCS5+ MCS6+MCS7+MCS8

	MCS3: 0 times=0; 0-0.5 times=5; 0.6-1 times=10, 1.1-1.5 times=15, 1.6-2 times=20,	20	
	MCS4: 0%=0; 1%-20%=4; 21%-40%=8; 41%- 60%=12; 61%-80%=16 ; 81%-100%=20	20	
	MCS5, MCS6, MCS7, and MCS8 Average score of survey items (1-5 points)	20	
Safety management structure (SMS)	SMS1: No=0; yes=30	30	SMS= SMS1+SMS2+ SMS3
	SMS2: No=0, neutral=20, yes=40	40	
	SMS3: No=0, natural=15, yes=30	30	
Physical work conditions (PWC)	PWC1: Average score of survey items (1-5 points)	100	PWC=PWC1*20
Safety motivation (SM)	SM1, SM2, and SM3 Average score of survey items (1-5 points)	50	SM=((SM1+SM2+S M3)/3*20+SM4)*0.5
	SM4: 0-100 points	50	
Safety knowledge (SK)	SK1 1-5 years=5; 6-10 years=15; 11-15 years=20, over 20 years=25	25	SK=SK1+SK2+SK3 +(SK4+SK5+SK6+S K7)/4*5
	SK2 0%=0; 1%-20%=4; 21%-40%=8; 41%- 60%=13; 61%-80%=18 ; 81%-100%=25	25	
	SK3 0%=0; 1%-20%=4; 21%-40%=8; 41%- 60%=13; 61%-80%=18 ; 81%-100%=25	25	
Safety climate (SC)	SK4, SK5, SK6, and SK7 Average score of survey items (1-5 points)	25	
	SCI: Average score of survey items (1-5 points)	100	SC=SCI*20
Social support (SS)	SS1, SS2, SS3, and SS4 Average score of survey items (1-5 points)	100	SS=(SS1+SS2+SS3+ SS4)/4*20
Safety outcomes	100, when TRIFR<=5, 90, when 6<=TRIFR<=7, 80, when 8<=TRIFR<=9, 70, when 10<=TRIFR<=11, 60, when 12<=TRIFR<=13, 50, when 14<=TRIFR<=15, 40, when 16<=TRIFR<=17, 30, when 18<=TRIFR<=19, 20, when 20<=TRIFR<=21, 10, when 22<=TRIFR<=23.	100	/

Table 8.7 presents the values of all state variables and safety outcomes that were determined by calculating the collected data based on the scoring system developed above. It should be noted that the values of subjective leading indicators were determined based on data collected from questionnaires. The values of objective indicators were determined based on both interviews and documentation.

Table 8.7 Safety state of three projects

Constructs	Leading indicators	Project A (May)	Project A (June)	Project A (July)	Project B	Project C
Management commitment to safety	MCS1	no	no	no	yes	yes
	MCS2	15	20	22	20	18
	MCS3	2/month	2/month	2/month	0.5/month	0.5/month
	MCS4	0%	30%	30%	50%	40%
	MCS5	3.75	4	4.5	4.33	4.12
	MCS6	3.91	4	4.5	4.42	4.33
	MCS7	3.83	4	5	4.67	4.41
	MCS8	3.83	4	5	4.12	4.12
Safety management structure	SMS1	no	no	no	yes	yes
	SMS2	neutral	yes	yes	yes	yes
	SMS3	neutral	yes	yes	yes	yes
Physical work conditions	PWC1	3.21	3.51	3.51	3.42	3.23
Safety motivation	SM1	3.83	4.17	4.33	3.83	4
	SM2	3.66	3.91	4.5	4.17	3.76
	SM3	3	4.25	4.5	4.25	3.87
	SM4	60	70	75	75	70
Safety knowledge	SK1	5 years	5 years	5 years	8 years	7 years
	SK2	100%	100%	100%	100%	100%
	SK3	0	0	0	60%	50%
	SK4	3.6	4	4	4.17	4.4
	SK5	4	4	4	4.67	4.67
	SK6	4	4	4	4.17	4.23
Safety climate	SCI	3.51	4.08	4.33	4.12	4.01
Social support	SS1	4.17	3.91	4.5	4.12	4
	SS2	4.25	4.5	4.67	3.83	4.43
	SS3	3.83	4.33	4.5	4.17	4.21
	SS4	3.67	4.25	4.25	3.83	3.83
Safety outcomes	Total recordable injury frequency rate	30	60	70	70	60

Safety practices that were implemented and existed pressures in the three projects are presented in Table 8.8.

Table 8.8 Safety practices implemented in three projects

Project	Safety practices implemented	Pressures
Project A	task analysis, emergency plan and procedures, hazard register, toolbox safety meeting, accident/incident register, accident and incident investigation	production pressure, safety pressure
Project B	H&S induction, tasks analysis, safety training, safety inspection, toolbox talks, hazard management & site safety statement, ladder policy, working at heights checklist, mobile scaffold use policy, mobile plant certification, mobile plant checklist, personal protective equipment policy, code of safety conduct, concrete pumping check sheet, handheld grinders policy, accident/incident investigation, post contract evaluation, near missing reporting	production pressure, peer pressure, safety pressure
Project C	H&S induction, tasks analysis, safety training, safety inspection, toolbox talks, hazard management & site safety statement, ladder policy, working at heights checklist, mobile scaffold use policy, mobile plant certification, mobile plant checklist, personal protective equipment policy, code of safety conduct, concrete pumping check sheet, handheld grinders policy, accident/Incident investigation, post contract evaluation, near missing reporting	production pressure, peer pressure, safety pressure

Information interpretation

The cross-sectional and longitudinal information generated from the three projects was interpreted based on the framework developed earlier in this paper (see Fig. 8-2). In order to compare the safety state among the three projects, the values of proposed leading indicators were calculated according to the scoring system.

(1) Longitudinal comparison

According to the data collected in May, project A had a low safety level as shown in Fig. 8-3. The score of management commitment to safety was relatively low (45 points). In addition, this project did not employ a professional safety manager on site, although some subcontractors have their own safety officers who were only responsible for checking personal protective equipment (PPE) and organizing safety meetings. The assignment of safety responsibilities and authorities was unclear. In general, only six formal safety practices and programs were implemented on site, which left some dimensions of safety state underdeveloped and unmaintained. For

example, workers were not provided with formal safety training. As a result, the score of safety knowledge is relatively low (50 points). Due to limited safety practices, workers' perceptions of safety practices were not high. This was proved by the relatively low score of safety climate (70 points). As suggested by the project manager, during the period between April and May, managers had been under considerable production pressure (schedule delay days=30 days), which was one of the reasons for the low level of management commitment to safety. The safety officer of the main contractor stated that during this period managers' attention was primarily paid to productivity and some safety activities, such as safety meeting and task analysis, were somewhat ignored. As a result, the TRIFR in the May was 18 per million hours worked.

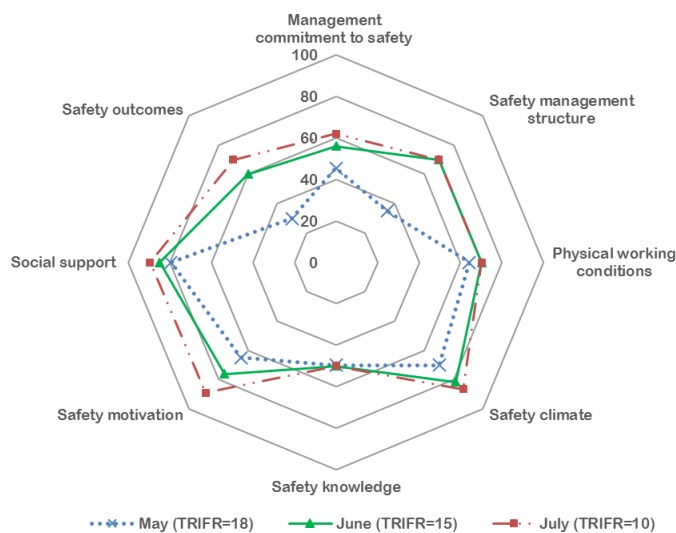


Figure 8.3 Safety level of project A at three different time points

Compared with May, June has seen significant improvements in all dimensions of safety state, except safety knowledge. The project production data suggested that production pressure had been relieved significantly (schedule delay days=12 days). As a result, senior managers placed more attention on site safety. This was proved by the fact that a full-time health and safety manager was hired to implement and

coordinate safety activities and that the number of safety walkthroughs performed by senior managers per month was increased from 15 to 20. The improvements in safety goals and values and safety management structure lead to positive changes in other dimensions. For example, values of workers' safety motivation, social support, and safety climate were increased. As workers still did not receive formal safety training, the score of safety knowledge remained unchanged. Because of these changes, the TRIFR of June was decreased to 15 per million hours worked.

Incidents and accidents were further reduced in July (TRIFR=10). The trend is consistent with most dimensions of safety state, except that safety management structure, physical working conditions, and safety knowledge. Although there had not been much improvement in terms of schedule delay (schedule delay days=8 days), managers demonstrated a higher level of commitment to safety. In specific, they conducted more on-site inspections and started to select subcontractors in part based on historical safety performance. As stated by one worker in the interview, there were consistencies between "what managers say" and "what managers do" in site safety management. As a consequence, the tone and tempo established by managers for safety management further improved the psychosocial dimension.

(2) Cross-sectional comparison

Data collected in May from project A were calculated and compared to that of project B and C. As shown in Fig. 8-4, project B and C were managing safety almost equally well in many aspects, except that project B had a higher level of management commitment to safety, safety motivation, and safety climate. Both two projects established a healthy safety management structure, where health and safety managers were set up and there is a clear assignment of safety responsibilities and authorities.

This provided a platform to organize and coordinate safety practices. Both project B and C had a well-designed safety management system, within which over eighteen safety practices were implemented. These safety practices played important roles in buffering against various pressures (e.g., changing working conditions) and maintaining a good level of safety. It is evident that the values of leading indicators of project A in May were the lowest among the three projects, and that project B had the best performance with respect to the eight state variables and safety outcomes. The scores are consistent with the total recordable injury frequency rate of the three projects.

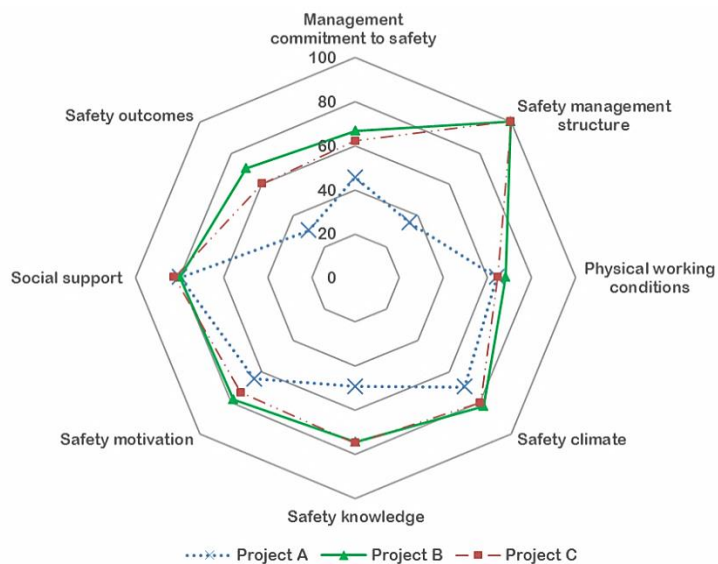


Figure 8.4 Comparison of leading indicator scores

Low values of project A can be attributed to the fact that, compared to project B and C, project A placed less emphasis on safety. According to the PSP model, a lack of management commitment to safety has two significant implications. First, managers are reluctant to implement safety practices and establish safety management structure, since they both cost time and money and influence productivity in a short term. This is manifested by the fact that managers of project A implemented only six safety

practices and that project A did not even hire a professional safety manager. The second consequent implication is that managers created a social environment in which safety was communicated and managed. Supervisors and workers experienced and perceived what their managers said and did on a daily basis and tended to develop similar perceptions on safety, due to some pressures such as fear of position. Although project A, B and C did equally well in terms of improving physical working conditions by hazard management, the psychosocial environment of project A was relatively poor. Possible consequences of a lack of safety climate, social support, and safety motivation were risky behavior became acceptable on site and accidents and incidents became more frequent.

Practicability and cost-effectiveness

The project manager of project A, health and safety managers of project B and C were invited to evaluate the practicability and cost-effectiveness of the proposed leading indicators. They were first asked questions:

- (1) Are the leading indicators compatible with practical safety management?
- (2) Is data collection cost-effective?
- (3) Are they able to drive appropriate behavior?

In implementation, leading indicators must be able to help decide where, how, and who to take actions (Hale, 2009). From this perspective, compatibility of leading indicators and practical safety management refers to the linkage between leading indicators and specific safety practices and activities. Compatible leading indicators are able to generate information that can be easily interpreted and transferred to remedial actions. For example, the indicator “frequency that senior managers attend safety meeting” is compatible with practical safety management when there are

corresponding safety policies and practices, such as safety meeting register. The cost-effectiveness of a leading indicator refers to the indicator's ability to offer best possible benefits (i.e., foresight) in comparison with the time and money it costs. For example, when measuring safety meeting, the indicator "the frequency of safety meeting" is more cost-effective than "the effectiveness of safety meeting", since the latter requires more efforts to decide the value. In addition, indicators are able to drive appropriate behavior when they are explicitly linked with safety practices and people in right positions so that the information is not confusing and corrections can be easily planned and implemented.

They were then asked to evaluate the set of leading indicators based on a five-point Likert scale (1 = lowest level; 5 = highest level), in which ratings of 1–2, 2–4, and 4–5 were considered "invalid," "indeterminate," and "highly valid," respectively. Table 8.9 presents the average ratings for the practicability and cost-effectiveness of all leading indicators. Results indicate that the leading indicators are considered as a reasonably practical and cost-effective tool for safety performance measurement.

Table 8.9 Results of evaluation

Participant	Practicability	cost-effectiveness
project manager (project A)	4.0	4.0
health and safety manager (Project B)	4.1	3.9
health and safety manager (Project B)	4.2	4.0

8.4 Discussion

This chapter represents an effort to develop and validate a set of leading indicators for measuring safety performance and facilitating safety assessment in construction projects. One major difficulty in designing leading indicators has been that simplifying

complex safety reality into a set of manageable leading indicators is a conceptual, epistemological, and methodological challenge. To tackle this challenge, a pressure-state-practice model was developed to guide the development process. The PSP model draws upon concepts and principles of systems theory and conceptualizes safety level as a dynamic phenomenon that is determined by the interactions among safety state, pressures, and safety practices.

One of the strengths of the PSP model is that it captures and assesses multiple dimensions of safety. In essence, the PSP model views safety as one of the subsystems of a construction project. This is a useful way to conceptualize safety level, holistically and dynamically. By differentiating among, but linking with, safety state, safety practices, and pressures, it is easier to interpret the dynamics of safety level. The PSP model also adopts a contingency view of management (Kast and Rosenzweig, 1979), that is, there is no one way to manage safety and appropriate safety practices need to be designed and implemented for specific situations. By classifying leading indicators into three types (i.e., state, pressure, and practice indicators), emphasis is placed on deriving information about how safety practices, as well as emerging and long-lasting pressures, affect dimensions of safety state. Such a view allows leading indicators to neatly fit into existing safety management systems. This view also emphasizes that safety management can be adaptive by virtue of leading indicators. The pursuit for “holism” and “comprehensiveness”, however, needs to be balanced with a consideration of other qualities of leading indicators such as practicability and cost-effectiveness.

The leading indicators developed in this paper provide the construction industry a tool to measure safety level and identify safety problems. By simplifying and

quantifying complex safety reality into a manageable amount of meaningful information, they can facilitate proactive safety management strategies. In practice, safety practitioners tend to interpret and understand leading indicators in different ways, which may hinder construction companies from integrating them into safety programs (Hinze et al., 2013b). The PSP model classifies leading indicators into three groups and explicates the relationships among them. Thus, it can be helpful in directing safety practitioners' and managers' efforts in data collection. Collected information can be interpreted based on the framework, as shown in Fig. 8-2. As the leading indicators developed in this paper demonstrated ability to predict the trend of TRIFR, they can be used to monitor safety level at the project level. Data can be collected on a regular basis and possible problems in all five subsystems can be identified and fixed before safety level deteriorates further. This requires managers to adopt the principles of feedforward control which emphasize the importance of maintaining and improving safety level based on foresight rather than hindsight (Hollnagel, 2008b). In addition, the evidence of concurrent validity supports an application of leading indicators to benchmarking programs and auditing. As safety standards of construction projects often vary considerably, improvement opportunities can be identified by comparing safety level among construction projects. These developments can help them embrace the approach of leading indicators and shift the safety paradigm from being reactive towards proactive.

8.5 Summary

This chapter developed a set of leading indicators by following a systematic process that consists of conceptualization, operationalization, indicator generation, and validation and revision. The pressure-state-practice (PSP) model provides an overall framework for developing leading indicators. One of the unique strengths of the PSP model is that it conceptualizes safety level from a systemic and dynamic perspective, which is consistent with the role of leading indicators in safety management. A classification of state indicators, pressure indicators, and practice indicators considerably facilitates the interpretation of information generated by leading indicators. The multiple-case study provided the qualitative evidence that the safety leading indicators have ability to indicate the weaknesses and strengths of safety state and correspond to actual safety outcomes.

The role of leading indicators is to generate foresight, motivate people to work on safety and contribute to fix safety problems and maintain a high safety standard. Underlying the idea of leading indicators is a proactive and dynamic mindset towards safety management. The set of leading indicators provides the construction companies with an alternative to assessing safety conditions and measuring safety performance at the project level. By capturing multiple sides of safety (e.g., technical, psychosocial, and organizational), the use of leading indicators can extend traditional safety efforts beyond hazard management and safety training. It is suggested that construction companies, particularly those that embrace the “zero harm” philosophy, integrate leading indicators in safety management systems and link the information with current safety practices and activities.

Chapter 9 Conclusions and Recommendations for Future Research

9.1 Introduction

This chapter reviews the objectives and how they have been achieved through the research. It then presents the original contributions to the leading indicators, safety performance measurement, and construction safety management. This chapter discusses the limitations of this research and concludes with recommendations for future research.

9.2 Review of research objectives

Objective 1: Develop a pragmatic method for systematically identifying a set of leading indicators for construction projects

A conceptual framework was first developed with an attempt to clarify the definition, purpose, type, and development process of leading indicators. The framework defines leading indicators as a *set* of quantitative and/or qualitative measurements that can describe and monitor validly and reliably the *safety conditions* of a construction project. According to the framework, safety conditions are seen as a dynamic phenomenon, affected by safety practices and pressures (e.g., production pressure). Safety practices are conceptualized as positive forces that create, improve and/or maintain a system's safety conditions, while pressures are defined as negative forces

that tend to worsen a system's safety conditions. The independence between safety practices and safety conditions highlights that leading indicators should not be randomly selected to measure existing safety practices but should be developed to describe and monitor specific safety conditions through a systematic development process.

A four-step development method was proposed which consists of: conceptualization, operationalization, indicator generation, and validation and revision. Section 3.1 provides details of how each step should be undertaken. Overall, the method underscores a transition from abstract safety conditions toward concrete safety practices and emphasizes the importance of validation of leading indicators. To illustrate the development process, Section 3.2 developed a set of leading indicators for a hypothetical construction project. Dimensions of safety conditions were identified based on a literature review (see Table 3.1 Dimensions of first order safety construct). These abstract safety constructs were transferred to concrete safety practices according to the mechanisms by which safety practices and pressures change safety conditions. A set of 32 leading indicators were developed to capture the safety conditions of the hypothetical project. Although the main objective of Section 3.2 was to illustrate the method and no efforts were made to develop leading indicators for a real construction project, the validity of the leading indicators developed was tested by conducting three types of validation (i.e., conceptual, output, and end-use). Results suggest that they are potentially effective in safety assessment and proactive safety management.

Objective 2: Explore and understand the dynamics and complexity of construction safety management

To better understand the dynamics and complexity of construction safety management, the Chapter 4 adopted the ground theory method (GTM) and 22 interviews were conducted with participants in various positions (government safety inspector, client, health and safety manager, safety consultant, safety auditor, and safety researcher). Eight archetypes were emerged from the collected data:

- (1) safety regulations,
- (2) incentive programs,
- (3) procurement and safety,
- (4) safety management in small businesses
- (5) production and safety,
- (6) workers' conflicting goals,
- (7) blame on workers, and
- (8) reactive and proactive learning.

The eight archetypes represent an effort to identify and categorize common behaviour patterns that recur again and again in construction safety management. They capture the interactions between a wide range of factors within and among various hierarchical levels (government, company project and individual) and subsystems (regulation, procurement, cost, production, human resources and safety). The eight archetypes, as a form of systems thinking, advance the understanding of complexity and dynamics of construction safety management. They illustrate how complex feedback processes can generate problematic patterns of behaviour at different hierarchical levels. They aid in visualizing common construction safety problems and underlying structures that drive these problems. The archetypes suggest that a systemic and dynamic view on safety conditions is needed when developing leading indicators. It is clear that causes

and effects are often distant in time and space and thus it is not effective to treat safety problems like snapshots.

In addition, in order to gain an in-depth understanding of the dynamics and complexity of construction safety at the project level, a system dynamics (SD) model of safety conditions of a construction project was built and validated. Numerical, written, and mental data were collected from the project by interview, questionnaire, and documentation. A causal loop diagram (CLD) was developed which consists of four balancing and two reinforcing loops. The CLD was then converted to stock and flow diagram that provides a quantitative description of safety conditions of the project. The model was validated through parameter verification testing, extreme condition testing, behaviour reproduction testing, sensitivity analysis, and statistical screening. Overall, the validity and usefulness of the model is supported by the results of these tests.

The SD model of safety conditions represents an application of systems thinking to construction safety. The study enhanced an understanding of the dynamics and complexity of construction safety at the project level. Based on the actual data, it modelled the causal links between safety conditions and safety outcomes (i.e., incident/accident rate). Safety conditions were conceptualized as the state of the project with regard to its capability for producing safety. Simulation results indicated that the capability was determined not only by the state of single factors (e.g., management commitment to safety), but also by the interrelationships among safety and other subsystems (i.e., regulation, production, and human resource).

This study generated meaningful insights into the development of leading indicators. First, although the conceptual framework developed in Chapter 2 defines the function

of leading indicators, it begs the question as to what safety conditions really are and how they change over time. The results of model simulation provided the basis for developing a theoretical framework of safety conditions a construction project and demonstrated the dynamics of the safety conditions. Second, as suggested in sensitivity analysis, system performance (e.g., incident and accident rate) has sensitive dependence on initial conditions. Thus, leading indicators that measure the initial conditions of site safety have power to predict safety outcomes.

Objective 3: Investigate workers' safety behaviour shaping mechanisms

A priori model of safety behaviour was proposed based on a literature review (see Figure 6.1). Empirical data were then collected through sampling from workers of the New Zealand construction industry. Of 500 questionnaires initially distributed in three training centres and four construction projects, 215 were completed and returned. Of those, 213 were sufficiently completed to be included in data analysis, producing a usable response rate of 43%. Structural equation modelling (SEM) was used to test eight competing models. Results suggest that Model 8 was the best representation of the observed relationships (see Figure 6.3).

This study enhanced the understanding of the mechanisms by which organizational, group and individual factors (i.e., safety knowledge and safety motivation) affect workers' safety behaviour at the sharp end. Results indicated that management safety commitment had an indirect influence towards safety behaviour (safety participation and compliance), via group-level social support and perceived production pressure and individual factors (safety knowledge and safety motivation). In addition, social support has both direct and indirect effects on safety behaviour. Production pressure can negatively influence workers' safety knowledge and motivation and lead to unsafe

behaviour. The tested model identified potential useful measurement bases and provided empirical evidence that the measurement bases are statistically related to safety behaviours and safety outcomes.

Due to the fact that research on safety climate in the construction industry primarily focused on either large companies or the whole industry, while little is known about whether the meaning and measurement of a safety climate measure is equivalent across the small (with 20 or fewer employees) and large companies (with over 20 employees). Another study (Chapter 7) was conducted to test the validity of the integrative model of safety behaviour across small- and large-company groups. Data were collected using the questionnaire from 253 construction workers from large (n= 123) and small (n= 130) construction in New Zealand (NZ). Results suggested that the relationships among safety climate factors and safety behavior were equivalent across the two groups. Findings of this study provided strong support for a meaningful use of the safety climate measure in construction companies in different sizes. They also suggest that similar strategies (e.g., a safe organization, safe groups, and safe workers) for developing safety climate and improving safety performance could be used across small and large companies.

Objective 4: Develop and validate a set of leading indicators for the construction industry

A study (Chapter 8) was undertaken to develop a set of leading indicators by following the method proposed in Chapter 3 and to validate the leading indicators through a multiple-case study. In the conceptualization step, a pressure-state-practice (PSP) model was developed by drawing upon concepts of systems theory, current safety knowledge, and research findings of Chapter 2, 3, 4, 5, 6, and 7. The PSP model

conceptualizes safety level as a dynamic phenomenon that is determined by the interactions among safety state, pressures, and safety practices. One of strengths of the PSP model is that it captures and assesses multiple dimensions of safety. In essence, the PSP model views safety as one of subsystems of a construction project. This is a useful way to conceptualize safety level, holistically and dynamically. By differentiating among, but linking with, safety state, safety practices, and pressures, it is easier to interpret the dynamics of safety level.

A multiple-case study was conducted to obtain initial evidence of the criterion validity of the leading indicators. The validation process filled the research gap left in Chapter 3. Results indicated that the leading indicators have ability to simplify complex safety phenomena, measuring safety performance, and corresponding to actual safety outcomes.

Compared to the leading indicators developed in Chapter 3, the set of leading indicators developed in this study are more advanced and powerful in several aspects. First, they simplify and quantify complex safety realities to a manageable amount of meaningful information, based on the PSP model. Their construct validity lies in the ability of the PSP model to capture the “holism” and interpret measurement information. Thus, their analytical soundness has been considerably improved. Second, their predictive power was tested by the comparative case study. Third, the leading indicators integrated different measurement methods (i.e., subjective, objective, or hybrid method) when measuring eight safety state variables. The selection of the methods was determined by the nature of the state variables. Last but not least, the scoring system developed in this study can facilitate the safety assessment at the project level. Values of safety state variables can be interpreted based on the

theoretical framework. These leading indicators can also be used as a benchmarking tool to identify improvement opportunities as well as monitoring the performance of competitors of other projects of the same company. As safety standards between different companies may vary considerably, such improvement opportunities can be relatively easily identified.

9.3 Original contributions and significance of the research

Results of this PhD research project have both research and practical implications. Leading indicators represent an advanced topic in the field of safety research. As aforementioned, the concept is ambiguous with respect to definition, function, and development process. This research added to the body of scientific knowledge in these aspects through pioneering efforts. First, the conceptual framework developed in Chapter 2 clarifies the concept of a leading indicator in terms of definition, purpose and role. Second, the development method of leading indicator proposed in the research improves the process of developing leading construction industry indicators. The novelty of the method is that it addresses the scientific and managerial attributes of leading indicators simultaneously and that it acknowledges current knowledge gap as to fundamental issues of safety such as “What is safety?” and “How it can be achieved?”. In addition, the research project made exploratory efforts to understand the dynamics and complexity of construction safety. By adopting a systems thinking approach, it contributes to further developments in safety theory and demonstrates how to put systems archetypes in a practical context for the safety practitioner (i.e., safety manager or risk analyst). The eight construction safety archetypes constitute a

library of fundamental dynamic structures that generate counter-intuitive behaviours with which managers must cope. By investigating and analysing dynamics and complexity of construction safety at different hierarchical levels, the research facilitates a broader definition of construction accident that goes beyond workers unsafe behaviour and thus provides insights into accident analysis and prevention. Furthermore, this research project enhances the understanding of workers' safety behaviour shaping mechanism. Last but not least, this research project demonstrated measurement equivalence of a safety climate measure across small and large construction companies, which added to a body of scientific knowledge of the difference of safety between small and large construction companies.

From a practical standpoint, findings of the research project provide significant insights into construction safety management. For example, the eight construction safety archetypes developed in Chapter 4 generate systemic insights into design and implementation of safety management systems. The system dynamics model of construction safety developed in Chapter 5 can be a practical tool for the industry to assess safety risk at the project level. The integrative model of safety behaviour developed and tested in Chapter 6 suggested a combination of three accident prevention strategies, namely "a safe organization", "safe groups" and "safe workers". These strategies are potentially effective to reduce unsafe behaviour on site. More importantly, as the primary goal of the research, the leading indicators proposed in Chapter 8 provide with the construction industry with a practical tool to measure safety performance and, more importantly, manage site safety in a proactive manner. The research facilitates a mind-set shift from being reactive and standardized towards proactive and adaptive with respect to construction safety management.

9.4 Research limitations and recommendations for future research

The research limitations of each study and recommendations for the future research for are discussed as follows:

The validation of the proposed leading indicators in Chapter 3 was mainly based on qualitative interviews and experts' judgments, which were subjective in nature owing to the small sample size and personal biases. However, the limitation has been compensated for by the output validation process conducted in Chapter 8.

This exploratory study presented in Chapter 4 has several limitations. Firstly, this study made no attempt to identify all behaviour patterns in the field of construction safety management. The eight construction safety archetypes developed in this chapter only represent ones that emerged from data collected via interviews. Secondly, as the grounded theory method does not use probability sampling, it is not possible to generalize the findings. The third limitation is associated with the nature of system archetypes. Construction safety archetypes developed in this chapter were partly based on Senge's (1990) eight system archetypes. Lane and Smart (1996) argued that Senge's counter-intuitive system archetypes take shortcuts from problematic behaviours straight to management principles: "*Counter-intuitive system archetypes move user from an idea of problematic behaviour, through a causally-based diagnosis of the reason for the dysfunction and then straight to a surprising management principle indicating ways of alleviating the problem.*" In addition, Lane and Smart claimed that although system archetypes do provide qualitative insight into the real world, they may produce a one-sided kind of insight as they may obscure certain

aspects of the world. It is therefore suggested that the behaviour of system factors in these archetypes should be interpreted with caution. Nevertheless, archetypes have long been used to enhance the understanding of dynamic behaviour of complex systems. Lane and Smart (1996) acknowledged that archetypes do provide a compelling summary of system insights. Wolstenholme (2003) held a similar view, stating that archetypes can be used, as a formal and free-standing way, to communicate people with dynamic insights and to facilitate system dynamics modelling process. Due to the limitations mentioned above, future research is needed to identify additional construction safety archetypes. In addition, future research in different cultural settings is needed to further consolidate the findings of this chapter.

In addition, although the system dynamics model developed in Chapter 5 has demonstrated its capability to generate systemic insights into site safety management, the findings of this study should be used with caution due to the following limitations. First, there are uncertainties in the values of variables. For example, this chapter defines some variables (e.g., workers' safety motivation, management commitment to safety, and workers' safety competency) at the ratio scale level, but measuring them at the interval scale level. In addition, the accuracy of the number of incidents/accidents each week may be subject to underreporting. Second, many relationships among variables have not been empirically tested. As such, the results of the simulation model are open to criticism. To address this issue, the model has been validated by various tests. This chapter made no attempt to build an objectively correct model of safety conditions of a construction project. As Barlas (1994) argued, *“Accordingly, model validation cannot be entirely objective, quantitative and formal. Since validity means ‘usefulness with respect to a purpose’, model validation has to*

have informal, subjective and qualitative components.” It is argued that reasonable confidence has been established into the usefulness of the model according to the testing results. The third limitation is about the limited ability of this model to predict incidents and accidents in a timely fashion. Although the results of behaviour reproduction testing have demonstrated the forecasting ability of the model, the model should not be used as a tool for “point-prediction”. Nevertheless, the results of this study enhance our understanding of the safety management in a complex and dynamic construction project, which is the main purpose of this study. Given these limitations, future research is needed to examine, quantify, and test causal relationships between system variables. This is particularly important for gaining an in-depth understanding of effects of safety processes on safety outcomes. Arguably, this can lay a foundation for developing a “safety model” for the construction industry. In addition, the model developed in this chapter should be validated in other construction projects based on appropriate and relevant modifications.

Furthermore, the findings of Chapter 6 should be interpreted in light of the following limitations. First, due to financial and time constraints, only cross-sectional survey was possible and time sequence of events cannot be considered. Thus, correlations tested in this study do not imply causation. This study examined the correlation only from top management level to sharp-end, rather than the reverse. However, reverse direction may also be valid. Research has provided evidence suggesting that production pressure may decrease the level of management safety commitment (Han et al., 2014a). Therefore, future research is needed to test these relationships in other settings. A second limitation involves common method bias. However, this study tested a common latent factor measurement model and found support for the

multidimensional nature of these constructs. The poor fit of the one factor model provides evidence that these results are not due to a common method factor. Finally, another limitation relates to the finding that the majority of respondents were male (88.7%). Such imbalance in respondents gender might affect the findings of this study in that, compared with males, females are less likely to have accidents (Jensen et al., 2014). Although such imbalance is not surprising since the construction industry is male dominated, a multi-group analysis of the model between female and male could provide another fruitful insight on safety behaviour.

A major limitation of this study presented in Chapter 7 is that sample size was relatively small. Despite this, it does not appear to be biased in any direction. Respondents appear to be representative of New Zealand construction industry as a whole, because of the fact that questionnaires were collected from different regional safety training centers and projects in three different cities. In addition, although we presented a rigorous test of the ME of the safety climate measure and related theoretical model, we only did so by comparing small and large construction companies in New Zealand context. The definition of small businesses (with 20 or fewer employees) adopted in this paper does not necessarily apply to other regions (e.g., Europe and US). Caution should be exercised in generalizing these findings to all cultural and national contexts. Clearly, further research is needed in other cultural and national contexts. Future studies are also needed to improve a better understanding of how safety climate can be developed in small construction companies.

Furthermore, the study presented in Chapter 8 has a number of limitations. First, it was not possible to fully estimate the reliability of these leading indicators based on the multiple-case study design, as instrument reliability is a statistical concept.

Traditionally, a test-retest method is often used to estimate the reliability of measurement instrument. However, in this study, it has been impractical to implement these indicators at the three projects twice in a short time interval (e.g., one day), since each test was time-consuming and the three construction projects showed no willingness to participate the test again. In addition, the test-retest method is not appropriate to estimate the reliability of the leading indicators that are designed to measure dynamic phenomena (e.g., safety level) (Wewers and Lowe, 1990). Therefore, future research is needed to estimate the reliability of these indicators by using a split-halves method or an internal consistency method (Carmines and Zeller, 1979). The second major limitation of this study is that the validation of the proposed leading indicators is qualitative in nature. Although both cross-sectional and longitudinal consistencies were identified between the scores of safety leading indicators and TRIFR in three construction projects, a larger sample size will be needed to validate the concurrent and predictive validity of the safety leading indicators by using quantitative validation techniques. The last limitation is that this paper made no attempt to design a normative evaluative standard to interpret these leading indicators. Hence, how better 60-point is than 55-point in management commitment to safety still depends on subjective judgement. To determine reference points requires more empirical evidence. Therefore, future efforts should be made to propose and test such reference points so that construction companies could make better use of leading indicators.

Finally, the leading indicators were developed based on the PSP model to serve the purpose of simplifying complex safety phenomena, measuring safety performance, and predicting safety trend. It should be noted that the PSP model is a descriptive

model and it by no means represents a fully valid model, since it was developed by drawing upon the concepts from systems theories and by basing itself on current safety knowledge. This means that the leading indicators developed in the research are not the final and perfect set and there must be missing leading indicators. However, this is understandable, since these leading indicators are descriptive in nature and they are not aimed at providing normative reference points for safety performance evaluation. To further improve the leading indicators requires to implement them in real construction projects. As discussed in Chapter 3 (the conceptual framework, Fig. 3-1), double-loop learning is required to reflect the PSP model, facilitate the construction of a new one, and capture the missing leading indicators.

Bibliography

- AKSORN, T. & HADIKUSUMO, B. 2008a. Critical success factors influencing safety program performance in Thai construction projects. *Safety Science*, 46, 709-727.
- AKSORN, T. & HADIKUSUMO, B. H. W. 2008b. Measuring effectiveness of safety programmes in the Thai construction industry. *Construction Management and Economics*, 26, 409-421.
- AL-REFAIE, A. 2013. Factors affect companies' safety performance in Jordan using structural equation modeling. *Safety Science*, 57, 169-178.
- ALBRECHT, T. L. & ADELMAN, M. B. 1987. *Communicating social support*, Sage Publications, Inc.
- ALE, B. 2009. More thinking about process safety indicators. *Safety Science*, 47, 470-471.
- ALTEREN, B. 1999. Implementation and evaluation of the Safety Element Method at four mining sites. *Safety science*, 31, 231-264.
- ANDRIESSEN, J. 1978. Safe behaviour and safety motivation. *Journal of Occupational Accidents*, 1, 363-376.
- ARGYRIS, C. 1999. *On Organizational Learning*, Wiley.
- ARGYRIS, C. & SCHÖN, D. A. 1996. *Organizational learning II: theory, method, and practice*, Addison-Wesley.
- AROCENA, P. & NÚÑEZ, I. 2010. An empirical analysis of the effectiveness of occupational health and safety management systems in SMEs. *International Small Business Journal*, 28, 398-419.
- BACCARINI, D. 1996. The concept of project complexity-a review. *International Journal of Project Management*, 14, 201-204.
- BAEK, J.-B., BAE, S., HAM, B.-H. & SINGH, K. P. 2008. Safety climate practice in Korean manufacturing industry. *Journal of Hazardous Materials*, 159, 49-52.
- BAKER, J., LEVESON, N., BOWMAN, F., PRIEST, S., ERWIN, G., ROSENTHAL, I., GORTON, S., TEBO, P., HENDERSHOT, D. & WIEGMANN, D. 2007. The report of the BP US refineries independent safety review panel. *BP US Refineries Independent Safety Review Panel*.
- BARLAS, Y. Model validation in system dynamics. Proceedings of the 1994 International System Dynamics Conference, 1994. Sterling, Scotland, 1-10.
- BARLING, J., LOUGHLIN, C. & KELLOWAY, E. K. 2002. Development and test of a model linking safety-specific transformational leadership and occupational safety. *Journal of Applied Psychology*, 87, 488-496.
- BEDFORD, T. & COOKE, R. 2001. *Probabilistic risk analysis: foundations and methods*, Cambridge University Press.
- BENTLER, P. M. 1990. Comparative fit indexes in structural models. *Psychological bulletin*, 107, 238.
- BENTLER, P. M. & BONETT, D. G. 1980. Significance tests and goodness of fit in the analysis of covariance structures. *Psychological bulletin*, 88, 588.
- BHATTACHARJEE, S., GHOSH, S. & YOUNG-CORBETT, D. 2011. Safety Improvement Approaches in Construction Industry: A Review and Future Directions. *47th ASC Annual International Conference* Omaha, Nebraska.
- BLEWETT, V. & O'KEEFFE, V. 2011. Weighing the pig never made it heavier: Auditing OHS, social auditing as verification of process in Australia. *Safety Science*, 49, 1014-1021.

- BLEWETT, V. & O'KEEFFE, V. 2011. Weighing the pig never made it heavier: Auditing OHS, social auditing as verification of process in Australia. *Safety science*, 49, 1014-1021.
- BOCKSTALLER, C. & GIRARDIN, P. 2003. How to validate environmental indicators. *Agricultural Systems*, 76, 639-653.
- BOLLEN, K. A. 1989. A new incremental fit index for general structural equation models. *Sociological Methods & Research*, 17, 303-316.
- BOULOIZ, H., GARBOLINO, E., TKIOUAT, M. & GUARNIERI, F. 2013. A system dynamics model for behavioral analysis of safety conditions in a chemical storage unit. *Safety science*, 58, 32-40.
- BOYLAN, J. E., SYNTETOS, A. A. & SANDERS, N. R. Qualitative System Dynamics and the Bullwhip Effect The 26th International Conference of the System Dynamics Society, 2008 Athens, Greece.
- BROCKNER, J., HIGGINS, E. T. & LOW, M. B. 2004. Regulatory focus theory and the entrepreneurial process. *Journal of Business Venturing*, 19, 203-220.
- BROWN, K. A., WILLIS, P. G. & PRUSSIA, G. E. 2000. Predicting safe employee behavior in the steel industry: Development and test of a sociotechnical model. *Journal of Operations Management*, 18, 445-465.
- BROWN, R. & HOLMES, H. 1986. The use of a factor-analytic procedure for assessing the validity of an employee safety climate model. *Accident Analysis & Prevention*, 18, 455-470.
- BRYANT, A. & CHARMAZ, K. 2010. *The SAGE Handbook of Grounded Theory: Paperback Edition*, SAGE Publications.
- BYRNE, B. M. 2004. Testing for multigroup invariance using AMOS graphics: A road less traveled. *Structural Equation Modeling*, 11, 272-300.
- BYRNE, B. M. 2009. *Structural equation modeling with AMOS: basic concepts, applications, and programming*, New York, Routledge.
- BYRNE, B. M. 2013. *Structural equation modeling with LISREL, PRELIS, and SIMPLIS: Basic concepts, applications, and programming*, Psychology Press.
- CAGLIANO, R., BLACKMON, K. & VOSS, C. 2001. Small firms under MICROSCOPE: international differences in production/operations management practices and performance. *Integrated Manufacturing Systems*, 12, 469-482.
- CAMPBELL, J. P., MCCLOY, R. A., OPPLER, S. H. & SAGER, C. E. 1993. A Theory of Performance. In: SCHMITT, N., BORMAN, W. C., INDUSTRIAL, S. F. & PSYCHOLOGY, O. (eds.) *Personnel selection in organizations*. Jossey-Bass.
- CARMINES, E. G. & ZELLER, R. A. 1979. *Reliability and validity assessment*, Sage publications.
- CARRILLO, R. A. 2011. Complexity and safety. *Journal of Safety Research*, 42, 293-300.
- CARTER, G. & SMITH, S. D. 2006. Safety Hazard Identification on Construction Projects. *Journal of Construction Engineering and Management*, 132, 197-205.
- CASSANO-PICHE, A. L., VICENTE, K. J. & JAMIESON, G. A. 2009. A test of Rasmussen's risk management framework in the food safety domain: BSE in the UK. *Theoretical Issues in Ergonomics Science*, 10, 283-304.
- CAVE, M. 1997. *The Use of Performance Indicators in Higher Education: The Challenge of the Quality Movement*, J. Kingsley Publishers.
- CELIK, M. & CEBI, S. 2009. Analytical HFACS for investigating human errors in shipping accidents. *Accident Analysis & Prevention*, 41, 66-75.
- CHAMPOUX, D. & BRUN, J.-P. 2003. Occupational health and safety management in small size enterprises: an overview of the situation and avenues for intervention and research. *Safety science*, 41, 301-318.
- CHARMAZ, K. 2006. *Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis*, SAGE Publications.
- CHECKLAND, P. 1981. *Systems thinking, systems practice*, J. Wiley.

- CHEN, C.-F. & CHEN, S.-C. 2014. Measuring the effects of Safety Management System practices, morality leadership and self-efficacy on pilots' safety behaviors: Safety motivation as a mediator. *Safety science*, 62, 376-385.
- CHEN, G.-X. & FOSBROKE, D. E. 1998. Work-related fatal-injury risk of construction workers by occupation and cause of death. *Human and Ecological Risk Assessment*, 4, 1371-1390.
- CHEUNG, G. W. & RENSVOLD, R. B. 2000. Assessing extreme and acquiescence response sets in cross-cultural research using structural equations modeling. *Journal of Cross-Cultural Psychology*, 31, 187-212.
- CHHOKAR, J. S. & WALLIN, J. A. 1984. Improving Safety through Applied Behavior Analysis. *Journal of Safety Research*, 15, 141-151.
- CHI, S., HAN, S. & KIM, D. 2013. Relationship between Unsafe Working Conditions and Workers' Behavior and Impact of Working Conditions on Injury Severity in U.S. Construction Industry. *Journal of construction engineering and management*, 139, 826-838.
- CHIN, W. W., MARCOLIN, B. L. & NEWSTED, P. R. 2003. A partial least squares latent variable modeling approach for measuring interaction effects: Results from a Monte Carlo simulation study and an electronic-mail emotion/adoption study. *Information systems research*, 14, 189-217.
- CHOUDHRY, R. M. & FANG, D. 2008a. Why operatives engage in unsafe work behavior: Investigating factors on construction sites. *Safety science*, 46, 566-584.
- CHOUDHRY, R. M., FANG, D. & AHMED, S. M. 2008. Safety management in construction: Best practices in Hong kong. *Journal of Professional Issues in Engineering Education and Practice*, 134, 20-32.
- CHOUDHRY, R. M., FANG, D. & LINGARD, H. 2009. Measuring safety climate of a construction company. *Journal of construction engineering and management*, 135, 890-899.
- CHOUDHRY, R. M., FANG, D. & MOHAMED, S. 2007. Developing a model of construction safety culture. *Journal of Management in Engineering*, 23, 207-212.
- CHOUDHRY, R. M. & FANG, D. P. 2008b. Why operatives engage in unsafe work behavior: Investigating factors on construction sites. *Safety Science*, 46, 566-584.
- CHRISTIAN, M. S., BRADLEY, J. C., WALLACE, J. C. & BURKE, M. J. 2009. Workplace safety: a meta-analysis of the roles of person and situation factors. *Journal of Applied Psychology*, 94, 1103.
- CIGULAROV, K. P., ADAMS, S., GITTLEMAN, J. L., HAILE, E. & CHEN, P. Y. 2013. Measurement equivalence and mean comparisons of a safety climate measure across construction trades. *Accident Analysis & Prevention*, 51, 68-77.
- CIPOLLA, D., BIGGS, H. C., DINGS DAG, D. & KIRK, P. J. 2009. *Safety Effectiveness Indicators Project Workbook*, Cooperative Research Centre for Construction Innovation.
- CLARKE, S. 2006. The relationship between safety climate and safety performance: a meta-analytic review. *Journal of occupational health psychology*, 11, 315.
- CLOQUELL-BALLESTER, V. A., CLOQUELL-BALLESTER, V. A., MONTERDE-DIAZ, R. & SANTAMARINA-SIURANA, M. C. 2006. Indicators validation for the improvement of environmental and social impact quantitative assessment. *Environmental Impact Assessment Review*, 26, 79-105.
- COHEN, A. & COLLIGAN, M. J. 1998. Assessing Occupational Safety and Health Training-A Literature Review. National Institute for Occupational Safety and Health (NIOSH).
- CONCHIE, S. M., MOON, S. & DUNCAN, M. 2013. Supervisors' engagement in safety leadership: Factors that help and hinder. *Safety Science*, 51, 109-117.
- COOKE, D. L. 2003. A system dynamics analysis of the Westray mine disaster. *System Dynamics Review*, 19, 139-166.
- COOKE, D. L. & ROHLEDER, T. R. 2006a. Learning from incidents: from normal accidents to high reliability. *System Dynamics Review*, 22, 213-240.

- COOKE, D. L. & ROHLEDER, T. R. 2006b. Learning from incidents: from normal accidents to high reliability. *System Dynamics Review*, 22, 213-239.
- COOPER, D. 1998. *Improving safety culture: a practical guide*, Wiley.
- COOPER, M. D. & PHILLIPS, R. A. 2004. Exploratory analysis of the safety climate and safety behavior relationship. *Journal of safety research*, 35, 497-512.
- CORBIN, J. M. & STRAUSS, A. L. 2008. *Basics of qualitative research: techniques and procedures for developing grounded theory*, Sage Publications, Inc.
- COSTELLA, M. F., SAURIN, T. A. & DE MACEDO GUIMARÃES, L. B. 2009. A method for assessing health and safety management systems from the resilience engineering perspective. *Safety Science*, 47, 1056-1067.
- COYLE, G. 2000. Qualitative and quantitative modelling in system dynamics: some research questions. *System Dynamics Review*, 16, 225-244.
- COYLE, I. R., SLEEMAN, S. D. & ADAMS, N. 1996. Safety climate. *Journal of Safety Research*, 26, 247-254.
- CRESWELL, J. W. 1998. *Qualitative inquiry and research design: choosing among five traditions*, Sage Publications.
- CUI, L., FAN, D., FU, G. & ZHU, C. J. 2013. An integrative model of organizational safety behavior. *Journal of Safety Research*, 45, 37-46.
- CURTIS, M. & PAGE, I. 2014. Small construction firms in New Zealand. In: 315, S. (ed.). BRANZ.
- DAINTY, A. & LOOSEMORE, M. 2013. *Human Resource Management in Construction Projects*, Routledge.
- DAVOUDIAN, K., WU, J.-S. & APOSTOLAKIS, G. 1994. The work process analysis model (WPAM). *Reliability Engineering & System Safety*, 45, 107-125.
- DEARMOND, S., SMITH, A. E., WILSON, C. L., CHEN, P. Y. & CIGULAROV, K. P. 2011. Individual safety performance in the construction industry: Development and validation of two short scales. *Accident Analysis and Prevention*, 43, 948-954.
- DECI, E. L. & FLASTE, R. 1996. *Why We Do what We Do: Understanding Self-motivation*, Penguin Books.
- DEDOBBELEER, N. & BELAND, F. 1991. A Safety Climate Measure for Construction Sites. *Journal of Safety Research*, 22, 97-103.
- DEDOBBELEER, N. & BÉLAND, F. 1991. A safety climate measure for construction sites. *Journal of Safety Research*, 22, 97-103.
- DEDOBBELEER, N. & GERMAN, P. 1987. Safety practices in construction industry. *Journal of Occupational and Environmental Medicine*, 29, 863-868.
- DEJOY, D. M. 2005. Behavior change versus culture change: Divergent approaches to managing workplace safety. *Safety Science*, 43, 105-129.
- DEKKER, S. 2006. *The Field Guide to Understanding Human Error*, Ashgate.
- DEKKER, S. 2011. *Drift into failure: from hunting broken components to understanding complex systems*, Ashgate Pub.
- DEKKER, S. 2013. *The Field Guide to Understanding Human Error: Second Edition*, Ashgate Publishing, Ltd.
- DEKKER, S., CILLIERS, P. & HOFMEYR, J.-H. 2011. The complexity of failure: Implications of complexity theory for safety investigations. *Safety Science*, 49, 939-945.
- DEKKER, S., HOLLNAGEL, E., WOODS, D. & COOK, R. 2008. Resilience Engineering: New directions for measuring and maintaining safety in complex systems. Lund University School of Aviation.
- DEKKER, S. W. 2002. Reconstructing human contributions to accidents: the new view on error and performance. *Journal of Safety Research*, 33, 371-385.
- DELERY, J. E. & DOTY, D. H. 1996. Modes of theorizing in strategic human resource management: Tests of universalistic, contingency, and configurational performance predictions. *Academy of management Journal*, 39, 802-835.

- DEPARTMENT OF EMPLOYMENT AND WORKPLACE RELATIONS 2005. Guidance for Small Business on the Use of Positive Performance Indicators.
- DEVELLIS, R. F. 2003. *Scale Development: Theory and Applications*, SAGE Publications.
- DEVELLIS, R. F. 2012. *Scale Development: Theory and Applications*, SAGE Publications.
- DINGS DAG, D. P., BIGGS, H. C. & CIPOLLA, D. Safety Effectiveness Indicators (SEI's): Measuring construction industry safety performance. In: THOMAS, J. & PIEKKALA-FLETCHER, A., eds. Third International Conference of the Cooperative Research Centre (CRC) for Construction Innovation – Clients Driving Innovation: Benefiting from Innovation, 2008 Gold Coast, Australia.
- DUBOIS, A. & GADDE, L.-E. 2001. The Construction Industry as a Loosely Coupled System-Implications for productivity and innovativity. *the 17th IMP Conference*. Oslo, Norway.
- DYREBORG, J. 2009. The causal relation between lead and lag indicators. *Safety Science*, 47, 474-475.
- EDWARDS, D. J. & HOLT, G. D. 2008. Construction workers' health and safety knowledge: Initial observations on some test-result data. *Journal of Engineering, Design and Technology*, 6, 65-80.
- EPRI 2000. Guidelines for trial use of leading indicators of human performance: the human performance assistance package. Palo Alto, CA: EPRI.
- ERIKSON, S. G. 2009. Performance indicators. *Safety Science*, 47, 468.
- FANG, D., CHEN, Y. & WONG, L. 2006. Safety Climate in Construction Industry: A Case Study in Hong Kong. *Journal of construction engineering and management*, 132, 573-584.
- FANG, D. & WU, H. 2013. Development of a Safety Culture Interaction (SCI) model for construction projects. *Safety science*, 57, 138-149.
- FANG, D. P., XIE, F., HUANG, X. Y. & LI, H. 2004. Factor analysis-based studies on construction workplace safety management in China. *International Journal of Project Management*, 22, 43-49.
- FENG, Y., ZHANG, S. & WU, P. 2015. Factors influencing workplace accident costs of building projects. *Safety Science*, 72, 97-104.
- FEWINGS, P. 2005. *Construction Project Management: An Integrated Approach*, Taylor & Francis.
- FLEMING, M. 2012a. Assessing Employee Safety Motivation.
- FLEMING, M. 2012b. Assessing Employee Safety Motivation. WorkSafe BC.
- FLIN, R., MEARNS, K., O'CONNOR, P. & BRYDEN, R. 2000a. Measuring safety climate: identifying the common features. *Safety Science*, 34, 177-192.
- FLIN, R., MEARNS, K., O'CONNOR, P. & BRYDEN, R. 2000b. Measuring safety climate: identifying the common features. *Safety science*, 34, 177-192.
- FLOOD, R. L. & CARSON, E. R. 1993. *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science*, Springer.
- FORD, A. & FLYNN, H. 2005. Statistical screening of system dynamics models. *System Dynamics Review*, 21, 273-303.
- FORRESTER, J. W. 1961. *Industrial dynamics*, Wiley.
- FORRESTER, J. W. 1980. Information sources for modeling the national economy. *Journal of the American Statistical Association*, 75, 555-566.
- FRUHEN, L. S., K.J., M., R., F. & B., K. 2013. Skills, knowledge and senior managers' demonstrations of safety commitment. *Safety Science*.
- GALLAGHER, C., UNDERHILL, E. & RIMMER, M. 2003a. Occupational safety and health management systems in Australia: barriers to success. *Policy and practice in health and safety*, 1.
- GALLAGHER, C., UNDERHILL, E. & RIMMER, M. 2003b. Occupational safety and health management systems in Australia: Barriers to success. *Policy and Practice in Health and Safety*, 1, 67-81.

- GELLER, E. S. 1999. Behavior-based safety: confusion, controversy, and clarification. *Occupational Health & Safety*, 68, 40-49.
- GELLER, E. S., PERDUE, S. R. & FRENCH, A. 2004. Behavior-Based Safety Coaching: 10 guidelines for successful application. *Professional Safety*, 49, 42-49.
- GHOBIADIAN, A. & GALLEAR, D. 1997. TQM and organization size. *International journal of operations & production management*, 17, 121-163.
- GILLEN, M., BALTZ, D., GASSEL, M., KIRSCH, L. & VACCARO, D. 2002. Perceived safety climate, job demands, and coworker support among union and nonunion injured construction workers. *Journal of Safety Research*, 33, 33-51.
- GLASER, B. G. & STRAUSS, A. L. 1967. *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Aldine.
- GLASER, B. G. & STRAUSS, A. L. 2009. *The discovery of grounded theory: Strategies for qualitative research*, Transaction Publishers.
- GLENDON, A. I. & LITHERLAND, D. K. 2001. Safety climate factors, group differences and safety behaviour in road construction. *Safety science*, 39, 157-188.
- GOH, Y. M., BROWN, H. & SPICKETT, J. 2010. Applying systems thinking concepts in the analysis of major incidents and safety culture. *Safety Science*, 48, 302-309.
- GOH, Y. M., LOVE, P. E., BROWN, H. & SPICKETT, J. 2012a. Organizational accidents: a systemic model of production versus protection. *Journal of Management Studies*, 49, 52-76.
- GOH, Y. M. & LOVE, P. E. D. 2012. Methodological application of system dynamics for evaluating traffic safety policy. *Safety Science*, 50, 1594-1605.
- GOH, Y. M., LOVE, P. E. D., BROWN, H. & SPICKETT, J. 2012b. Organizational Accidents: A Systemic Model of Production versus Protection. *Journal of Management Studies*, 49, 52-76.
- GOH, Y. M., LOVE, P. E. D., STAGBOUER, G. & ANNESLEY, C. 2012c. Dynamics of safety performance and culture: A group model building approach. *Accident Analysis and Prevention*, 48, 118-125.
- GOULD, F. E. & JOYCE, N. E. 2002. *Construction project management*, Prentice Hall.
- GRABOWSKI, M., AYYALASOMAYAJULA, P., MERRICK, J., HARRALD, J. R. & ROBERTS, K. 2007a. Leading indicators of safety in virtual organizations. *Safety Science*, 45, 1013-1043.
- GRABOWSKI, M., AYYALASOMAYAJULA, P., MERRICK, J. & MCCAFFERTY, D. 2007b. Accident precursors and safety nets: leading indicators of tanker operations safety. *Maritime Policy & Management*, 34, 405-425.
- GRIBBLE, A., MORTIMER, L. & SMITH, R. 2006. Occupational Health and Safety in New Zealand. Wellington: NOHSAC.
- GRIFFIN, M. A., HODKIEWICZ, M. R., DUNSTER, J., KANSE, L., PARKES, K. R., FINNERTY, D., CORDERY, J. L. & UNSWORTH, K. L. 2014. A conceptual framework and practical guide for assessing fitness-to-operate in the offshore oil and gas industry. *Accident Analysis & Prevention*, 68, 156-171.
- GRIFFIN, M. A. & NEAL, A. 2000. Perceptions of safety at work: a framework for linking safety climate to safety performance, knowledge, and motivation. *Journal of occupational health psychology*, 5, 347.
- GRIMM, V., ASHAUER, R., FORBES, V., HOMMEN, U., PREUSS, T. G., SCHMIDT, A., VAN DEN BRINK, P. J., WOGRAM, J. & THORBEEK, P. 2009. CREAM: a European project on mechanistic effect models for ecological risk assessment of chemicals. *Environmental Science and Pollution Research*, 16, 614-617.
- GULDENMUND, F. W. 2000. The nature of safety culture: a review of theory and research. *Safety science*, 34, 215-257.
- GUO, B. & YIU, T. W. How Traditional Construction Safety Performance Indicators Fail to Capture the Reality of Safety. In: YIU, T. W. & GONZALEZ, V., eds. The 38th Australasian Universities Building Education Association Conference, 2013 Auckland, New Zealand.

- GUO, B. & YIU, T. W. 2015. Developing Leading Indicators to Monitor the Safety Conditions of Construction Projects. *Journal of Management in Engineering*, 0, 04015016.
- GUO, B. H., YIU, T. W. & GONZÁLEZ, V. A. 2015a. Identifying behaviour patterns of construction safety using system archetypes. *Accident Analysis & Prevention*, 80, 125-141.
- GUO, B. H. W. & YIU, T. W. 2016. Developing Leading Indicators to Monitor the Safety Conditions of Construction Projects. *Journal of Management in Engineering*, 32, 04015016.
- GUO, B. H. W., YIU, T. W. & GONZÁLEZ, V. A. 2015b. Identifying behaviour patterns of construction safety using system archetypes. *Accident Analysis & Prevention*, 80, 125-141.
- GUO, B. H. W., YIU, T. W. & GONZÁLEZ, V. A. 2015c. A System Dynamics View of Safety Management in Small Construction Companies. *Journal of Construction Engineering and Project Management*, 5.
- GUO, B. H. W., YIU, T. W. & GONZÁLEZ, V. A. 2016. Predicting safety behavior in the construction industry: Development and test of an integrative model. *Safety Science*, 84, 1-11.
- GÜRCANLI, G. E. & MÜNGEN, U. 2009. An occupational safety risk analysis method at construction sites using fuzzy sets. *International Journal of Industrial Ergonomics*, 39, 371-387.
- HAADIR, S. A. & PANUWATWANICH, K. 2011. Critical Success Factors for Safety Program Implementation among Construction Companies in Saudi Arabia. *Procedia Engineering*, 14, 148-155.
- HAINES, V. Y., MERRHEIM, G. & ROY, M. 2001. Understanding reactions to safety incentives. *Journal of Safety Research*, 32, 17-30.
- HAIR, J., BLACK, W., BABIN, B. & ANDERSON, R. 2010. Multivariate data analysis. 7th ed2010. Upper Saddle River, NJ: Prentice Hall, Inc.
- HAIR, J. F. 2006. *Multivariate Data Analysis*, Pearson Prentice Hall.
- HALE, A. 2009. Why safety performance indicators? *Safety Science*, 47, 479-480.
- HALE, A., BORYS, D. & ADAMS, M. 2015. Safety regulation: the lessons of workplace safety rule management for managing the regulatory burden. *Safety science*, 71, 112-122.
- HALE, A. R. 2003. Safety management in production. *Human Factors and Ergonomics in Manufacturing*, 13, 185-201.
- HALE, A. R., BIANCHI, G., DUDKA, G., HAMEISTER, W., JONES, R., PERTTULA, P. & YTERHUS, I. 2005. Survey the Role of Safety Professionals: Objectives, Methods and Early Results. *Safety Science Monitor*.
- HALE, A. R., HEMING, B., CARTHEY, J. & KIRWAN, B. 1997a. Modelling of safety management systems. *Safety Science*, 26, 121-140.
- HALE, A. R., HEMING, B. H. J., CARTHEY, J. & KIRWAN, B. 1997b. Modelling of safety management systems. *Safety Science*, 26, 121-140.
- HALE, A. R. & HOVDEN, J. 1998. Management and culture: the third age of safety. A review of approaches to organizational aspects of safety, health and environment. *Occupational injury: Risk, prevention and intervention*, 129-165.
- HALLOWELL, M., HINZE, J., BAUD, K. & WEHLE, A. 2013. Proactive Construction Safety Control: Measuring, Monitoring, and Responding to Safety Leading Indicators. *Journal of Construction Engineering and Management*, 139.
- HALLOWELL, M. R. 2011. Safety-knowledge management in American construction organizations. *Journal of Management in Engineering*, 28, 203-211.
- HALLOWELL, M. R. & GAMBATESE, J. A. 2009. Construction Safety Risk Mitigation. *Journal of Construction Engineering and Management-Asce*, 135, 1316-1323.
- HAN, S., SABA, F., LEE, S., MOHAMED, Y. & PENA-MORA, F. 2014a. Toward an understanding of the impact of production pressure on safety performance in construction operations. *Accident Analysis and Prevention*, 68, 106-116.

- HAN, S., SABA, F., LEE, S., MOHAMED, Y. & PEÑA-MORA, F. 2013. Toward an understanding of the impact of production pressure on safety performance in construction operations. *Accident Analysis & Prevention*.
- HAN, S., SABA, F., LEE, S., MOHAMED, Y. & PEÑA-MORA, F. 2014b. Toward an understanding of the impact of production pressure on safety performance in construction operations. *Accident Analysis & Prevention*, 68, 106-116.
- HARDISON, D., BEHM, M., HALLOWELL, M. R. & FONOONI, H. 2014. Identifying construction supervisor competencies for effective site safety. *Safety science*, 65, 45-53.
- HARMS-RINGDAHL, L. 2009. Dimensions in safety indicators. *Safety Science*, 47, 481-482.
- HASLAM, R., HIDE, S., GIBB, A. G., GYI, D. E., PAVITT, T., ATKINSON, S. & DUFF, A. 2005a. Contributing factors in construction accidents. *Applied Ergonomics*, 36, 401-415.
- HASLAM, R. A., HIDE, S. A., GIBB, A. G. F., GYI, D. E., PAVITT, T., ATKINSON, S. & DUFF, A. R. 2005b. Contributing factors in construction accidents. *Applied Ergonomics*, 36, 401-415.
- HASLE, P. & LIMBORG, H. J. 2006. A review of the literature on preventive occupational health and safety activities in small enterprises. *Industrial health*, 44, 6-12.
- HECHANOVA-ALAMPAY, R. & BEEHR, T. A. 2001. Empowerment, span of control, and safety performance in work teams after workforce reduction. *Journal of Occupational Health Psychology*, 6, 275.
- HECKER, S. & GOLDENHAR, L. 2014. Understanding safety culture and safety climate in construction: Existing evidence and a path forward. *Silver Spring, MD: CPWR—The Center for Construction Research and Training*.
- HEINK, U. & KOWARIK, I. 2010. What are indicators? On the definition of indicators in ecology and environmental planning. *Ecological Indicators*, 10, 584-593.
- HEINRICH, H. W. 1931. *Industrial Accident Prevention: A Scientific Approach*, McGraw-Hill book Company, Incorporated.
- HINZE, J. 1997. *Construction Safety*, Prentice Hall PTR.
- HINZE, J. & FIGONE, L. 1988. Subcontractor safety as influenced by general contractors on small and medium sized projects.: Dept. of Civil Engineering, Univ. of Washington, Seattle.
- HINZE, J., HALLOWELL, M. & BAUD, K. 2013a. Construction-Safety Best Practices and Relationships to Safety Performance. *Journal of Construction Engineering and Management*, 139.
- HINZE, J., THURMAN, S. & WEHLE, A. 2013b. Leading indicators of construction safety performance. *Safety Science*, 51, 23-28.
- HODGE, B. J. 1996. *Organization theory: A strategic approach*, Pearson College Division.
- HOFMANN, D. A. & MORGESON, F. P. 1999. Safety-related behavior as a social exchange: The role of perceived organizational support and leader-member exchange. *Journal of Applied Psychology*, 84, 286-296.
- HOFMANN, D. A. & STETZER, A. 1996. A CROSS-LEVEL INVESTIGATION OF FACTORS INFLUENCING UNSAFE BEHAVIORS AND ACCIDENTS. *Personnel Psychology*, 49, 307-339.
- HOLLNAGEL, E. 2008a. Risk+barriers=safety? *Safety Science*, 46, 221-229.
- HOLLNAGEL, E. 2008b. Safety management, looking back or looking forward. In: HOLLNAGEL, E., NEMETH, C. P. & DEKKER, S. (eds.) *Resilient Engineering Perspectives*, . Aldershot: Ashgate.
- HOLLNAGEL, E. 2013. Is safety a subject for science? *Safety Science*.
- HOLTON, J. A. 2010. The Coding Process and Its Challenges. In: BRYANT, A. & CHARMAZ, K. (eds.) *The SAGE Handbook of Grounded Theory: Paperback Edition*. SAGE Publications.

- HON, C. K., CHAN, A. P. & YAM, M. C. 2012. Determining safety climate factors in the repair, maintenance, minor alteration, and addition sector of Hong Kong. *Journal of construction engineering and management*, 139, 519-528.
- HOPKINS, A. 2007. *Lessons from Gretley: Mindful Leadership and the Law*, CCH Australia, Limited.
- HOPKINS, A. 2009a. Reply to comments. *Safety Science*, 47, 508-510.
- HOPKINS, A. 2009b. Thinking about process safety indicators. *Safety Science*, 47, 460-465.
- HOVDEN, J., ALBRECHTSEN, E. & HERRERA, I. A. 2010. Is there a need for new theories, models and approaches to occupational accident prevention? *Safety Science*, 48, 950-956.
- HOWELL, G. A., BALLARD, G., ABDELHAMID, T. S. & MITROPOULOS, P. Working near the edge: A new approach to construction safety. The 10th Annual Conference of the International Group for Lean Construction, 2002 Brazil.
- HOYLE, R. H. 1995. The Structural Equation Modeling Approach. In: HOYLE, R. H. (ed.) *Structural Equation Modeling: Concepts, Issues, and Applications*.
- HOYLE, R. H. & PANTER, A. T. 1995. Writing About Structural Equation Models. In: HOYLE, R. H. (ed.) *Structural Equation Modeling: Concepts, Issues, and Applications*.
- HSE 2002. Evaluating the effectiveness of the Health and Safety Executive's Health and Safety Climate Survey Tool. Edinburgh, UK: Health and Safety Executive.
- HSE 2006. *Developing process safety indicators: A step-by-step guide for chemical and major hazard industries*, Health and Safety Executive.
- HSE(HEALTH AND SAFETY EXECUTIVE) 2006. *Developing process safety indicators: A step-by-step guide for chemical and major hazard industries*. Rugby: Health and Safety Executive.
- HSU, S. H., LEE, C. C., WU, M. C. & TAKANO, K. 2010. The influence of organizational factors on safety in Taiwanese high-risk industries. *Journal of Loss Prevention in the Process Industries*, 23, 646-653.
- HU, L.-T. & BENTLER, P. M. 1995. Evaluating model fit. In: HOYLE, R. H. (ed.) *Structural Equation Modeling: Concepts, Issues, and Applications*.
- HU, L. T. & BENTLER, P. M. 1999. Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal*, 6, 1-55.
- HU, Y., CHAN, A. P., LE, Y., JIANG, W.-P., XIE, L.-L. & HON, C. H. 2011. Improving megasite management performance through incentives: Lessons learned from the Shanghai Expo construction. *Journal of Management in Engineering*, 28, 330-337.
- HUANG, X. & HINZE, J. 2006. Owner's Role in Construction Safety. *Journal of Construction Engineering and Management*, 132, 164-173.
- HUDSON, P. T. W. 2009. Process indicators: Managing safety by the numbers. *Safety Science*, 47, 483-485.
- HUGHES, P. & FERRETT, E. 2011. *Introduction to Health and Safety in Construction* Oxon, Routledge.
- HUGHES, P. & FERRETT, E. 2012. *Introduction to Health and Safety in Construction*, Taylor & Francis.
- IAEA 2000. Operational safety performance indicators for nuclear power plants. Vienna, Austria: IAEA.
- IDRIS, M. A., DOLLARD, M. F., COWARD, J. & DORMANN, C. 2012. Psychosocial safety climate: Conceptual distinctiveness and effect on job demands and worker psychological health. *Safety Science*, 50, 19-28.
- IMRIYAS, K., PHENG, L. S. & TEO, E. A. L. 2007. A fuzzy knowledge-based system for premium rating of workers' compensation insurance for building projects. *Construction Management and Economics*, 25, 1177-1195.
- ISMAIL, Z., DOOSTDAR, S. & HARUN, Z. 2011. Factors influencing the implementation of a safety management system for construction sites. *Safety Science*.

- JANNADI, O. A. & ALMISHARI, S. 2003. Risk assessment in construction. *Journal of construction engineering and management*, 129.
- JAWAHAR-NESAN, L. & PRICE, A. 1997. Formulation of best practices for owner's representatives. *Journal of Management in Engineering*, 13, 44-51.
- JENSEN, S. Q., KYED, M., CHRISTENSEN, A.-D., BLOKSGAARD, L., HANSEN, C. D. & NIELSEN, K. J. 2014. A gender perspective on work-related accidents. *Safety Science*, 64, 190-198.
- JEONG, B. Y. 1998. Occupational deaths and injuries in the construction industry. *Applied Ergonomics*, 29, 355-360.
- JIANG, Z., FANG, D. & ZHANG, M. 2014. Understanding the Causation of Construction Workers' Unsafe Behaviors Based on System Dynamics Modeling. *Journal of Management in Engineering*, 0, 04014099.
- JOHNSON, S. E. 2007. The predictive validity of safety climate. *Journal of safety research*, 38, 511-521.
- JÖRESKOG, K. G. 1971. Simultaneous factor analysis in several populations. *Psychometrika*, 36, 409-426.
- JÖRESKOG, K. G. 1993. Testing structural equation models. *Sage focus editions*, 154, 294-294.
- JÖRESKOG, K. G. & SÖRBOM, D. 1993. *LISREL 8: Structural equation modeling with the SIMPLIS command language*, Scientific Software International.
- KAPP, E. 2012. The influence of supervisor leadership practices and perceived group safety climate on employee safety performance. *Safety science*, 50, 1119-1124.
- KAST, F. E. & ROSENZWEIG, J. E. 1979. *Organization and management: a systems and contingency approach*, McGraw-Hill.
- KJELLÉN, U. 2000. *Prevention of accidents through experience feedback*, London ; New York, Taylor & Francis.
- KJELLÉN, U. 2009. The safety measurement problem revisited. *Safety Science*, 47, 486-489.
- KLEINERT, H. L. & KEARNS, J. F. 1999. A validation study of the performance indicators and learner outcomes of Kentucky's alternate assessment for students with significant disabilities. *Research and Practice for Persons with Severe Disabilities*, 24, 100-110.
- KLETZ, T. A. 1997. Hazop—past and future. *Reliability Engineering & System Safety*, 55, 263-266.
- KOH, T. Y. & ROWLINSON, S. 2012. Relational approach in managing construction project safety: A social capital perspective. *Accident Analysis & Prevention*, 48, 134-144.
- KONTOGIANNIS, T. 2012. Modeling patterns of breakdown (or archetypes) of human and organizational processes in accidents using system dynamics. *Safety Science*, 50, 931-944.
- KÖRVERS, P. M. W. & SONNEMANS, P. J. M. 2008. Accidents: A discrepancy between indicators and facts! *Safety Science*, 46, 1067-1077.
- KYLE, B. 2013. Stop the bullying. *Build*. BRANZ.
- LAMM, F. 1999. *Occupational health & safety in Australian small business: what can be done to reduce the lack of awareness and raise the level of compliance in Australian small business?*, Industrial Relations Research Centre, University of New South Wales.
- LANE, D. C. & SMART, C. 1996. Reinterpreting 'generic structure': Evolution, application and limitations of a concept. *System Dynamics Review*, 12, 87-120.
- LAUFER, A. & LEDBETTER, W. B. 1986. Assessment of Safety Performance-Measures at Construction Sites. *Journal of Construction Engineering and Management-Asce*, 112, 530-542.
- LAWTON, R. & WARD, N. J. 2005. A systems analysis of the ladbroke grove rail crash. *Accident Analysis & Prevention*, 37, 235-244.
- LE COZE, J. C. 2005. Are organisations too complex to be integrated in technical risk assessment and current safety auditing? *Safety Science*, 43, 613-638.
- LE COZE, J. C. 2009. A taxonomy issue. *Safety Science*, 47, 490-490.

- LE COZE, J. C. 2013a. New models for new times. An anti-dualist move. *Safety Science*, 59, 200-218.
- LE COZE, J. C. 2013b. Outlines of a sensitising model for industrial safety assessment. *Safety Science*, 51, 187-201.
- LEE, J., HUANG, Y.-H., MURPHY, L. A., ROBERTSON, M. M. & GARABET, A. 2015. Measurement equivalence of a safety climate scale across multiple trucking companies. *Journal of Occupational and Organizational Psychology*, n/a-n/a.
- LEGG, S., BATTISTI, M., HARRIS, L., LAIRD, I., LAMM, F., MASSEY, C. & OLSEN, K. 2009. Occupational Health and Safety in Small Business. NOHSAC, Technical report 12.
- LEGG, S., OLSEN, K., LAIRD, I. & HASLE, P. 2015. Managing safety in small and medium enterprises. *Safety Science*, 71, 189-196.
- LEHR, J. K. & RICE, R. E. 2002. Organizational measures as a form of knowledge management: A multitheoretic, communication-based exploration. *Journal of the American Society for Information Science and Technology*, 53, 1060-1073.
- LENNÉ, M. G., SALMON, P. M., LIU, C. C. & TROTTER, M. 2012. A systems approach to accident causation in mining: An application of the HFACS method. *Accident Analysis & Prevention*, 48, 111-117.
- LEU, S.-S. & CHANG, C.-M. 2013. Bayesian-network-based safety risk assessment for steel construction projects. *Accident Analysis & Prevention*, 54, 122-133.
- LEVESON, N. 2004. A new accident model for engineering safer systems. *Safety Science*, 42, 237-270.
- LEVESON, N. G. 2012. Complexity and Safety. In: HAMMAMI, O., KROB, D. & VOIRIN, J. L. (eds.) *Complex Systems Design & Management: Proceedings of the Second International Conference on Complex Systems Design & Management Csdm 2011* Springer.
- LEVINE, R. L. System Dynamics Applied To Psychological and Social Problems. In: DAVIDSEN, P. I., FORD, D. N. & MASHAYEKHI, A. N., eds. The 18th International Conference of The System Dynamics Society, 2000 Bergen, Norway. The System Dynamics Society.
- LEWIS, C. D. 1982. *Industrial and business forecasting methods: A practical guide to exponential smoothing and curve fitting*, Butterworth-Heinemann.
- LIAO, P., LEI, G., XUE, J. & FANG, D. 2013. Influence of Person-Organizational Fit on Construction Safety Climate. *Journal of Management in Engineering*, 04014049.
- LINGARD, H., COOKE, T. & BLISMAS, N. 2011. Coworkers' response to occupational health and safety: An overlooked dimension of group-level safety climate in the construction industry? *Engineering, Construction and Architectural Management*, 18.
- LINGARD, H., COOKE, T. & BLISMAS, N. 2012. Do Perceptions of Supervisors' Safety Responses Mediate the Relationship between Perceptions of the Organizational Safety Climate and Incident Rates in the Construction Supply Chain? *Journal of Construction Engineering and Management*, 138, 234-241.
- LINGARD, H. & HOLMES, N. 2001. Understandings of occupational health and safety risk control in small business construction firms: barriers to implementing technological controls. *Construction Management & Economics*, 19, 217-226.
- LINGARD, H. C., COOKE, T. & BLISMAS, N. 2010. Safety climate in conditions of construction subcontracting: a multi-level analysis. *Construction Management and Economics*, 28, 813-825.
- LOOSEMORE, M. 1998. Psychology of accident prevention in the construction industry. *Journal of Management in Engineering*, 14, 50-56.
- LOWRY, P. B., GASKIN, J., TWYMAN, N., HAMMER, B. & ROBERTS, T. 2012. Taking 'Fun and Games' Seriously: Proposing the Hedonic-Motivation System Adoption Model (HMSAM). *Journal of the Association for Information Systems*, 14, 617-671.
- LU, C.-S. & SHANG, K.-C. 2005. An empirical investigation of safety climate in container terminal operators. *Journal of Safety Research*, 36, 297-308.

- LUNA-REYES, L. F. & ANDERSEN, D. L. 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review*, 19, 271-296.
- LUNT, J., BATES, S., BENNETT, V. & HOPKINSON, J. 2008. Behaviour change and worker engagement practices within the construction sector. *Prepared by the Health and Safety Laboratory for the Health and Safety Executive (HSE)* <http://www.hse.gov.uk/research>.
- MA, Q. & YUAN, J. 2009. Exploratory study on safety climate in Chinese manufacturing enterprises. *Safety Science*, 47, 1043-1046.
- MAANI, K. E. & MAHARAJ, V. 2004. Links between systems thinking and complex decision making. *System Dynamics Review*, 20, 21-48.
- MACCALLUM, R. C. 1995. Model specification *In*: HOYLE, R. H. (ed.) *Structural Equation Modeling: Concepts, Issues, and Applications*.
- MACCALLUM, R. C., BROWNE, M. W. & SUGAWARA, H. M. 1996. Power analysis and determination of sample size for covariance structure modeling. *Psychological methods*, 1, 130.
- MAHER, R. 2009. Value for the principal. *Safeguard*.
- MAIER, N. R. F. 1955. *Psychology in Industry*, Houghton Mifflin.
- MAN, T. W., LAU, T. & CHAN, K. 2002. The competitiveness of small and medium enterprises: A conceptualization with focus on entrepreneurial competencies. *Journal of Business Venturing*, 17, 123-142.
- MARAIS, K., SALEH, J. H. & LEVESON, N. G. 2006. Archetypes for organizational safety. *Safety Science*, 44, 565-582.
- MARTIN, P. Y. & TURNER, B. A. 1986. Grounded Theory and Organizational Research. *Journal of Applied Behavioral Science*, 22, 141-157.
- MARTORELL, S., SANCHEZ, A., MUNOZ, A., PITARCH, J., SERRADELL, V. & ROLDAN, J. 1999. The use of maintenance indicators to evaluate the effects of maintenance programs on NPP performance and safety. *Reliability Engineering & System Safety*, 65, 85-94.
- MARUYAMA, G. 1997. *Basics of structural equation modeling*, Sage.
- MASI, D. & CAGNO, E. 2015. Barriers to OHS interventions in Small and Medium-sized Enterprises. *Safety Science*, 71, 226-241.
- MAYER, D. G. & BUTLER, D. G. 1993. Statistical Validation. *Ecological Modelling*, 68, 21-32.
- MCDONALD, M. A., LIPSCOMB, H. J., BONDY, J. & GLAZNER, J. 2009. "Safety is everyone's job." The key to safety on a large university construction site. *Journal of safety research*, 40, 53-61.
- MCVITTIE, D., BANIKIN, H. & BROCKLEBANK, W. 1997. The effects of firm size on injury frequency in construction. *Safety Science*, 27, 19-23.
- MEADOWS, D. & RANDERS, J. 2004. *Limits to Growth: The 30-Year Update*, Chelsea Green Publishing.
- MEARNS, K. 2009. From reactive to proactive - Can LPIs deliver? *Safety Science*, 47, 491-492.
- MEARNS, K. & READER, T. 2008. Organizational support and safety outcomes: An un-investigated relationship? *Safety Science*, 46, 388-397.
- MELIÁ, J. L., MEARNS, K., SILVA, S. A. & LIMA, M. L. 2008. Safety climate responses and the perceived risk of accidents in the construction industry. *Safety Science*, 46, 949-958.
- MEREDITH, W. 1993. Measurement invariance, factor analysis and factorial invariance. *Psychometrika*, 58, 525-543.
- MICHAEL, J. H., EVANS, D. D., JANSEN, K. J. & HAIGHT, J. M. 2005. Management commitment to safety as organizational support: Relationships with non-safety outcomes in wood manufacturing employees. *Journal of Safety Research*, 36, 171-179.

- MINCHIN JR, R. E., GLAGOLA, C. R., GUO, K. & LANGUELL, J. L. 2006. Case for drug testing of construction workers. *Journal of Management in Engineering*, 22, 43-50.
- MINISTRY OF BUSINESS INNOVATION & EMPLOYMENT 2013. Construction report.
- MINISTRY OF BUSINESS INNOVATION & EMPLOYMENT 2014. Working Safer: Progress towards the 2020 target.
- MINISTRY OF BUSINESSES, I. E. 2014. The Small Business Sector Report 2014.
- MITROPOULOS, P., ABDELHAMID, T. S. & HOWELL, G. A. 2005. Systems Model of Construction Accident Causation. *Journal of construction engineering and management*, 131.
- MITROPOULOS, P. & CUPIDO, G. 2009. The role of production and teamwork practices in construction safety: A cognitive model and an empirical case study. *Journal of Safety Research*, 40, 265-275.
- MOHAGHEGH, Z. & MOSLEH, A. 2009a. Incorporating organizational factors into probabilistic risk assessment of complex socio-technical systems: Principles and theoretical foundations. *Safety Science*, 47, 1139-1158.
- MOHAGHEGH, Z. & MOSLEH, A. 2009b. Measurement techniques for organizational safety causal models: Characterization and suggestions for enhancements. *Safety Science*, 47, 1398-1409.
- MOHAMED, S. 2002. Safety climate in construction site environments. *Journal of construction engineering and management*, 128, 375-384.
- MOIZER, J. D., ARTHUR, D. & MOFFATT, I. A formal but non-automated method to test the sensitivity of system dynamics models. Proceedings of the 19th International Conference of the System Dynamics Society, 2001. 23-27.
- MOLENAAR, K. R., PARK, J.-I. & WASHINGTON, S. 2009. Framework for measuring corporate safety culture and its impact on construction safety performance. *Journal of Construction Engineering and Management*, 135, 488-496.
- MOORKAMP, M., KRAMER, E.-H., VAN GULIJK, C. & ALE, B. 2014. Safety management theory and the expeditionary organization: A critical theoretical reflection. *Safety Science*, 69, 71-81.
- MORGAN, G. 1997. Images of organization. *SAGE Publications. California–USA*.
- MORSE, J. M. 2010. Sampling in Grounded Theory. In: BRYANT, A. & CHARMAZ, K. (eds.) *The SAGE Handbook of Grounded Theory: Paperback Edition*. SAGE Publications.
- MULLEN, J. 2004. Investigating factors that influence individual safety behavior at work. *Journal of Safety Research*, 35, 275-285.
- NATIONAL OCCUPATIONAL HEALTH & SAFETY 1999. OHS Performance Measurement in the Construction Industry-Development of Positive Performance Indicators. Canberra: AusInfo.
- NEAL, A. & GRIFFIN, M. 2004. Safety climate and safety at work. In: BARLING, J. & FRONE, M. R. (eds.) *The Psychology of Workplace Safety*.: Psychological Association, United States,.
- NEAL, A. & GRIFFIN, M. A. 2006. A study of the lagged relationships among safety climate, safety motivation, safety behavior, and accidents at the individual and group levels. *Journal of Applied Psychology*, 91, 946-953.
- NEAL, A., GRIFFIN, M. A. & HART, P. M. 2000. The impact of organizational climate on safety climate and individual behavior. *Safety Science*, 34, 99-109.
- NEW ZEALAND CONSTRUCTION INDUSTRY COUNCIL 2004. Best Practice Procurement in Construction and Infrastructure in New Zealand.
- OECD 1993. Core Set of Indicators for Environmental Performance Reviews. Paris, France: OECD.
- OECD 2008. Guidance on Developing Safety Performance Indicators Related to Chemical Accident Prevention, Preparedness and Response for Industry 2nd Edition ed. Paris.
- ØIEN, K. 2001a. A framework for the establishment of organizational risk indicators. *Reliability Engineering & System Safety*, 74, 147-167.

- ØIEN, K. 2001b. *Risk Control of Offshore Installations. A Framework for the Establishment of Risk Indicators*. Doctoral dissertation, University of Science and Technology (NTNU).
- ØIEN, K. 2008. Development of Early Warning Indicators based on Accident Investigation. *International Probabilistic Safety Assessment and Management Conference PSAM9*. Hong Kong, China.
- ØIEN, K., MASSAIU, S., TINMANN SVIK, R. K. & STØRSETH, F. 2010. Development of Early Warning Indicators based on Resilience Engineering *International Probabilistic Safety Assessment and Management Conference*. Seattle, USA.
- ØIEN, K., UTNE, I. B. & HERRERA, I. A. 2011a. Building Safety indicators: Part 1 - Theoretical foundation. *Safety Science*, 49, 148-161.
- ØIEN, K., UTNE, I. B., TINMANN SVIK, R. K. & MASSAIU, S. 2011b. Building Safety indicators: Part 2 - Application, practices and results. *Safety Science*, 49, 162-171.
- OLSEN, N. S. & SHORROCK, S. T. 2010. Evaluation of the HFACS-ADF safety classification system: Inter-coder consensus and intra-coder consistency. *Accident Analysis & Prevention*, 42, 437-444.
- OZMEC, M., KARLSEN, I., KINES, P., ANDERSEN, L. & NIELSEN, K. J. 2015. Negotiating safety practice in small construction companies. *Safety Science*, 71, 275-281.
- PARKER, S. K., AXTELL, C. M. & TURNER, N. 2001. Designing a Safer Workplace: Importance of Job Autonomy, Communication Quality, and Supportive Supervisors. *Journal of Occupational Health Psychology*, Volume 6(3).
- PATTERSON, J. M. & SHAPPELL, S. A. 2010. Operator error and system deficiencies: analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS. *Accident Analysis & Prevention*, 42, 1379-1385.
- PATTON, M. Q. 2002. *Qualitative Research & Evaluation Methods*, SAGE Publications.
- PELLICER, E. & MOLENAAR, K. R. 2009. Discussion of "Developing a Model of Construction Safety Culture" by Rafiq M. Choudhry, Dongping Fang, and Sherif Mohamed. *Journal of Management in Engineering*, 25, 44-45.
- PEREZGONZALEZ, J. 2005. *Construction Safety Management, A Systems Approach (Knowledge Management Edition)*, Lulu.com.
- PERLMAN, A., SACKS, R. & BARAK, R. 2014. Hazard recognition and risk perception in construction. *Safety Science*, 64, 22-31.
- PINTO, A. 2014. QRAM a qualitative occupational safety risk assessment model for the construction industry that incorporate uncertainties by the use of fuzzy sets. *Safety Science*, 63, 57-76.
- PINTO, A., NUNES, I. L. & RIBEIRO, R. A. 2011. Occupational risk assessment in construction industry – Overview and reflection. *Safety Science*, 49, 616-624.
- POUSETTE, A., LARSSON, S. & TÖRNER, M. 2008. Safety climate cross-validation, strength and prediction of safety behaviour. *Safety Science*, 46, 398-404.
- PRUSSIA, G. E., BROWN, K. A. & WILLIS, P. G. 2003. Mental models of safety: do managers and employees see eye to eye? *Journal of Safety Research*, 34, 143-156.
- PUGH, D. S. & WEBER, M. 1971. *Organization theory: selected readings*, Penguin.
- RASMUSSEN, J. 1997. Risk management in a dynamic society: A modelling problem. *Safety Science*, 27, 183-213.
- RASMUSSEN, J., SVEDUNG, R. & SVEDUNG, I. 2000. *Proactive Risk Management in a Dynamic Society*, Swedish Rescue Services Agency.
- RAYKOV, T. 2004. Behavioral scale reliability and measurement invariance evaluation using latent variable modeling. *Behavior Therapy*, 35, 299-331.
- REASON, J. 2000. Human error: models and management. *British Medical Journal*, 320, 768-770.
- REASON, J. T. 1997. *Managing the risks of organizational accidents*, Ashgate.
- REIMAN, T. & PIETIKAINEN, E. 2012. Leading indicators of system safety - Monitoring and driving the organizational safety potential. *Safety Science*, 50, 1993-2000.

- REIMAN, T. & ROLLENHAGEN, C. 2014. Does the concept of safety culture help or hinder systems thinking in safety? *Accident Analysis & Prevention*, 68, 5-15.
- RICHMOND, B. System dynamics/systems thinking: Let's just get on with it. International Systems Dynamics Conference, Sterling, Scotland, 1994.
- ROCHLIN, G. I. 1999. Safe operation as a social construct. *Ergonomics*, 42, 1549-1560.
- RODRIGUES, M. A., AREZES, P. & LEÃO, C. 2015. Safety climate and its relationship with furniture companies' safety performance and workers' risk acceptance. *Theoretical Issues in Ergonomics Science*, 16, 412-428.
- ROELEN, A., WEVER, R., HALE, A., GOOSSESNS, L., COOKE, R., LOPUHAA, R., SIMONS, M. & VALK, P. 2003. Causal modeling for integrated safety at airports. Safety and reliability. *Swets & Zeitlinger, Lisse. ISBN, 90, 551.*
- ROWLINSON, S. 2004. *Construction Safety Management Systems*, Taylor & Francis.
- ROWLINSON, S., MOHAMED, S. & LAM, S.-W. 2003. Hong Kong construction foremen's safety responsibilities: a case study of management oversight. *Engineering, Construction and Architectural Management*, 10, 27-35.
- ROYAL COMMISSION ON THE PIKE RIVER COAL MINE TRAGEDY 2012. Royal Commission on the Pike River Coal Mine Tragedy-Part 1+What happened at Pike River. Wellington, New Zealand.
- ROZENFELD, O., SACKS, R., ROSENFELD, Y. & BAUM, H. 2010. Construction Job Safety Analysis. *Safety Science*, 48, 491-498.
- RUBENOWITZ, S. 1997. Survey and intervention of ergonomic problems at the workplace. *International Journal of Industrial Ergonomics*, 19, 271-275.
- RUNDMO, T., HESTAD, H. & ULLEBERG, P. 1998. Organisational factors, safety attitudes and workload among offshore oil personnel. *Safety Science*, 29, 75-87.
- SALGE, M. & MILLING, P. M. 2006. Who is to blame, the operator or the designer? Two stages of human failure in the Chernobyl accident. *System Dynamics Review*, 22, 89-112.
- SALMON, P. M., CORNELISSEN, M. & TROTTER, M. J. 2012. Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP. *Safety Science*, 50, 1158-1170.
- SAMPSON, J. M., DEARMOND, S. & CHEN, P. Y. 2014a. Role of safety stressors and social support on safety performance. *Safety Science*, 64, 137-145.
- SAMPSON, J. M., DEARMOND, S. & CHEN, P. Y. 2014b. Role of safety stressors and social support on safety performance. *Safety Science*, 64, 137-145.
- SANTOS-REYES, J. & BEARD, A. N. 2009. A systemic analysis of the Edge Hill railway accident. *Accident Analysis & Prevention*, 41, 1133-1144.
- SAURIN, T. A., FORMOSO, C. T. & CAMBRAIA, F. B. 2005. Analysis of a safety planning and control model from the human error perspective. *Engineering, Construction and Architectural Management*, 12, 283-298.
- SAURIN, T. A., FORMOSO, C. T. & CAMBRAIA, F. B. 2008a. An analysis of construction safety best practices from a cognitive systems engineering perspective. *Safety Science*, 46, 1169-1183.
- SAURIN, T. A., FORMOSO, C. T. & CAMBRALA, F. B. 2008b. An analysis of construction safety best practices from a cognitive systems engineering perspective. *Safety Science*, 46, 1169-1183.
- SAWACHA, E., NAOUM, S. & FONG, D. 1999. Factors affecting safety performance on construction sites. *International Journal of Project Management*, 17, pp.309-315.
- SCHIRNDING, Y. V. 2002. Health in Sustainable Development Planning: The Role of Indicators. World Health Organization.
- SENGE, P. M. 1980. Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences*, 14, 209-228.
- SENGE, P. M. 1990. *The Fifth Discipline: The Art and Practice of the Learning Organization*, Doubleday/Currency.
- SEO, D. C. 2005. An explicative model of unsafe work behavior. *Safety Science*, 43, 187-211.

- SEXTON, M. & BARRETT, P. 2003. Appropriate innovation in small construction firms. *Construction management and economics*, 21, 623-633.
- SGOUROU, E., KATSAKIORI, P., GOUTSOS, S. & MANATAKIS, E. 2010. Assessment of selected safety performance evaluation methods in regards to their conceptual, methodological and practical characteristics. *Safety Science*, 48, 1019-1025.
- SHAPPELL, A. S. & WIEGMANN, A. D. 2000. The Human Factors Analysis and Classification System-HFACS. Washington,DC.
- SHIN, M., LEE, H. S., PARK, M., MOON, M. & HAN, S. 2014. A system dynamics approach for modeling construction workers' safety attitudes and behaviors. *Accident Analysis and Prevention*, 68, 95-105.
- SITE SAFE NEW ZEALAND. 2012a. *Construction Safety Charter Accreditation* <<http://www.sitesafe.org.nz/Charter>> (Jun. 6, 2014). [Online].
- SITE SAFE NEW ZEALAND. 2012b. *Toolbox Talks* <<https://www.sitesafe.org.nz/toolboxtalks>> (May. 6, 2014). [Online].
- SMITH, G. & ROTH, R. 1991. Safety programs and the construction manager. *Journal of construction engineering and management*, 117, 360-371.
- SMITH, M. J. & CARAYON, P. 2009. Using the 'Balance Model' for occupational safety and health promotion. *Ergonomics and Health Aspects of Work with Computers*. Springer.
- SNOOK, S. A. 2002. *Friendly fire: The accidental shutdown of US Black Hawks over northern Iraq*, Princeton university press.
- SØRENSEN, O. H., HASLE, P. & BACH, E. 2007. Working in small enterprises—Is there a special risk? *Safety Science*, 45, 1044-1059.
- SOUACACOU, E. & SYLVA, K. 2010a. Developing Observation Instruments and Arriving at Inter-rater Reliability for a Range of Contexts and Raters: The Early Childhood Environment Rating Scales. In: WALFORD, G., TUCKER, E. & VISWANATHAN, M. (eds.) *The SAGE Handbook of Measurement*. SAGE Publications.
- SOUACACOU, E. & SYLVA, K. 2010b. Developing observation instruments and arriving at inter-rater reliability for a range of contexts and raters: The early childhood environment rating scales. In: G. WALFORD, E. TUCKER & VISWANATHAN, M. (eds.) *The sage handbook of measurement*. . London: Sage.
- STATISTICS NEW ZEALAND 2013. Injury Statistics – Work-related Claims: 2013 – trends tables for 2002–12 In: ZEALAND, S. N. (ed.).
- STEIGER, J. H., SHAPIRO, A. & BROWNE, M. W. 1985. On the multivariate asymptotic distribution of sequential chi-square statistics. *Psychometrika*, 50, 253-263.
- STEP CHANGE IN SAFETY. 2014. *Leading Performance Indicators: Guidance for Effective Use* [Online]. Available: <http://www.stepchangeinsafety.net/knowledgecentre/publications/publication.cfm/publicationid/26> [Accessed June, 6 2014].
- STERMAN, J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill.
- STERMAN, J. D. 1984. Appropriate summary statistics for evaluating the historical fit of system dynamics models. *Dynamica*, 10, 51-66.
- STROPPA, C. & SPIEB, E. 2010. Expatriates social networks: the role of company size. *The International Journal of Human Resource Management*, 21, 2306-2322.
- SUN, Y., FANG, D. P., WANG, S. Q., DAI, M. D. & LV, X. Q. 2008. Safety risk identification and assessment for Beijing Olympic venues construction. *Journal of Management in Engineering*, 24, 40-47.
- SURAJI, A., DUFF, A. R. & PECKITT, S. J. 2001. Development of causal model of construction accident causation. *Journal of construction engineering and management*.
- SWUSTE, P. & ARNOLDY, F. 2003. The safety adviser/manager as agent of organisational change: a new challenge to expert training. *Safety Science*, 41, 15-27.

- TAYLOR, D. C., MOHAMED, Z. A., SHAMSUDIN, M. N., MOHAYIDIN, M. G. & CHIEW, E. F. 1993. Creating a farmer sustainability index: a Malaysian case study. *American Journal of Alternative Agriculture*, 8, 175-184.
- THE ACCIDENT COMPENSATION CORPORATION 2014. Workplace Safety Discount Application. ACC.
- THE MINISTRY OF BUSINESS INNOVATION & EMPLOYMENT (MBIE) 2014. Small Business Factsheet 2014. In: THE MINISTRY OF BUSINESS, I. A. E. (ed.).
- THEIL, H. 1966. *Applied economic forecasting*, Amsterdam, North-Holland Publishing Company.
- TOELLNER, J. 2001. Improving safety & health performance: Identifying & measuring leading indicators. *Professional Safety*, 46, 42-47.
- TOOLE, T. M. 2002. Construction Site Safety Roles. *Journal of construction engineering and management*, 128, 203-210.
- TÖRNER, M. & POUSETTE, A. 2009. Safety in construction – a comprehensive description of the characteristics of high safety standards in construction work, from the combined perspective of supervisors and experienced workers. *Journal of Safety Research*, 40, 399-409.
- TSUCHIYA, S., TANABE, A., NARUSHIMA, T., ITO, K. & YAMAZAKI, K. An analysis of Tokaimura nuclear criticality accident: A systems approach. The 19th International Conference of the System Dynamics Society, System Dynamics Society, Atlanta, Georgia, 2001.
- TUCKER, L. R. & LEWIS, C. 1973. A reliability coefficient for maximum likelihood factor analysis. *Psychometrika*, 38, 1-10.
- U.S. CENSUS BUREAU 2011. Statistics about business size (including small business) from the U.S. Census Bureau.
- ULLMAN, J. B. & BENTLER, P. M. 2003. *Structural equation modeling*, Wiley Online Library.
- UNDERWOOD, P. & WATERSON, P. 2013. Systemic accident analysis: examining the gap between research and practice. *Accident Analysis & Prevention*, 55, 154-164.
- UNDERWOOD, P. & WATERSON, P. 2014. Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models. *Accident Analysis & Prevention*, 68, 75-94.
- VAN DOOREN, W. 2011. Better Performance Management: Some Single- and Double-Loop Strategies. *Public Performance & Management Review*, 34, 420-433.
- VANDENBERG, R. J. & LANCE, C. E. 2000. A review and synthesis of the measurement invariance literature: Suggestions, practices, and recommendations for organizational research. *Organizational research methods*, 3, 4-70.
- VELTRI, A. 1990. An accident cost impact model: The direct cost component. *Journal of Safety Research*, 21, 67-73.
- VICENTE, K. J. & CHRISTOFFERSEN, K. 2006. The Walkerton E. coli outbreak: a test of Rasmussen's framework for risk management in a dynamic society. *Theoretical Issues in Ergonomics Science*, 7, 93-112.
- VINNEM, J. Use of performance indicators for monitoring HSE operating achievement. Proceedings of ESREL, 1998. 127-35.
- VINNEM, J. E. 2010. Risk indicators for major hazards on offshore installations. *Safety Science*, 48, 770-787.
- VINNEM, J. E., AVEN, T., HUSEBØ, T., SELJELID, J. & TVEIT, O. J. 2006. Major hazard risk indicators for monitoring of trends in the Norwegian offshore petroleum sector. *Reliability Engineering & System Safety*, 91, 778-791.
- VINODKUMAR, M. & BHASI, M. 2009. Safety climate factors and its relationship with accidents and personal attributes in the chemical industry. *Safety Science*, 47, 659-667.

- VINODKUMAR, M. N. & BHASI, M. 2010. Safety management practices and safety behaviour: Assessing the mediating role of safety knowledge and motivation. *Accident Analysis and Prevention*, 42, 2082-2093.
- VISWANATHAN, M. 2005. *Measurement Error and Research Design*, SAGE Publications.
- VROOM, V. H. 1964. *Work and Motivation*, John Wiley & Sons, Inc.
- WACHTER, J. K. & YORIO, P. L. 2014a. A system of safety management practices and worker engagement for reducing and preventing accidents: An empirical and theoretical investigation. *Accident Analysis and Prevention*, 68, 117-130.
- WACHTER, J. K. & YORIO, P. L. 2014b. A system of safety management practices and worker engagement for reducing and preventing accidents: An empirical and theoretical investigation. *Accident Analysis & Prevention*, 68, 117-130.
- WACHTER, J. K. & YORIO, P. L. 2014c. A system of safety management practices and worker engagement for reducing and preventing accidents: An empirical and theoretical investigation. *Accident Analysis & Prevention*, 68, 117-130.
- WAEHRER, G. M., DONG, X. W. S., MILLER, T., HAILE, E. & MEN, Y. 2007. Costs of occupational injuries in construction in the United States. *Accident Analysis and Prevention*, 39, 1258-1266.
- WAHLSTRÖM, B. & ROLLENHAGEN, C. 2014. Safety management – A multi-level control problem. *Safety Science*, 69, 3-17.
- WALZ, R. 2000. Development of environmental indicator systems: experiences from Germany. *Environmental Management*, 25, 613-623.
- WAMUZIRI, S. Improving safety performance in construction through cultural change. 24th Annual, 2008.
- WEBB, P. 2009. Process safety performance indicators: A contribution to the debate. *Safety Science*, 47, 502-507.
- WELLS, J. & HAWKINS, J. 2014. Promoting Construction Health and Safety through Procurement: A briefing note for developing countries. Institution of Civil Engineers.
- WEWERS, M. E. & LOWE, N. K. 1990. A critical review of visual analogue scales in the measurement of clinical phenomena. *Research in nursing & health*, 13, 227-236.
- WHEATON, D. 1977. Assessing reliability and stability in panel models. *Sociological methodology*.
- WILSON, J. M. & KOEHN, E. E. 2000. Safety management: problems encountered and recommended solutions. *Journal of construction engineering and management*, 126, 77-79.
- WILSON, R. 2012. *Health and Safety in Employment: Act and Analysis*, Thomson Reuters.
- WIRTH, O. & SIGURDSSON, S. O. 2008. When workplace safety depends on behavior change: Topics for behavioral safety research. *Journal of Safety Research*, 39, 589-598.
- WOLSTENHOLME, E. F. 1999. Qualitative vs quantitative modelling: the evolving balance. *Journal of the Operational Research Society*, 50, 422-428.
- WOLSTENHOLME, E. F. 2003. Towards the definition and use of a core set of archetypal structure in system dynamics. *System Dynamics Review*, 19, 7-26.
- WOODS, D. 2009. Escaping failures of foresight. *Safety Science*, 47.
- WREATHALL, J. 2009. Leading? Lagging? Whatever! *Safety Science*, 47, 493-494.
- WU, T. C. 2011. The roles and functions of safety professionals in Taiwan: Comparing the perceptions of safety professionals and safety educators. *Journal of Safety Research*, 42, 399-407.
- WYER, P. & MASON, J. 1999. Empowerment in small businesses. *Participation and Empowerment: An International Journal*, 7, 180-193.
- YIN, R. K. 2003. *Case study research: Design and methods*, London, Sage publications.
- YOUNG, S. 1996. Construction safety: a vision for the future. *Journal of Management in Engineering*, 12, 33-36.

- ZHOU, Q., FANG, D. & MOHAMED, S. 2010. Safety climate improvement: case study in a Chinese construction company. *Journal of Construction Engineering and Management*, 137, 86-95.
- ZHOU, Z., GOH, Y. M. & LI, Q. 2015. Overview and analysis of safety management studies in the construction industry. *Safety Science*, 72, 337-350.
- ZOHAR, D. 1980a. Safety Climate in Industrial-Organizations - Theoretical and Applied Implications. *Journal of Applied Psychology*, 65, 96-102.
- ZOHAR, D. 1980b. Safety climate in industrial organizations: theoretical and applied implications. *Journal of applied psychology*, 65, 96.
- ZOHAR, D. 2002. The effects of leadership dimensions, safety climate, and assigned priorities on minor injuries in work groups. *Journal of Organizational Behavior*, 23, 75-92.
- ZOHAR, D. 2010a. Thirty years of safety climate research: Reflections and future directions. *Accident Analysis and Prevention*, 42, 1517-1522.
- ZOHAR, D. 2010b. Thirty years of safety climate research: Reflections and future directions. *Accident Analysis & Prevention*, 42, 1517-1522.
- ZOHAR, D. & LURIA, G. 2004. Climate as a social-cognitive construction of supervisory safety practices: scripts as proxy of behavior patterns. *Journal of applied psychology*, 89, 322.
- ZWETSLOOT, G. I. J. M. 2009. Prospects and limitations of process safety performance indicators. *Safety Science*, 47, 495-497.

Appendix A: Ethics approval and documents

Appendix B: Validation questionnaire

Appendix C: Construction safety questionnaire

Appendix D: Safety climate survey

Appendix A: Ethics approval and documents

Ethics approval letter A

Office of the Vice-Chancellor

Finance, Ethics and Compliance

The University of Auckland Private Bag 92019 Auckland, New Zealand

Level 10, 49 Symonds Street

Telephone: 64 9 373 7599

Extension: 87830 / 83761

Facsimile: 64 9 373 7432

UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS
COMMITTEE (UAHPEC)

14-Mar-2014

MEMORANDUM TO:

Dr Tak Wing Yiu

Civil & Environmental Engineer

Re: Application for Ethics Approval (Our Ref. 011290): Approved

The Committee considered your application for ethics approval for your project entitled **A Development of a Measuring Model of Proactive Safety Level.**

We are pleased to inform you that ethics approval is granted for a period of three years. The expiry date for this approval is 14-Mar-2017.

If the project changes significantly, you are required to submit a new application to UAHPEC for further consideration.

If you have obtained funding other than from UniServices, send a copy of this approval letter to the Research Office, at ro-awards@auckland.ac.nz. For UniServices contracts, send a copy of the approval letter to the Contract Manager, UniServices.

In order that an up-to-date record can be maintained, you are requested to notify UAHPEC once your project is completed.

The Chair and the members of UAHPEC would be happy to discuss general matters relating to ethics approvals. If you wish to do so, please contact the UAHPEC Ethics Administrators at ro-ethics@auckland.ac.nz in the first instance.

Please quote reference number: **011290** on all communication with the UAHPEC regarding this application.

(This is a computer generated letter. No signature required.)

UAHPEC Administrators

University of Auckland Human Participants Ethics Committee

c.c. Head of Department / School, Civil & Environmental Engineer Dr Vicente Gonzalez

Mr Hongwei Guo

Assoc Prof AshvinThambyah

Additional information:

Do not forget to fill in the 'approval wording' on the Participant Information Sheets and Consent Forms, giving the dates of approval and the reference number, before you send them out to your participants.

Should you need to make any changes to the project, please complete the online proposed changes and include any revised documentation.

At the end of three years, or if the project is completed before the expiry, please advise UAHPEC of its completion.

Should you require an extension, please complete the online Amendment Request form associated with this approval number giving full details along with revised documentation. An extension can be granted for up to three years, after which a new application must be submitted.

Please note that UAHPEC may from time to time conduct audits of approved projects to ensure that the research has been carried out according to the approval that was given.

Ethics approval letter B

Office of the Vice-Chancellor

Finance, Ethics and Compliance

The University of Auckland Private Bag 92019 Auckland, New Zealand

Level 10, 49 Symonds Street

Telephone: 64 9 373 7599

Extension: 87830 / 83761

Facsimile: 64 9 373 7432

UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE (UAHPEC)

12-May-2014

MEMORANDUM TO:

Dr Tak Wing Yiu

Civil & Environmental Engineer

Re: Application for Ethics Approval (Our Ref. 011842): Approved

The Committee considered your application for ethics approval for your project entitled **Exploratory analysis of dynamics of construction safety performance**.

We are pleased to inform you that ethics approval is granted for a period of three years. The expiry date for this approval is 12-May-2017.

If the project changes significantly, you are required to submit a new application to UAHPEC for further consideration.

If you have obtained funding other than from UniServices, send a copy of this approval letter to the Research Office, at ro-awards@auckland.ac.nz. For UniServices contracts, send a copy of the approval letter to the Contract Manager, UniServices.

In order that an up-to-date record can be maintained, you are requested to notify UAHPEC once your project is completed.

The Chair and the members of UAHPEC would be happy to discuss general matters relating to ethics approvals. If you wish to do so, please contact the UAHPEC Ethics Administrators at ro-ethics@auckland.ac.nz in the first instance.

Please quote reference number: **011842** on all communication with the UAHPEC regarding this application.

(This is a computer generated letter. No signature required.)

UAHPEC Administrators

University of Auckland Human Participants Ethics Committee

c.c. Head of Department / School, Civil & Environmental Engineer Assoc Prof
AshvinThambyah

Dr Vicente Gonzale

Mr Hongwei Guo

Additional information:

Do not forget to fill in the 'approval wording' on the Participant Information Sheets and Consent Forms, giving the dates of approval and the reference number, before you send them out to your participants.

Should you need to make any changes to the project, please complete the online proposed changes and include any revised documentation.

At the end of three years, or if the project is completed before the expiry, please advise UAHPEC of its completion.

Should you require an extension, please complete the online Amendment Request form associated with this approval number giving full details along with revised documentation. An extension can be granted for up to three years, after which a new application must be submitted.

Please note that UAHPEC may from time to time conduct audits of approved projects to ensure that the research has been carried out according to the approval that was given.

Ethics approval letter C

Office of the Vice-Chancellor

Finance, Ehtics andCompliance

The University of Auckland Private Bag 92019 Auckland, New Zealand

Level 10, 49 Symonds Street

Telephone: 64 9 373 7599

Extension: 87830 / 83761

Facsimile: 64 9 373 7432

UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE (UAHPEC)

26-Mar-2015

MEMORANDUM TO:

Dr Tak Wing Yiu

Civil & Environmental Engineer

Re: Application for Ethics Approval (Our Ref. 013774): Approved with comment

The Committee considered your application for ethics approval for your project entitled **Systemic Safety Assessment Tool (SSAT) — Development and Testing**.

Ethics approval was given for a period of three years with the following comment(s):

Please add the information about the process for returning the questionnaire to the PIS for the workers as was done for the PIS (Project Manager).

Please update the extension numbers and email address in the UAHPEC Chair contact details (ext 83711, ro-ethics@auckland.ac.nz).

The expiry date for this approval is 26-Mar-2018.

If the project changes significantly you are required to resubmit a new application to UAHPEC for further consideration.

In order that an up-to-date record can be maintained, you are requested to notify UAHPEC once your project is completed.

The Chair and the members of UAHPEC would be happy to discuss general matters relating to ethics approvals if you wish to do so. Contact should be made through the UAHPEC Ethics Administrators at ro-ethics@auckland.ac.nz in the first instance.

All communication with the UAHPEC regarding this application should include this reference number: **013774**.

(This is a computer generated letter. No signature required.)

Secretary

University of Auckland Human Participants Ethics Committee c. Head of Department / School, Civil & Environmental Engineer Dr Vicente Gonzalez

Mr Hongwei Guo

Assoc Prof Ashvin Thambyah

Additional information:

Should you need to make any changes to the project, write to the Committee giving full details including revised documentation.

Should you require an extension, write to the Committee before the expiry date giving full details along with revised documentation. An extension can be granted for up to three years, after which time you must make a new application.

At the end of three years, or if the project is completed before the expiry, you are requested to advise the Committee of its completion.

Do not forget to fill in the 'approval wording' on the Participant Information Sheets and Consent Forms, giving the dates of approval and the reference number, before you send them out to your participants.

Send a copy of this approval letter to the Awards Team at the, Research Office if you have obtained funding other than from UniServices. For UniServices contract, send a copy of the approval letter to: Contract Manager, UniServices.

Please note that the Committee may from time to time conduct audits of approved projects to ensure that the research has been carried out according to the approval that was given

PARTICIPANT INFORMATION SHEET (Chief Executive Officer)



THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Department of Civil & Environmental Engineering
Private Bag 92019
Auckland Mail Centre
Auckland 1142
New Zealand
Phone: +64 9 3737599 ext 88166
Fax: +64 9 3737462

The University of Auckland
Private Bag 92019 Auckland,
New Zealand

PARTICIPANT INFORMATION SHEET (Chief Executive Officer)

Project title: Developing Construction Safety Indicators
Name of Researcher: Hongwei Guo

Researcher Introduction

My name is Hongwei Guo and I am a PhD student in the Civil and Environmental Engineering Department at the University of Auckland. I am doing research on construction safety management. My supervisors are Dr. Kenneth Yiu and Dr. Vicente González. I have been awarded a Building Research Postgraduate Scholarship by BRANZ to undertake this research project.

Project Description and Invitation

The aim of the research project is to identify factors that explain and affect the proactive safety level of a construction site. By doing it, a measuring model of proactive safety level can be developed and a set of safety indicators can be designed. The researcher would like to collect information about your employees' perception of some health and safety issues on the project they are working on. The information is helpful for the researcher to understand how different factors affect safety performance on site. The expected findings may be able to help the construction industry to build a safer workplace and thus better protect workers.

The purpose of this Participant Information Sheet (PIS) is to provide you with information about the intended project and to then seek your permission/authority to approach employees within your organisation to request their participation in the anonymous questionnaire. A copy of the questionnaire is attached to this sheet. We seek your assurance that the participation or non-participation of your employees will not affect their employment status.

Project Procedures

To identify factors that explain and affect the proactive safety level of a construction site, participants will be requested to answer a number of questions about their perception on safety-related statements. The researcher will send the questionnaire and project information out to the workers on site. It will take your employees about 20 min to answer all questions. Participation in the questionnaire would be voluntary. Employees will be informed that you have given your permission for them to be invited to participate in this research, but they will still retain their right to decide whether or not to participate.

Data Storage/Retention/Destruction/Future use

The data will be stored in computer files format. The data will be used to identify factors that explain and affect the proactive safety level of a construction site. In no manner will they be passed on to any other parties for use. The purpose of the data will be for publication of the researcher's thesis and future publications relevant to its scope. The data will be stored for 6 years, after which the data will be destroyed through deleting those computer files. Research results will be available to participants via email or posting upon request.

Anonymity and Confidentiality

The questionnaire will be completed anonymously thus ensuring anonymity and confidentiality. The data your employees provide will be analysed and presented in the research report in the form of doctoral thesis or published papers. But this will be done in a way that does not identify you as their source.

Contact Details and Approval Wording

If you have more inquiries regarding to the interviews of the research project, please contact:

Researcher: Hongwei Guo
Mobile: 021 2675938
Email: hguo196@aucklanduni.ac.nz

Main Supervisor: Doctor Kenneth Yiu
Phone: 09 3737599 ext 83851
Email: k.yiu@auckland.ac.nz

Co Supervisor: Doctor Vicente González
Phone: 09 3737599 ext 84106
Email: v.gonzalez@auckland.ac.nz

Head of Department: Prof. Pierre Quenneville
Phone: 09 3737599 ext 87920
Email: p.quenneville@auckland.ac.nz

Chair contact details: —For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 extn. 87830/83761. Email: humanethics@auckland.ac.nz.l

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON for (3) years, Reference Number 011290

PARTICIPANT INFORMATION SHEET (Participant)



THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Department of Civil & Environmental Engineering
Private Bag 92019
Auckland Mail Centre
Auckland 1142
New Zealand
Phone: +64 9 3737599 ext 88166
Fax: +64 9 3737462

The University of Auckland
Private Bag 92019 Auckland,
New Zealand

PARTICIPANT INFORMATION SHEET (Participant)

Project title: Developing Construction Safety Indicators

Name of Researcher: Hongwei Guo

Researcher Introduction

My name is Hongwei Guo and I am a PhD student in the Civil and Environmental Engineering Department at the University of Auckland. I am doing research on construction safety management. My supervisors are Dr. Kenneth Yiu and Dr. Vicente González. I have been awarded a Building Research Postgraduate Scholarship by BRANZ to undertake this research project.

Project Description and Invitation

The aim of the research project is to identify factors that explain and affect the proactive safety level of a construction site. By doing it, a measuring model of proactive safety level can be developed and a set of safety indicators can be designed. The researcher would like to collect information about your perception of some health and safety issues on the project you are working on. The information is helpful for the researcher to understand how different factors affect safety performance on site. The expected findings may be able to help the construction industry to build a safer workplace and thus better protect workers.

The purpose of this Participant Information Sheet (PIS) is to provide you with information about the intended project and to then invite you to participate in the anonymous questionnaire.

Project Procedures

It will take you about 20 min to complete the questionnaire. You are being invited to participate because of your rich knowledge and experience in construction safety

management. This Participant Information Sheet has also been provided to your Chief Executive Officer (or other suitably authorized company manager) to obtain permission/authority to access you and the organization's information. Your CEO has given their assurance that participation or non-participation will not affect your employment status. While your Chief Executive Officer (or other suitably authorized company manager) has given their permission for you to participate in this research, you still have the right to decide whether or not to participate.

Data Storage/Retention/Destruction/Future use

The data will be stored in computer files format. The data will be used to identify factors that explain and affect the proactive safety level of a construction site. In no manner will they be passed on to any other parties for use. The purpose of the data will be for publication of the researcher's thesis and future publications relevant to its scope. The data will be stored for 6 years, after which the data will be destroyed through deleting those computer files. Research results will be available to participants via email or posting upon request.

Anonymity and Confidentiality

The questionnaire will be completed anonymously thus ensuring anonymity and confidentiality. The data you provide will be analysed and presented in the research report in the form of doctoral thesis or published papers. But this will be done in a way that does not identify you as their source.

Contact Details and Approval Wording

If you have more inquiries regarding to the interviews of the research project, please contact:

Researcher: Hongwei Guo

Mobile: 021 2675938

Email: hguo196@aucklanduni.ac.nz

Main Supervisor: Doctor Kenneth Yiu

Phone: 09 3737599 ext 83851

Email: k.yiu@auckland.ac.nz

Co Supervisor: Doctor Vicente González

Phone: 09 3737599 ext 84106

Email: v.gonzalez@auckland.ac.nz

Head of Department: Prof. Pierre Quenneville

Phone: 09 3737599 ext 87920

Email: p.quenneville@auckland.ac.nz

Chair contact details: —For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 extn. 87830/83761. Email: humanethics@auckland.ac.nz.¶

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON for (3) years, Reference Number 011290

CONSENT FORM (Chief Executive Officer)



THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Department of Civil & Environmental Engineering
Private Bag 92019
Auckland Mail Centre
Auckland 1142
New Zealand
Phone: +64 9 3737599 ext 88166
Fax: +64 9 3737462

The University of Auckland
Private Bag 92019 Auckland,
New Zealand

CONSENT FORM (Chief Executive Officer)

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Developing Construction Safety Indicators
Name of Researcher: Hongwei Guo

I have read the Participant Information Sheet and understood the nature of the research and why the participants have been selected, I have had the opportunity to ask questions and have had them answered to my satisfaction.

- I confirm that I hold the appropriate authority to provide consent for the following statements.
- I give permission for employees of my organization to take part in the research if they wish.
- I give permission for employees of my organization to provide information related to my organization to support this research.
- I understand that any such information will be treated confidentially and any reported information will appear in a general form.
- I confirm that the employees' participation or non-participation in this research will not, in any way, affect their employment in my organization.

- I understand that It will take my employees about 20 min to answer all questions.
- I understand that the data will be kept for 6 years, after which they will be destroyed.
- I understand that the data the participants provide will be stored securely within the university premises and only the researcher and supervisor will have access to it.
- I understand that the participating employees will have the right to review a draft report related to the information they provide to ensure that the information reported satisfies my organization's confidentiality requirements.
- I understand that although the data the participants provide will be reported, it will be done in a way that does not identify the source either by name, innuendo or inference. All results will appear in a generalized form without disclosing the identity of both individual participants and their organizations.
- I understand that I will be offered a copy of the research report upon my request.
- I would/would not like a copy of the Summary of Results.

(Please include your email address here: _____)

Name _____ Signature _____ Date _____

_____ APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ONFOR (3) YEARS REFERENCE NUMBER 011290

CONSENT FORM (Participant)



THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Department of Civil & Environmental Engineering
Private Bag 92019
Auckland Mail Centre
Auckland 1142
New Zealand
Phone: +64 9 3737599 ext 88166
Fax: +64 9 3737462

The University of Auckland
Private Bag 92019 Auckland,
New Zealand

CONSENT FORM (Participant)

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Developing Construction Safety Indicators

Name of Researcher: Brian Guo

I agree to voluntarily take part in this research. I have read the introduction of the questionnaire. I have understood the nature of the research and why I have been selected, I have had the opportunity to ask questions and have had them answered to my satisfaction.

- I agree to take part in this research.
- I understand that permission has been given by the Chief Executive Officer (or other suitably authorized manager) for my organization to take part in the study.
- I understand that my CEO has given assurance that my participation or non-participation will not affect my employment status.
- I understand that I am free to withdraw participation at any time without any explanation, and to withdraw any data traceable to me up to one month after the interview date
- I understand that the data will be kept for 6 years, after which they will be destroyed.

- I understand that the data I provide will be stored securely within the university premises and only the researcher and supervisor will have access to it.
- I understand that I will not be provided with a draft report of the information I provide. .
- I understand that although the data the participants provide will be reported, it will be done in a way that does not identify the source either by name, innuendo or inference. All results will appear in a generalized form without disclosing the identity of both individual participants and their organizations.
- I understand that this research has been fully approved by the University of Auckland Ethics Committee.
- I would/would not like a copy of the Summary of Results.

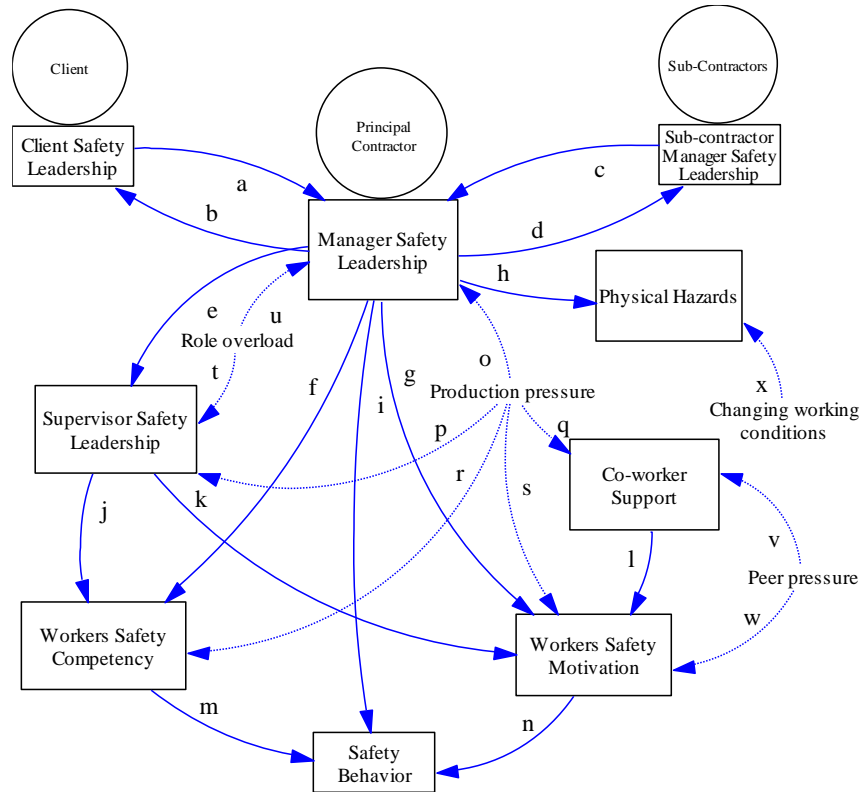
(Please include your email address here: _____)

Name _____ Signature _____ Date _____

_____ APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ONFOR (3) YEARS REFERENCE NUMBER 011290

Appendix B: Validation questionnaire

A safety condition map of a construction project



Evaluation criteria

Attributes	Description	
Scientific dimension	Analytic soundness	have a strong scientific and conceptual basis; based on a safety model
	Predictability	reflect causes of accidents be sensitive to change of safety condition.;
		allow for early warning by capturing changes in system state that have significant effects on safety risks
Managerial dimension	Practicability	be compatible with practical safety management; drive appropriate behavior

Cost-	easily observable;
effectiveness	cost-effective to be collected.

Evaluation of Safety Leading Indicators

Please rate each indicator with regard to its practicability and cost-effectiveness

(use √)

Key Themes	Safety Leading indicators	Practicability					Cost-effectiveness				
		Low ← → High					Poor ← → Good				
		1	2	3	4	5	1	2	3	4	5
Client Safety	1.principal contractors are selected in part on the basis of satisfying historical safety performance										
Leadership	2.frequency that safety representatives of client visit the site										
Links: a, b	3.frequency that client attend safety meeting on site										
Sub-contractors	4.percent of subcontractors selected in part on the basis of satisfying historical safety performance										
Manager	5.frequency that subcontractors attend safety meeting, toolbox meeting, and safety planning										
Safety Leadership	6.frequency that subcontractors report safety performance to the principal contractor										

Key Themes	Safety Leading indicators	Practicability					Cost-effectiveness						
		Low ← → High					Poor ← → Good						
		1	2	3	4	5	1	2	3	4	5		
Links: c,d													
Principal contractor Manager Safety Leadership Role overload Peer pressure Links: e, f, g, i, n, o, u	7.written safety policy signed by senior managers in place												
	8.frequency that senior managers attend safety meeting												
	9.a health and safety manager (administrator) is set up on site												
	10.adequate safety resources (e.g., PPE) are provided on site												
	11.employees are provided opportunities to be involved in safety management												
	12.frequency that senior managers provide feedback on safety performance												
	13.frequency that senior managers reward good safety performance												
Supervisor safety leadership Role overload	14.frequency that supervisors discuss safety with workers												
	15.frequency that supervisors attend safety meetings												
	16.frequency that supervisors involved in hazard management												
	17.ratio of the number of supervisors to workers												
	18.supervisors' job is supported by senior managers												

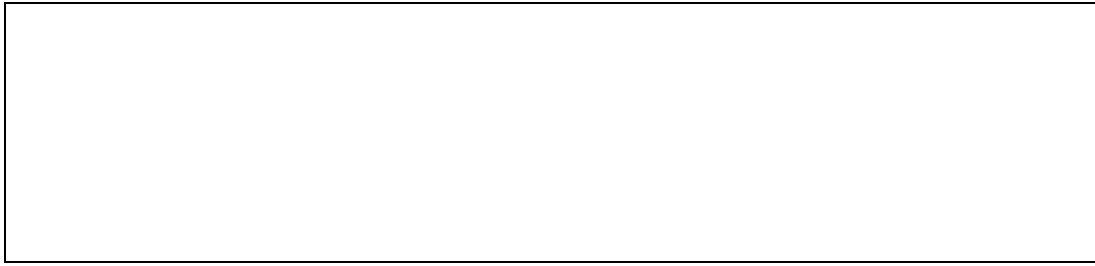
Key Themes	Safety Leading indicators	Practicability					Cost-effectiveness				
		Low ←					Poor ←				
		→ High					→ Good				
		1	2	3	4	5	1	2	3	4	5
Peer pressure	19.percent of supervisors with Site Safe Supervisor Gold Card										
Links: e, t, j, k, v, w, p	20.managers and supervisors emphasize safety when training new employees										
Co-worker support	21.Worker-to-worker observation program in place										
Worker Safety	22.frequency that co-workers caution each other when they behave unsafely										
Motivation	23.frequency that co-workers speak up for safety										
Links: l, q											
Worker safety	24.percent of workers with certificates to operate equipment, tools and plants										
competency	25.percent of workers of Principal contractor with Site Safe training passport										
Production pressure	26.percent of workers of subcontractors with Site Safe training passport										
Links: k, m, r, s	27.percent of workers provided with hazards information about the project										
	28. workers have stop-work authority										
	29.a fatigue management system is in place										
Physical hazards	30.frequency that safety planning is conducted before performing tasks										
	31.a systematic hazard management program is in place										

Key Themes	Safety Leading indicators	Practicability					Cost-effectiveness				
		Low ←					Poor ←				
		→ High					→ Good				
		1	2	3	4	5	1	2	3	4	5
Changing working conditions	32.safety rules and procedures are in place										
Links: h, x											

How do you rate the Analytic soundness and Predictability of these leading indicators
AS A WHOLE?

Points Attributes	Poor ← → Good									
	1	2	3	4	5	6	7	8	9	10
Analytic soundness										
Predictability										

Further comments:



Thank you very much

Appendix C: Construction safety questionnaire

Part I Introduction

This is a research project and we would like to invite you to complete a short questionnaire. This questionnaire aims to collect your perception on different health and safety issues and your safety behaviours on the project you are working on. The information you provide will be used to improve an understanding of how to create a safer organization and workplace so as to better protect workers on site. This research project is financially supported by BRANZ. The study has been approved by the UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE (UAHPEC) by 14 March 2014 (Ref. 011290).

Before you start, please read the following instructions:

- All information provided by you would be handled in the strictest of confidence and reported on an anonymous basis.
- Please understand your participation is entirely on a voluntary basis and you have the right to withdraw your consent or discontinue participation at any time without penalty.
- Please make sure that you have responded to every statement.
- For each item, please tick only ONE appropriate box that can best describe the safety conditions of **the project you are working on**. If you are not working on any project, you can respond according to the condition of the last project you have completed.

➤ It may take 10 minutes of your time to complete the questionnaire.

Thank you very much for your participation. If you have any questions, you are free to contact Brian at hguo196@aucklanduni.ac.nz or 021-2675938.

Part II: Safety Conditions

Organizational factors		Strongly	Disagree	Neutral	Agree	Strongly
		Disagree				agree
1	Management places a high priority on safety operations in company.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Management cares about the safety welfare of their employees.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Management works to upgrade the safety of its facilities or reduce safety problems.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Management provides resources to prevent the occurrence of safety-related incidents.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	Safety is compromised when determining production, schedules, overtime, and staffing.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	Management gets personally involved in safety programs.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Management becomes complacent during the days without an accident.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	When my supervisor and co-workers see me working at-risk, they caution me.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	Supervisor reports cases or shares safety-related experiences in the workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

10	Supervisor makes on-going safety instruction at workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11	Supervisor diligently reviews the safety behaviours of the employees.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12	Supervisor frequently moves around inspecting the workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13	Management considers employees' suggestions regarding safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14	Management asks employees for their opinions before making decisions regarding safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
15	Management involves employees in decisions regarding safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
16	Management encourages employees here to participate in decisions which affect their safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
17	Employees are given the opportunity to suggest improvements.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

	Working conditions	Strongly Disagree	Disagree	Neutral	Agree	Strongly agree
--	---------------------------	-------------------	----------	---------	-------	----------------

1	Overall, this is a safe place to work.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Housekeeping is maintained at a very high level at our site.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	The equipment in our workplace is properly safeguarded.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

4 The materials in our workplace are safe to use.

5 Site layout/space is problematic.

Individual factors		Strongly Disagree	Disagree	Neutral	Agree	Strongly agree
---------------------------	--	----------------------	----------	---------	-------	-------------------

1	I take short cuts when I need to get the job done in a timely manner.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	---	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

2	We are often in such a hurry that safety is temporarily overlooked.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	---	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

3	Short cuts and risk taking are common due to the heavy workload.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

4	There is a lot of pressure to complete jobs quickly.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

5	I do not want to be seen as “unmanly” or “weak” being overly safe.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

6	Getting others to be happy with the job I do is more important than my safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

7	I work unsafely to avoid being teased or made fun of by my co-workers.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

8	I have fun while working safely on site.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

9	I enjoy working safely on site.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
---	---------------------------------	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

10	Putting effort into working safely is important to me.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
----	--	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

- | | | | | | | |
|----|---|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 11 | Working safely aligns with my personal values. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 12 | I feel bad about myself when I don't work safely. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 13 | I feel guilty when I don't work safely. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 14 | I work safely in order to avoid being criticized by others (e.g., managers, supervisors, and colleagues). | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 15 | I work safely in order to get approval from others (e.g., managers, supervisors, and colleagues). | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 16 | I know how to perform my job in a safe manner. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 17 | I know how to use equipment, tools and plants in a safe manner. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 18 | I know how to maintain or improve workplace health and safety. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 19 | I know how to reduce the risk of accidents and incidents in the workplace. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 20 | I know what are the hazards associated with my jobs and the necessary precautions to be taken while doing my job. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 21 | I know my safety rights and responsibilities. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

How often do you.....

Safety behaviour		Frequency					
		Never	Once in a while	Sometimes	Quite often	Frequently	Always
1	Assist others to make sure they perform their work safely?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Speak up and encourage others to get involved in safety issues?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Explain to other workers that you will report safety violations?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Try to change the way the job is done to make it safer?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	Take action to stop safety violations in order to protect the well-being of co-workers?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	Attend non-mandatory safety orientated training?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Wear a hard hat in designated areas?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	Wear eyes protection in designated areas?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	Follow all safety rules and procedures?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	Correct slip/trip/fall hazards?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

- 11 Clean my work area when I am finished doing a task?
- 12 Report safety problems that I experience or witness?
- 13 Work clear of the influence of drugs and alcohol?
- 14 Wear proper PPE when working on or near live electricity?
- 15 Wear PPE when working at heights?

Near misses and Accidents

1. How many times have you experienced near misses in the project you are working on?

- 0 1-5 6-10 11-15 over 16

2. How many times have you experienced accidents and injuries in the project you are working on?

- 0 1 2 3 over 4

Part III: Background

Gender	Age	Construction Experience	Sub-sector	Size of your company
<input type="checkbox"/> Female	<input type="checkbox"/> <20	<input type="checkbox"/> 1-5 years	<input type="checkbox"/> Residential building	<input type="checkbox"/> over 50 employees

<input type="checkbox"/> Male	<input type="checkbox"/> 21-	<input type="checkbox"/> 6-10 years	<input type="checkbox"/> Commercial	<input type="checkbox"/> 20-49 employees
	30		building	
<input type="checkbox"/> 31-	<input type="checkbox"/> 11-20 years	<input type="checkbox"/> Heavy& civil	<input type="checkbox"/> 1-19 employees	
	40		engineering	
<input type="checkbox"/> 41-	<input type="checkbox"/> Over 21 years	<input type="checkbox"/> Trade	<input type="checkbox"/> Non-employing	
	50			
<input type="checkbox"/> 51-				
	60			
<input type="checkbox"/> >60				

Position	<input type="checkbox"/> Manager	<input type="checkbox"/> Supervisor/Foreman	<input type="checkbox"/> Worker
Employment type:	<input type="checkbox"/> Self-employed	<input type="checkbox"/> Fix-term employee	<input type="checkbox"/> Causal workers

Thank you

Appendix D: Safety Climate Survey

Part I Introduction

This is a research project and we would like to invite you to complete a short questionnaire. This questionnaire aims to collect your perception on different health and safety issues and your safety behaviours on the project you are working on. The information you provide will be used to improve an understanding of how to create a safer organization and workplace so as to better protect workers on site. This research project is financially supported by BRANZ. The study has been approved by the UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE (UAHPEC) by 26-Mar-2015 (Ref. 013774).

Before you start, please read the following instructions:

- All information provided by you would be handled in the strictest of confidence and reported on an anonymous basis.
- Please understand your participation is entirely on a voluntary basis and you have the right to withdraw your consent or discontinue participation at any time without penalty.
- Please make sure that you have responded to every statement.
- For each item, please tick only ONE appropriate box that can best describe the safety conditions of **the project you are working on**. If you are not working on any project, you can respond according to the condition of the last project you have completed.

- It may take 5 minutes of your time to complete the questionnaire.

Thank you very much for your participation. If you have any questions, you are free to contact Brian at hguo196@aucklanduni.ac.nz or 021-2675938.

2. Background information

Size of your company	Position	Construction Experience
<input type="checkbox"/> over 50 employees	<input type="checkbox"/> Manager	<input type="checkbox"/> 1-5 years
<input type="checkbox"/> 20-49 employees	<input type="checkbox"/> Supervisor/Foreman	<input type="checkbox"/> 6-10 years
<input type="checkbox"/> 1-19 employees	<input type="checkbox"/> Worker	<input type="checkbox"/> 11-20 years
<input type="checkbox"/> Non-employing		<input type="checkbox"/> 11-20 years

3.

Items	Strongly Disagree	Disagree	Neutral	Agree	Strongly agree
1 Management places a high priority on safety operations in company.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2 Management cares about the safety welfare of their employees.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3 Management works to upgrade the safety of its facilities or reduce safety problems.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

4	Management provides resources to prevent the occurrence of safety-related incidents.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	When my supervisor and coworkers see me working at-risk, they caution me.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	Supervisor reports cases or shares safety-related experiences in the workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Supervisor makes on-going safety instruction at workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	Supervisor diligently reviews the safety behaviors of the employees.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	Supervisor frequently moves around inspecting the workplace.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	I take short cuts when I need to get the job done in a timely manner.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11	We are often in such a hurry that safety is temporarily overlooked.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12	Short cuts and risk taking are common due to the heavy workload.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13	Management asks employees for their opinions before making decisions regarding safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14	Management involves employees in decisions regarding safety.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

- Management encourages employees here
- 15 to participate in decisions which affect their safety.
- 16 Employees are given the opportunity to suggest improvements.
- 17 Overall, this is a safe place to work.
- 18 Housekeeping is maintained at a very high level at our site.
- 19 The equipment in our workplace is properly safeguarded.
- 20 The materials in our workplace are safe to use.
- 21 Everyone aims to achieve high levels of safety performance.
- 22 Everyone plays an active role in identifying site hazards.
- 23 I received adequate training to perform my job safely.
- 24 I am skilled at avoiding the dangers of workplace hazards.
- 25 I am clear about what my responsibilities are for safety.

Thank you