Development of a building-specific life cycle sustainability assessment model

Liu, Siyu

2019

Liu, S. (2019). Development of a building-specific life cycle sustainability assessment model. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/100447>

<https://doi.org/10.32657/10220/47755>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**DEVELOPMENT OF A BUILDING-SPECIFIC LIFE
CYCLE SUSTAINABILITY ASSESSMENT MODEL**

LIU SIYU

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2019

**DEVELOPMENT OF A BUILDING-SPECIFIC LIFE
CYCLE SUSTAINABILITY ASSESSMENT MODEL**

LIU SIYU

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

1 March, 2019

Date

Liu, Siyu

Liu, Siyu

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

28 Feb. 2019

Date

Qian, Shunzhi

Authorship Attribution Statement

This thesis contains material from two papers published in the following peer-reviewed journal(s) where I was the first and/or corresponding author.

Chapter 5 is published as Siyu Liu, Uwe W. Schulz, Majid Haji Sapar, and Shunzhi Qian, Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore. *Building and Environment* 102 (2016), 207-216. DOI: 10.1016/j.buildenv.2016.03.005.

The contributions of the co-authors are as follows:

- Assistant Professor Shunzhi Qian provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript was revised by Dr. Uwe W. Schulz.
- I performed life cycle assessment of two air-conditioning systems at the School of Civil and Environmental Engineering, NTU. I also analyzed and presented the data.
- Mr. Majid Haji Sapar provided basic information and energy consumption data of chilled ceiling system.

Chapter 6 and 7 are published as Siyu Liu, and Shunzhi Qian, Evaluation of social life-cycle performance of buildings: Theoretical framework and impact assessment approach. *Journal of Cleaner Production* 213 (2019): 792-807. DOI: 10.1016/j.jclepro.2018.12.200

The contributions of the co-authors are as follows:

- Assistant Professor Shunzhi Qian suggested the research direction and edited the manuscript drafts.
- I wrote the drafts of the manuscript.

- I performed proposed social life cycle assessment method, collected data for case study, as well as analyzed and presented the data.

1 March, 2019

Date

Liu, Siyu

Liu, Siyu

ACKNOWLEDGEMENT

The author would like to express her most sincere appreciation and gratitude to her supervisor, Assistant Professor Qian Shunzhi, for his continuous support, valuable guidance, and scholarly input all throughout this Ph.D. project.

The author would also like to extend her sincere appreciation to her TAC members, Associate Professor Li Bing and Assistant Professor Fan Zheng, for their valuable advice and enlightenment.

Special thanks also go to the author's colleagues, in particular, Mr. Abdul Halim Hamdany, Dr. Ding Yuanzhao, Mr. Lu Bing, Ms. Tian Qingyun, Ms. Wang Ke, Mr. Weng Yiwei and Ms. Wu Yuanyuan, for their valuable discussion and kind assistance.

The author appreciates Nanyang Technological University for providing research scholarship and creating a good academic environment. All the staff in the School of Civil and Environmental Engineering are also greatly appreciated for their assistance and support.

All questionnaire participants and interviewees are highly appreciated for their time, effort and indispensable input to this study. The author would also like to thank Office of Development & Facilities Management, NTU, Singapore Building and Construction Authority and Zheng Keng Engineering and Construction Ltd. for the valuable support on this research.

Especially, the author would like to express her sincere thanks to her husband and all other family members for their patience, understanding and moral support.

TABLE OF CONTENTS

ACKNOWLEDGEMENT	i
TABLE OF CONTENTS	iii
SUMMARY	vii
LIST OF PUBLICATIONS	ix
LIST OF TABLES	xi
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xv
Chapter 1 Introduction	1
1.1 Research Background.....	2
1.2 Research Gaps	7
1.3 Aim and Objectives	7
1.4 Structure of Thesis	8
Chapter 2 Overview of Sustainable Construction and Sustainability Assessment	11
2.1 Sustainable Construction.....	12
2.1.1 Concept of Sustainable Construction	12
2.1.2 Moving towards Sustainable Construction.....	14
2.2 Sustainability Assessment of Buildings	18
2.2.1 Green Building Rating Systems	19
2.2.2 Quantitative Assessment Methods.....	25
2.3 Multi-Criteria Decision Analysis for Sustainability Assessment.....	28
2.4 Summary	29
Chapter 3 Review on Life-cycle Based Assessment Methods	31
3.1 Life Cycle Costing Analysis (LCCA)	32
3.2 Environmental Life Cycle Assessment (E-LCA).....	34
3.2.1 Overview of E-LCA	34
3.2.2 E-LCA Studies for Building Component and System.....	36
3.2.3 Future Development in E-LCA	44
3.3 Social Life Cycle Assessment (S-LCA).....	46
3.4 Life Cycle Sustainability Assessment (LCSA)	50
3.5 Summary	51

Chapter 4 Research Methodology	53
4.1 Overview of Research Design.....	54
4.2 Research Methods	56
4.2.1 Literature Review	56
4.2.2 Survey	57
4.2.3 Case Study	62
4.3 Summary	63
Chapter 5 Comparative E-LCA and LCCA Studies of Air-Conditioning Systems	65
5.1 Description of the CC System.....	66
5.2 Environmental Performance Analysis.....	67
5.2.1 E-LCA Model Establishment	67
5.2.2 Data Collection and E-LCI analysis	68
5.2.3 Life Cycle Impact Assessment	72
5.3 Economic Performance Analysis	80
5.3.1 LCCA Model Establish and Data Collection	80
5.3.2 LCCA Results.....	81
5.4 Summary	83
Chapter 6 Conceptual Framework for LCSA.....	85
6.1 Selection of Environmental Assessment Criteria.....	86
6.2 Selection of Social Assessment Criteria.....	90
6.2.1 Selection and Definition of Stakeholder Categories.....	91
6.2.2 Selection of Social Impact Subcategories	92
6.3 Conceptual Framework for LCSA Model	96
6.4 Summary	98
Chapter 7 Development of Social Life Cycle Impact Assessment Method for Building Projects.....	99
7.1 Overview of the Proposed S-LCIA Method.....	100
7.2 Indicators Selection	100
7.3 Scoring of Indicators	106
7.3.1 Quantitative Indicators in Generic Analysis.....	106
7.2.2 Site-Specific Analysis.....	108
7.4 Weights.....	112

7.5 Illustrative Case Study on CC and VAV Systems	114
7.5.1 Generic Analysis.....	115
7.5.2 Site-Specific Analysis.....	117
7.5.3 Integrated Social Sustainability Performance.....	118
7.6 Summary	120
Chapter 8 Dealing with Parameter Uncertainties in E-LCA	121
8.1 Overview of Approaches to Treating Uncertainty in E-LCA	122
8.2 Description of Methods to Be Compared.....	126
8.2.1 Sampling Methods.....	127
8.2.2 GSA Methods	128
8.3 Case Study.....	131
8.4 Comparison Results and Discussion	133
8.4.1 Comparison Results of Sampling Methods	134
8.4.2 Comparison Results of GSA Methods.....	137
8.5 Summary	140
Chapter 9 Establishment of LCSA Model Based on MCDA Methods.....	143
9.1 Overview of MCDA Methods.....	144
9.2 Fuzzy ELECTRE III.....	146
9.3 LCSA Model for Sustainability-Oriented Decision-Making	150
9.3.1 Procedure to Conducting LCSA	150
9.3.1 Preparation of Background Data	151
9.4 Summary	156
Chapter 10 Application and Validation of LCSA Model	159
10.1 Background Information and Data Collection	160
10.2 Comparison of Social Sustainability Performance of PPVC and Semi-Prefabrication Projects	166
10.2.1 Generic Analysis.....	166
10.2.2 Site-Specific Analysis.....	169
10.2.3 Integrated Social Sustainability Performance.....	172
10.2.4 Sensitivity Analysis	174
10.3 Ranking Three Building Projects in Terms of Life Cycle Sustainability Performance	175

10.3.1	Evaluation Matrix and Ranking Results	176
10.3.2	Sensitivity Analysis	177
10.3.3	Discussion.....	178
10.4	Summary	179
Chapter 11	Conclusions and Recommendations	181
11.1	Achievements and Contributions	182
11.2	Recommendations on Future Work.....	185
REFERENCE		187
APPENDIX		215
Appendix A	Sample of Questionnaire	215
Appendix B	Raw Data from Questionnaire Survey	219
Appendix C	Data Collection for Case Study on PPVC project	225
Appendix D	Background Data for S-LCA Case Study.....	246

SUMMARY

The construction industry is of high economic significance and has strong environmental and social impacts, and thus sustainable construction has attracted wide attention in the industry. In order to aid in the shift towards sustainable construction, there is a need to develop a reliable model for building sustainability assessment that encompasses three dimensions of sustainability and long-term impacts and is able to facilitate sustainability-oriented decision-making. Having recognized such research need, this study developed a building-specific life cycle sustainability assessment (LCSA) model, which integrated three life-cycle based methods, namely environmental life cycle assessment (E-LCA) for environmental impact evaluation, life-cycle cost analysis (LCCA) for economic analysis and social life cycle assessment (S-LCA) for social acceptability evaluation.

Firstly, a conceptual framework for LCSA model was established through extracting impact categories from three life-cycle-based methods. Economic aspect was evaluated using life-cycle costs. Environmental impact categories were extracted from a selected environmental life cycle impact assessment method, which is ReCiPe endpoint approach in this study. As for social impact assessment, impact categories were selected using stakeholder-based approach. Four groups of stakeholders were identified, including worker, occupant, local community and society. This was followed by the identification of impact subcategories through content analysis.

Secondly, a building-specific social life cycle impact assessment (S-LCIA) method was proposed. Indicators were selected for each subcategory based on the assessment objective and data availability. They were categorized into three groups, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis; corresponding scoring methods were also provided. Weights among impact subcategories were generated through questionnaire survey based on consistent fuzzy preference relation (CFPR) based analytic hierarchy process (AHP) method, and weights among life-cycle phases were determined considering the possibility to impose measures to control as well as level of concern of construction practitioners.

Thirdly, to address the issue of uncertainty of E-LCA studies, and more specifically the uncertainty induced by input parameters, a comparative assessment on global sensitivity analysis (GSA) methods was conducted. Focusing on sampling-based GSA methods, the assessment started by comparing three sampling methods regarding convergence rate and computation effort. This was followed by the comparison of four GSA methods, whereby each method was evaluated on its capability in explaining total output variance as well as the ranking of variance contribution of individual input parameters. Accordingly, suggestions were given on characterizing uncertainties through GSA.

Finally, an integrated LCSA model was established based on fuzzy ELECTRE III method. The applicability and validity of this model were demonstrated using a case study. The case study compared the sustainability performance of a modular construction project, a semi-prefabrication one and a conventional cast-in-place one. Ranking results showed that semi-prefabrication project is the best option regarding sustainability level achieved, while modular project is ranked the second.

LIST OF PUBLICATIONS

Liu, Siyu, Uwe W. Schulz, Majid Haji Sapar, and Shunzhi Qian. "Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore." *Building and Environment* 102 (2016): 207-216. <https://doi.org/10.1016/j.buildenv.2016.03.005>

Liu, Siyu, and Shunzhi Qian. "Evaluation of social life-cycle performance of buildings: Theoretical framework and impact assessment approach." *Journal of Cleaner Production* (2018). <https://doi.org/10.1016/j.jclepro.2018.12.200>

LIST OF TABLES

Table 2-1	Comparison of main concerns in green and sustainable buildings, adapted from (Berardi 2013).....	13
Table 2-2	Reasons that drive and prevent sustainable construction movement in Singapore, adapted from (Chan, Qian et al. 2009)	16
Table 2-3	Basic features of Green Mark, BREEAM and LEED	22
Table 2-4	Assessment scope of Green Mark, BREEAM and LEED.....	23
Table 3-1	E-LCA case studies of building components and building systems.....	37
Table 3-2	List of uncertainties associated with E-LCA.....	45
Table 3-3	Stakeholder categories and subcategories proposed in the <i>Guidelines</i>	48
Table 4-1	Scale of relative importance	60
Table 5-1	Thermal comfort parameters of the CC system.....	68
Table 5-2	Material quantities of main components of CC and VAV systems.....	69
Table 5-3	Annual electricity consumption for CC and VAV systems.....	70
Table 5-4	Emissions for 1MWh of electricity generation in Singapore	71
Table 5-5	Percentages of different approaches to waste material disposal	71
Table 5-6	E-LCIA results for life cycle phases of CC system over a 20-year lifespan	73
Table 5-7	Changes in impact of different life cycle phases of CC system upon VAV system	77
Table 5-8	Compositions of fuel mix for electricity generation in 2010, 2012 and 2014	78
Table 5-9	Summary of cost of CC system and VAV system	81
Table 5-10	LCCA results of the CC system and VAV system.....	83
Table 6-1	Comparison of commonly used E-LCIA methods	87
Table 6-2	Summary of three perspectives in ReCiPe and their corresponding weighting sets (Goedkoop, Heijungs et al. 2009).....	90
Table 6-3	Selection of stakeholder categories and subcategories.....	93
Table 7-1	Selection of indicators for generic analysis	103
Table 7-2	Selection of indicators for site-specific analysis	104
Table 7-3	Example of performance reference scale: managerial practices regarding workers' safety and health.....	110
Table 7-4	Weights of social impact categories	113
Table 7-5	Weights of life cycle phases	114
Table 7-6	Activity contribution of countries involved in raw material extraction and manufacturing processes.....	116
Table 7-7	Social performance score of CC and VAV systems in raw material extraction and manufacturing phases	116
Table 7-8	Social performance score of CC and VAV systems in O&M phase ..	118
Table 8-1	Emission factors for main activities associated with concrete production and placement.....	132
Table 8-2	Mean and standard deviation values (SD, shown in brackets) obtained from MCS, <i>LHS</i> and <i>LDS</i> in four scenarios (unit: <i>ton CO_{2-e}</i>).....	134

Table 8-3	Output variance (unit: ton^2) and variance explainable (shown in brackets) for different GSA methods in four scenarios.....	138
Table 8-4	Suggestion on method selection based on uncertainty levels of input parameters.....	140
Table 9-1	Background data on endpoint environmental impacts	152
Table 10-1	Data collection results for PPVC, Semi-Prefabrication and Conventional projects	165
Table 10-2	Activity contribution of countries involved in raw material extraction, manufacturing and fabrication processes	167
Table 10-3	Social performance score of PPVC and semi-prefabrication building in raw material extraction, and manufacturing and fabrication phase...	169
Table 10-4	social performance score of PPVC and semi-prefabricated building in construction and use phases.....	170
Table 10-5	Relative change of the score of PPVC project to semi-prefabrication project	175
Table 10-6	LCCA, E-LCA, and S-LCA results of three alternatives	176
Table 10-7	Sensitivity analysis results due to weight change.....	178

LIST OF FIGURES

Figure 2-1	Concept of E-LCA and its relationship with LCEA and LCCEA	26
Figure 3-1	Life cycle cost components of a building project	33
Figure 3-2	Life-cycle phases of building system	42
Figure 4-1	Illustration of research framework	55
Figure 4-2	Part of the questionnaire for pairwise comparison regarding social acceptability.....	58
Figure 5-1	Schematic view of the chilled ceiling system	67
Figure 5-2	Environmental impacts of CC system by system components over a 20-year lifespan.....	74
Figure 5-3	Contribution of materials to the production impact	75
Figure 5-4	Contribution of system components to the production impact	76
Figure 5-5	Comparison of normalized environmental impacts of CC and VAV systems	77
Figure 5-6	Comparison of the environmental impact based on three different fuel mix compositions for electricity generation	79
Figure 5-7	Contribution of operation phase to the life cycle environmental impact in 2010, 2012 and 2014	80
Figure 5-8	Cumulative net present cost of CC system and VAV system.....	83
Figure 6-1	Schematic representation of ReCiPe (Goedkoop, Heijungs et al. 2009)	89
Figure 6-2	Relationship between life-cycle phases and stakeholder categories ...	91
Figure 6-3	Hierarchical structure of LCSA model	97
Figure 7-1	Methodological framework for social impact assessment	100
Figure 7-2	Data specificity change along life cycle phases and their corresponding data sources and indicator types	101
Figure 7-3	Example of normalized country-level social performance score for various impact subcategories.....	107
Figure 7-4	Membership function of linguistic terms	111
Figure 7-5	Distribution of responses of questionnaire survey	113
Figure 7-6	Scores of social impact subcategories for CC and VAV systems.....	119
Figure 7-7	Comparison of normalized sustainability performance of CC and VAV systems	119
Figure 8-1	Illustration of process of LCA with GSA and its difference compared with traditional LCA.....	126
Figure 8-2	Breakdown of GHG emissions generated by 1 m ³ concrete in structure	134
Figure 8-3	Relationship between standard error of the mean (SEM) and sample size for MCS, LHS and LDS in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty	136

Figure 8-4	Calculation time of MCS, LHS and LDS in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty.....	137
Figure 8-5	Contribution of each parameter uncertainty to the output variance computed from different GSA methods in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty.....	139
Figure 9-1	Problem types and their corresponding ELECTRE versions (adapted from (Majdi 2013)).....	146
Figure 9-2	Methodological frameworks for LCSA model based on MCDA methods	150
Figure 9-3	Screenshot of normalized country-level social performance scores prepared in Excel.....	155
Figure 9-4	Screenshot of percentages of extraction or production from different countries	156
Figure 10-1	Typical PPVC modular designs	160
Figure 10-2	Elevation view of PPVC project	161
Figure 10-3	Weight decomposition of a typical PPVC module	162
Figure 10-4	Monthly diesel consumption during construction phase of PPVC project	163
Figure 10-5	Six-month record on monthly electricity consumption per tenant for PPVC and Semi-prefabrication projects.....	164
Figure 10-6	Activity contribution of countries involved in raw material extraction, manufacturing and fabrication processes	166
Figure 10-7	Comparison of social performance score of PPVC and Semi-Prefabrication buildings in raw material extraction, and manufacturing and fabrication phases	168
Figure 10-8	Scores of social impact subcategories for PPVC and semi-prefabrication projects	173
Figure 10-9	Scores of stakeholder categories for PPVC and semi-prefabrication projects	174

LIST OF ABBREVIATIONS

AC	Air-Conditioning
AFR	Accident Frequency Rate
AHP	Analytic Hierarchy Process
AHU	Air Handling Unit
AoP	Area of Protection
AP	Acidification Potential
BCA	Building and Construction Authority
BEAM	Building Environmental Assessment Method
BEES	Building for Environmental and Economic Sustainability
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
C&D	Construction and Demolition
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CC	Chilled Ceiling
CFPR	Consistent Fuzzy Preference Relation
DALY	Disability-Adjusted Loss of Life Years
EAC	Equivalent Annual Cost
E-LCA	Environmental Life Cycle Assessment
E-LCI	Environmental Life Cycle Inventory
E-LCIA	Environmental Life Cycle Impact Assessment
ELECTRE	Elimination And Choice Expressing Reality
EP	Eutrophication Potential
FAST	Fourier Amplitude Sensitivity Test
FU	Functional Unit
GBRS	Green Building Rating System
GHG	Greenhouse Gas
GSA	Global Sensitivity Analysis
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air-Conditioning
IEQ	Indoor Environmental Quality
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCCA	Life Cycle Costing Analysis
LCCEA	Life Cycle Carbon Emissions Analysis
LCEA	Life Cycle Energy Analysis

LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
LDS	Low-Discrepancy Sampling
LEED	Leadership in Energy and Environmental Design
LHS	Latin Hypercube Sampling
MAUT	Multi Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCS	Monte Carlo Sampling
NPV	Net Present Value
O&M	Operation and Maintenance
OAT	One-At-A-Time
ODP	Ozone Depletion Potential
PCM	Phase Change Materials
PV system	Photovoltaic System
PMV	Predicted Mean Vote
POCP	Photochemical Ozone Creation Potential
PPVC	Prefabricated Prefinished Volumetric Construction
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluation
PRS	Performance Reference Scale
PRV	Performance Reference Value
SEM	Standard Error of The Mean
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
S-LCIA	Social Life Cycle Impact Assessment
SPS	Social Performance Scores
SRC	Standardized Regression Coefficient
SRRC	Standardized Rank Regression Coefficient
TBL	Triple Bottom Line
UNEP	United Nations Environment Programme
USGBC	U.S. Green Building Council
VAV	Variable Air Volume
WBS	Whole Building System

Chapter 1 Introduction

This chapter firstly introduces the research background, such as the concepts of sustainable development and sustainability assessment, as well as motivations for this research area. Then some of the research gaps associated with this area are presented followed by the aim and objectives, which are set to address research issues and bridge research gaps. Finally, each chapter is briefly introduced to highlight the structure of this thesis.

1.1 Research Background

The construction industry, which is a greatly active industry in both developed and developing countries, is of great economic significance and influences human being's well-being and the environment in both positive and negative manners (Rwelamila, Talukhaba et al. 2000, Burgan and Sansom 2006, Berardi 2012, Kamali and Hewage 2017). On one hand, buildings, as shelters, satisfy people's basic needs and improve their life quality. The development of building projects create numerous employment opportunities and contribute greatly to national economy (Love and Irani 2004, Zuo and Zhao 2014). For example, the Singapore construction industry accounts for 4.3% of national GDP (DOS 2018) and provides jobs for over 100 thousand residents (MOM 2017).

On the other hand, building projects contribute to global environmental burdens through consuming raw materials and energy to construct and operate, releasing greenhouse gases (GHG), generating solid waste, causing pollution and occupying land (Ding 2008, Wong and Fan 2013). It is estimated that buildings globally consume 40% of energy, 40% of resources, 25% of water, and release 35% of GHG (UNEP 2013). In addition, building projects are responsible for safety and health issues due to high possibility of unsafe working environment during construction process (Shen, Tam et al. 2010, Zhang, Wu et al. 2015). It is reported that the construction industry has been continuously the top contributor these years to both fatal and major injuries in Singapore, accounting for around 40% of all industrial injuries (WSH 2016). Besides, construction activities inevitably cause disturbance to the surroundings and influence the comfort and health of the neighbours; the quality of building products and indoor environment quality also have great effect on the occupational health (Zuo, Pullen et al. 2017).

With the awareness of above-mentioned issues, there is an increasing consensus that proper strategies and actions are desired to avoid or mitigate negative impacts and to create a balance among economic development, environmental protection and social acceptability for both short- and long-term consideration (Ortiz, Castells et al. 2009). In other words, there is a growing demand on sustainable development, or sustainable construction in the context of the construction industry, which shifts the development

focus from traditional objectives, such as time and cost, towards much broader ones. Sustainable development is defined as the development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission 1987). Generally, sustainability is identified and monitored based on the Triple Bottom Line (TBL) theory, which identifies the three dimensions of sustainable development namely, environment, economy, social equity (Adams 2006). These three dimensions interact with each other; economic development is always the major pursuit while the degradation of the environment and decline in human welfare will restrain the economic growth in the long term (Kahuthu 2006).

The concept of sustainable construction has drawn a worldwide attention (Hill and Bowen 1997, Bossel 1999, Krajnc and Glavič 2005, Ding 2008, Kibert 2008, Ortiz, Castells et al. 2009, Kibert 2012). Policies, laws and regulations have been established in many countries to encourage the construction industry to adopt sustainable innovations in respect of building products and development processes. In Singapore, the Building Control Act and the Building Control (Environmental Sustainability) Regulations have been initiated and put in place by the Building and Construction Authority (BCA) for many years. This is to ensure the conformity of a minimum environmental sustainability standard as defined in BCA Green Mark Scheme (BCA 2017). In the latest Green Building Masterplan, a target of making 80% of the buildings in Singapore green by 2030 has been set with corresponding efforts such as greening the existing building stocks and increasing support on the development of green building technologies and solutions (Urban Redevelopment Authority 2012, BCA 2014). With an international movement in the past years, it is observed that various resource-efficient solutions have been proposed and explored, such as recycling and reusing construction and demolition waste (Silva, De Brito et al. 2014), adopting renewable energy technologies in buildings (such as solar water heater and solar PV) (Kannan, Leong et al. 2006, Gunerhan and Hepbasli 2007), and active or passive energy efficient strategies (such as improvements to HVAC systems and building envelope elements) (Sadineni, Madala et al. 2011, Liu, Schulz et al. 2016).

While technical innovations undoubtedly facilitate the movement towards sustainable construction, sustainability also relies on appropriate decisions and strategies made by various stakeholders involved in the entire project development process, such as owners, designers, contractors, government, etc. Responsible and sensible decision-making should be based on the awareness of key issues and understanding of impacts of individual actions, which highlights the necessity of identification, evaluation and monitoring of the sustainable performance in various aspects. Accordingly, development of building-specific sustainability assessment methods becomes crucial to attaining the goals of sustainable construction (Wallhagen and Glaumann 2011, Berardi 2012).

Up until now, different methods, frameworks or tools have been proposed and developed to evaluate the greenness or sustainability of building materials, components, systems or the entire projects. They can be divided roughly into two categories (Forsberg and Von Malmborg 2004), including qualitative ones based on scores and criteria, such as green building rating system/schemes, as well as quantitative ones based on quantitative input and output data on material and energy flows, such as life cycle assessment (LCA) methods at different levels of complexity (Alshamrani, Galal et al. 2014, Cao, Li et al. 2015, Cobut, Blanchet et al. 2015, Liu, Schulz et al. 2016, Sierra-Pérez, Boschmonart-Rives et al. 2016).

Green building rating systems (GBRSs) are quite popular in the industrial practices. It is estimated that over 600 GBRSs are available globally and are being updated continuously (Doan, Ghaffarianhoseini et al. 2017). BREEAM (Building Research Establishment Environmental Assessment Method) from the UK, launched in 1990, is seen as the first attempt to assess building's environmental performance through a broad coverage of criteria (Lee 2013, Awadh 2017). Due to its flexibility in adapting different application scenarios, BREEAM certifications have been issued to more than 560,000 building projects in 78 countries and territories today (BRE 2017). Another globally recognized GBRS is LEED (Leadership in Energy and Environmental Design) from the US, which is the most widely used GBRS in the world with 92,000 projects in over 165 countries and territories (USGBC 2018). BREEAM and LEED are two mainstream methods, and have greatly influenced the

development of later GBRs, such as BEAM (Building Environmental Assessment Method) from Hong Kong, CASBEE (Comprehensive Assessment System for Built Environment Efficiency) from Japan, Green Star from Australia and Green Mark from Singapore. The initiation of these GBRs has greatly encouraged the involvement of construction practitioners into the sustainable actions. Buildings with certification increase the overall reputation of the property, which benefits the developers; meanwhile, certificated buildings are believed to perform better in terms of energy consumption and indoor environment quality. For instant, it is estimated that Green Mark Gold^{PLUS} buildings and Green Mark Platinum buildings can achieve at least 25% and 30% savings respectively in annual energy consumption compared to the non-certificated buildings that reach the minimum requirements of Singapore building Regulations only (BCA 2017).

With a broad coverage of sustainable assessment criteria, GBRs may serve as easy-to-adopt guides for planning and design. However, using scoring approach in assessing most of the impact categories, GBRs only provide a subjective rating scale of the examined built environment system or offer a qualitative evaluation, rather than an illustration of the actual performance, which makes their assessment results more of a declaration of sustainable practices. The effectiveness and the reliability of GBRs assessment results used as decision-making basis are thus questionable. There have also been criticisms that the point-based system of GBRs sometimes makes decision-makers focus merely on chasing the points in order to reach rating goals while distracts their attention away from setting and achieving sustainability targets (Cole 2005, Wedding and Crawford-Brown 2007).

The shortcomings of GBRs have given rise to the need of reliable quantitative information on project's sustainability performance, especially for comparison purpose and multi-alternative decision-making, which have driven the development of another group of methods, namely, quantitative assessment methods. These methods address different sustainability aspects, mainly environmental impacts, and vary in the assessment scope and intended application. Some of them are mono-indicator calculation methods, such as energy analysis accounting for the energy inputs (which could be embodied energy or operating energy), and carbon footprint

analysis estimating the direct and indirect GHG emissions in a certain process. Some of them are more systematic, such as material flow analysis, cost-benefit analysis, environmental risk assessment and life cycle assessment (LCA).

Among these methods, LCA is the most widely applied method in the building-related sustainability assessment (Buyle, Braet et al. 2013). It investigates and quantifies environmental burdens of a product system through its life cycle (ISO 2006), typically starting from raw material extraction, followed by production, construction, operation, maintenance and final demolition. The “cradle-to-gate” approach of LCA makes it unique among other methods (Forsberg and Von Malmborg 2004, Finnveden, Hauschild et al. 2009), while other methods, when extending their evaluation scope to the entire life cycle, can be a part or complement of LCA. Through investigating life-cycle activities and their relevant environmental impacts in terms of natural environment, human health and resource depletion, LCA method can avoid problem-shifting between different life-cycle stages, between regions and between environmental problems, and thus it can help decision makers understand long-term environmental impact of a given technology under a certain regional condition (Bribián, Uson et al. 2009, Malmqvist, Glaumann et al. 2011, Basbagill, Flager et al. 2013).

However, as LCA was developed intending for environmental assessment, it does not address all of the dimensions of sustainability (Reijnders and Van Roekel 1999, Forsberg and Von Malmborg 2004, Haapio and Viitaniemi 2008, Berardi 2012, Khoshnava, Rostami et al. 2016). It is, therefore, desirable and worthwhile to conduct a study on the development of a quantitative sustainability assessment method based on life-cycle approach, extending the current assessment scope of LCA and embracing all the sustainability dimensions. A conceptual model proposed by Klöpffer (2003, 2008), life cycle sustainability assessment (LCSA) model, serves as the basis for method development. It identifies the sustainability of a product from a life-cycle perspective through the combination of LCA for environmental impact evaluation, as well as life-cycle cost analysis (LCCA) for economic analysis and social life cycle assessment (S-LCA) for social acceptability evaluation. To stress the

environmentally relevant feature of LCA and to avoid possible confusion, in the rest part of the thesis, the term, environmental LCA (E-LCA) is used instead of LCA.

1.2 Research Gaps

LCSA model is seen as a very promising approach for sustainability assessment from life-cycle perspective, yet it is still in its infancy, with many methodological details unclear or poorly addressed, not to mention its application in the building-specific analysis. As LCSA is a method via integrating three independent methods, issues existing in the individual methods should be addressed; two of them are highlighted: (1) methodological development of S-LCA (2) Characterization of uncertainties in E-LCA.

Review on existing studies of S-LCA indicates that S-LCA is still in its infancy and many aspects of S-LCA remain unclear. It has been pointed out that there is no consensus on the selection of the impact categories in S-LCA (Jørgensen, Le Bocq et al. 2008). In addition, it is still unclear how to characterize these social impact categories (Parent, Cucuzzella et al. 2010). As for E-LCA method, although it is widely recognized that uncertainties are significant and need to be made explicit, a standardized approach to addressing uncertainty issues is still lacking (Ciroth, Fleischer et al. 2004, Haapio and Viitaniemi 2008). In general, uncertainty and sensitivity analysis are recommended in ISO 14040 (2006) as additional data quality analyses in E-LCA, yet no specific techniques are provided.

In addition to the development or improvement of individual methods, how to integrate LCCA, E-LCA and S-LCA into a holistic model to facilitate decision-making process is also an important research topic. In order to make proper and rational decisions, especially for the decision-making problems with multiple alternatives that have conflicting results regarding economic, environmental and social performance, a solid and logical backbone should be embedded in the LCSA model. A detailed discussion on research gaps will be provided in Chapters 2 and 3.

1.3 Aim and Objectives

Motivated by global trend of sustainable development in the construction industry, as well as the necessity of providing quantitative information on both short- and long-

term performance of building systems to facilitate sustainability-oriented decision-making, this study aims *to develop a building-specific sustainability assessment model that encompasses three dimensions of sustainability and long-term impacts and is able to facilitate sustainability-oriented decision-making.*

In line with the research aim and the identification of research gaps, five research objectives are identified, including:

- To obtain an in-depth understanding of existing building-specific assessment methods or tools,
- To establish a set of assessment criteria and corresponding indicators for measuring building performances in terms of three dimensions of sustainability,
- To propose a social impact assessment approach for quantitative evaluation of life-cycle social impacts of buildings,
- To provide suggestions on method selection for characterizing parameter uncertainties in E-LCA,
- To develop an integrated LCSA model for sustainability-oriented decision-making

1.4 Structure of Thesis

This thesis is organized into eleven chapters in the following sequence.

Chapter 1 provides an overall introduction with a rationale for the research related to the development of building-specific sustainability assessment model. Research gaps are then discussed, followed by the aim and objectives of this study.

Chapter 2 provides an overview of the concept of sustainable construction and also sustainability assessment tools and methods.

Chapter 3 reviews life-cycle based assessment methods, which are LCCA, E-LCA, S-LCA and LCSA. Research gaps and questions are identified and discussed.

Chapter 4 outlines the research framework with detailed research procedure and tasks and describes research method in detail.

Chapter 5 presents a comparative case study on the environmental and economic performance of CC and VAV systems. This chapter is associated with the first research objective, which will lead to a more in-depth understanding of these two life-cycle based assessment techniques.

Chapter 6 presents the conceptual framework for LCSA. This chapter, as the first step for assessment model development, extracts assessment criteria from three life-cycle methods, and constructs a hierarchical framework for sustainability assessment. Discussions in this chapter focus on selecting impact categories for the evaluation of environmental and social performance.

Chapter 7 presents a social life cycle impact assessment method, which deals with indicators selection, weights determination and calculation of social impact scores. The proposed method is illustrated via a case study that compares social performance of CC and VAV systems.

Chapter 8 provides a comparative analysis on those commonly used methods for uncertainty characterization of E-LCA, and discusses advantages of each method, based on which suggestions on method selection are given.

Chapter 9 presents an integrated LCSA model based on fuzzy ELECTRE III method. Procedures to conducting sustainability assessment and making sustainability-oriented decisions using LCSA model are also provided.

Chapter 10 demonstrates the applicability and validity of the proposed model through a case study. The case study investigates the sustainability performance of adopting prefabricated prefinished volumetric construction (PPVC) method in building construction and compares its sustainability performance with other commonly adopted construction techniques.

Chapter 11 summarizes the outcomes and contributions of this study and states the limitations and future research need.

Chapter 2 Overview of Sustainable Construction and Sustainability Assessment

Sustainability movement in the construction industry was motivated by finding answers to two critical questions: one is what is sustainability and sustainable construction, and the other is how to determine the sustainable performance of a building (Kibert 2016). The first one is obviously fundamental since a solid understanding on the concept of sustainable construction could serve as the basis for further efforts towards sustainability; while the answer to the second question aims at examining the outcomes of these efforts by conducting building assessments, which illustrate the sustainability performance of a building in multiple impact categories.

This chapter therefore provides a general review on these two issues. The definitions and principles of sustainable construction are firstly discussed, followed by a brief introduction of green building rating systems (GBRSs) and quantitative sustainability assessment methods. GBRSs are further examined through an in-depth comparison and discussion. At last, multi-criteria decision analysis (MCDA) methods are introduced considering the need of dealing with multiple concerns regarding sustainability in developing integrated sustainable assessment method.

2.1 Sustainable Construction

2.1.1 Concept of Sustainable Construction

The sustainable construction movement was stimulated by the idea of sustainable development or sustainability. In *Our Common Future*, sustainable development was defined as the development that “*meets the needs of the present generation without compromising the ability of future generations to meet their own needs*” (Brundtland Commission 1987). This well-known definition implies the justice between generations, highlighting the responsibility of the contemporaries to the future inhabitants of this world. It also implies that environmental quality and human well-being are as crucial as economic growth; these three aspects are interdependent and deserve fair consideration during the development process. This widely cited definition has become a conceptual guiding principle or benchmark for governments, authorities, industry and academia regarding further sustainability-oriented efforts. It is now widely accepted that environmental, economic, social dimensions, also known as ‘3Es’ (environment, economy, social equity) or ‘3Ps’ (planet, profit, people), are the three key dimensions of sustainability, which should be comprehensively examined to judge the success of a project regarding sustainable development (Adams 2006, Sev 2009). Based on the definition and three-dimension interpretation, wide discussions have been made in both academic and policy areas for over three decades, debating different approaches to achieving sustainability in different industrial areas.

In the context of the construction industry, sustainable development is expressed as green construction or sustainable construction; buildings following the sustainable principles are named as high-performance buildings, ecological buildings, green buildings or sustainable buildings (Ali and Al Nsairat 2009, Korkmaz, Riley et al. 2010, Vakili-Ardebili and Boussabaine 2010, Häkkinen and Belloni 2011, Ionescu, Baracu et al. 2015). These terms are sometimes interchangeable; yet strictly speaking, terms such as greenness or high-performance focus on the environmental dimension, while sustainable construction and sustainable building encompass environmental, economic and social aspects more comprehensively. The differences in the concern of two terms are listed in Table 2-1, which are adapted from Berardi’s study (2013).

Table 2-1 Comparison of main concerns in green and sustainable buildings,
adapted from (Berardi 2013)

Main Concerns	Green Building	Sustainable Building
Energy consumption	√	√
Water consumption	√	√
Material consumption	√	√
Solid waste and liquid effluents	√	√
Emissions (such as, GHG and ozone depletion substances)	√	√
Land use	√	√
Impacts on-site ecology	√	√
Urban and planning issues	√*	√
Indoor well-being (air quality, lighting, acoustics, etc.)	√ *	√
Longevity, adaptability, flexibility		√
Operations and maintenance		√
Facilities management		√
Economic benefit	√ *	√
Social issues (access, education, inclusion, cohesion)		√
Cultural perception and inspiration		√

* Not always included

The broadened concerns of sustainable construction are the result of continuously deepened understanding of the concept of sustainable construction. Starting from the first definition of sustainable construction proposed in 1994, indicating sustainable construction is “*the creation and operation of a healthy built environment based on resource efficient and ecological principle*”(Kibert 1994), sustainable construction never stops asking for more besides the tradition focus on cost, quality and delivery as well as typical greenness-related focus on resource reservation and environmental protection. It further requires the improvement in social equity, human physical and mental health, and social infrastructure, as well as preservation of culture, heritage and traditions (Du Plessis 2007, Robichaud and Anantatmula 2010, Berardi 2013). As summarized in ISO 15392, sustainable construction is supposed to “*match the appropriate fitness for use, with minimum adverse environmental impacts, while*

encouraging improvements in economic, social and cultural aspects at local, regional and global levels” (ISO 2008). With more socially related concerns involved, interests and rights of multiple stakeholders, such as workers and the neighbourhood, are supposed to be respected and fairly treated (Pitt, Tucker et al. 2009, Robichaud and Anantatmula 2010).

Sustainable construction also needs to cover the entire construction life cycle including not only the on-site construction work and operation but also the upstream and downstream processes (Tan, Shen et al. 2011). Therefore, practices in other phases, such as life-cycle based design and end-of-life strategies (CIB 2010), have become the part of sustainable construction requirements. Such cradle-to-grave consideration is featured in some definitions. For instance, USEPA (2016) defined it as *“the practice of creating structures and using processes that are environmentally responsible and resource efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction”*. Berardi (2013) defined it as *“designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community”*.

Inspired by above discussions, sustainable construction in this study is defined as *a holistic and balanced process that aims at meeting a building's functional requirement throughout its entire life cycle in a resource-efficient manner, and at the same time, minimizing negative environmental impact, increasing economic acceptability, and improving human's well-being via protection of occupants' satisfaction and other stakeholder's rights*. This definition sets the tone for further discussion in this thesis, in which functional serviceability is the prerequisite; all the life-cycle phases (from planning and designs to construction and O&M, and eventually to deconstruction and recycling) need to be considered; and the balances of three-dimension sustainability performances and multi-stakeholder interests need to be attained.

2.1.2 Moving towards Sustainable Construction

Numerous benefits have been identified associated with the sustainable construction practices. Sustainable buildings are believed to be more resource-efficient compared

with conventional buildings particularly in terms of savings in energy consumption, enhancement of material efficiency and reduction in waste streams (Bullen 2007, Jaillon, Poon et al. 2009, Raut, Ralegaonkar et al. 2011), which further reduce the negative environmental impacts such as GHG emissions and pollutants. Sustainable buildings also help with urban biodiversity improvement and ecosystem protection through implementing sustainable land use planning (Henry and Frascaria-Lacoste 2012).

Tightly associated with environmental benefits such as energy saving and improved water and material efficiency, sustainable buildings also achieve great savings in operational costs, and thus are economic sound from long-term consideration although may be more costly on initial costs (Kibert 2016). In addition, sustainable buildings have positive impacts on the human well-being. Sustainable buildings are usually designed with a comprehensive consideration of thermal, acoustical and visual comfort, as well as indoor environmental quality (IEQ). Through advance simulation of important parameters, such as temperature, humidity and illuminance, and the continuous monitor and control during operational phase, sustainable buildings may enhance occupants' health and comfort, and also improve their productivity, as evidenced in previous studies (Ries, Bilec et al. 2006, Pan, Yin et al. 2008, Singh, Mahapatra et al. 2011, Gou, Lau et al. 2012).

Although potentially multifaceted benefits can be realized from sustainable construction, for construction practitioners, it is economic benefits that drive them towards sustainable construction movement, together with legislation and regulations that create mandatory pushes. According to a Singapore-context survey on sustainable construction (Chan, Qian et al. 2009), as summarized in Table 2-2, the top three reasons that attract business interests are all economic-related, including lower operation costs, lower lifetime cost and higher building values. Correspondingly, when it comes to the obstacles to the sustainable construction movement, cost is also one of the leading reasons. Higher initial costs due to the adoption of green materials or advanced techniques may stop construction practitioners from stepping into the sustainable construction movement (Chan, Qian et al. 2009). Although long-term cost savings can potentially recover those costs, it

is hard to convince the developer to pay for the higher initial costs and to expect higher rental or occupancy rate as the tenants will benefit from cost savings and better indoor environment. On the other hand, tenants are not ready or willing to pay for the sustainable building concepts which are still not widely acknowledged and highly valued (Robichaud and Anantatmula 2010, Yudelso 2010). In addition, deep-rooted perception of the traditional way to construct a building, incomplete understanding of sustainable construction, as well as insufficient information on green materials and products, also remain as the main obstacles (Hwang and Tan 2012).

Table 2-2 Reasons that drive and prevent sustainable construction movement in Singapore, adapted from (Chan, Qian et al. 2009)

Ranking	Drives	Obstacles
1	Lower operation costs	Perceived higher upfront costs
2	Lower lifetime cost	Lack of education
3	Higher building values	Lack of awareness
4	Higher return on investment	No fiscal incentives from the government
5	Enhanced marketability	Different accounting methods
6	Help to transform the market	Lack of research and cases study
7	Reduced liability and risk	No coordination and consistency in rating tools and standards
8	Increased staff productivity and retention	Unrecognized eco-labeling for products and materials

To enable the sustainable construction movement, supportive actions need to be taken by various stakeholders in different aspects. As summarized in Du Plessis's study (2007), actions could be technological, institutional, or value-system-related. Sustainability-oriented value systems drive and guide the technological and institutional actions, technology development outcomes deliver essential knowledge and technical capacity for specific actions, while institutional enablers promote and encourage the adoption of new technologies.

As for technological aspects, a wide variety of resource-efficient strategies and innovations have emerged. Special attention has been paid to optimizing energy consumption. Strategies, such as employing energy and daylighting simulation in the

early design stage (Crawley, Hand et al. 2008, Pacheco, Ordóñez et al. 2012), adopting passive design strategies (Ochoa and Capeluto 2008, Stevanović 2013) and maximizing the thermal performance of the building envelope (Wang, Zhang et al. 2009), have been widely discussed and gradually employed in today's construction practices. Innovative energy optimization techniques have also been developed, serving as alternatives to the traditional ones. For example, radiant cooling systems are seen as a good alternative to traditional VAV systems owing to its lower operational energy consumption, better thermal comfort, space saving and noise level reduction (Strand and Baumgartner 2005, Hao, Zhang et al. 2007). Utilizing renewable energy systems, such as solar PV cells, small-scale wind turbines and solar water heating systems (Kannan, Leong et al. 2006, Gunerhan and Hepbasli 2007, Korjenic, Petráněk et al. 2011), can address the issue of energy crisis and the negative environmental issues associated with conventional energy resources. These renewable energy systems act an important role in achieving net zero energy buildings (Marszal, Heiselberg et al. 2011).

Another focus is on increasing material utilization efficiency and minimizing construction and demolition (C&D) waste. Reduction, reuse and recycling, called the "3Rs", are summarized as the three main strategies for C&D waste minimization. Implementation of prefabricated, modular and standardized building components is seen as a promising solution to waste reduction at source, along with other benefits such as increasing construction productivity and quality, and improving site management (Jaillon, Poon et al. 2009), which is also encouraged by Singapore BCA. Some other techniques, such as using reusable formwork systems (steel or aluminium formworks) (Poon, Yu et al. 2004), recycled aggregate concrete (Li 2008), BIM for material usage planning (Wu 2017), indirectly help reduce waste through reuse and recycling or better material control (Thormark 2006).

In addition to the hard technologies as mentioned, some 'softer' aspects have also attracted wide attention (Du Plessis 2007). As stated by Häkkinen and Belloni (2011), it is procedural and organizational issues rather than the lack of new technologies that beset the sustainable construction movement. Previous studies have highlighted the importance of sustainability-oriented project management and have proposed various

strategies including early involvement of the entire team members, establishing a collaborative team environment, applying lean concepts, continuous monitoring and assessment, involving sustainable building experts and so on (Robichaud and Anantatmula 2010, Wu and Low 2010, Li, Chen et al. 2011).

Among these managerial practices, it is of importance to understand project's sustainability goals and impacts of individual actions, as well as make sustainability-oriented decisions. Being weak in these aspects may hinder the sustainable construction practices at the project/organization level. Construction practitioners are curious about answers to questions such as: What are the requirements for sustainable construction? How much benefit can be expected from adopting sustainable technologies, design strategies or management practices? How is the sustainability performance of a building project/system actually? How to select from several design options or technology alternatives based on sustainable consideration? This thesis, therefore, centres on addressing these concerns through developing sustainability assessment methods and applying suitable decision-making models in sustainable construction.

2.2 Sustainability Assessment of Buildings

Sustainability assessment is a process to identify, predict and evaluate the potential impact of a certain product or process (Devuyst 2000). Up until now, different methods, frameworks or tools have been proposed and developed to perform sustainability assessment, with the coverage of different assessment scopes (i.e., different pillars of sustainability) and scales (i.e., micro or macro). These tools can be divided into three categories, as proposed by Ness et al. (2007), which include indicators and indices, product-related assessment tools and integrated assessment systems. Indicators could be either non-integrated ones, which are simple measures converting individual aspects of sustainable development concerns into manageable quantitative information, or integrated ones, which represent a wide coverage of sustainable development concerns using countable indexes, such as Wellbeing Index (Prescott-Allen 2001) and Human Development Index (UNDP 2016). Product-related assessment tools focus on flows associated with production and consumption of products or services. These tools evaluate resource consumption, energy uses, and

/or sustainability-related impacts (mostly refers to environmental and economic impacts), such as material flow analysis, energy analysis, E-LCA and LCCA. Integrated assessment systems are used to support decision-making regarding a project or a policy with the integration of various sustainability aspects. They are established based on system analysis approaches, such as risk analysis, cost-benefit analysis and multi-criteria analysis.

As for building-specific sustainability assessment, existing methods can be categorized in different ways. According to the evaluation purpose, ATHENA Institute divided existing tools (particularly environmental assessment tools) into three levels (Trusty 2000), including (1) product comparison tools, such as BEES (US), (2) whole building design or decision support tools, such as Eco-Quantum (Netherlands), Envest (UK) and ATHENA (Canada), and (3) whole building assessment frameworks or systems, such as EcoEffect (Sweden), BREEAM (UK) and LEED (US). There are also several studies separating these tools from the perspective of methodological difference (Forsberg and Von Malmberg 2004, Ali and Al Nsairat 2009, Mateus and Bragança 2011). In their studies, tools are classified into (1) qualitative tools based on scores and criteria, and (2) quantitative tools investigating quantitative input and output data on material and energy flows. The first ones mainly refer to those known as green building rating systems (GBRSs), such as BREEAM (UK) and LEED (US), while the second ones mainly refer to those tools based on E-LCA methods with different evaluation objectives, such as BEES (US), Eco-Quantum (Netherlands), ATHENA (Canada) and EcoEffect (Sweden). This classification system was also adopted in this study for the following discussion on assessment methods.

2.2.1 Green Building Rating Systems

GBRSs are quite popular in the industrial practices, which refers to the tools that examine the performance or expected performance of the entire building and translate the examination results into an overall assessment allowing for comparison against other buildings (Fowler and Rauch 2006, Doan, Ghaffarianhoseini et al. 2017). Different rating systems have been developed worldwide, among which BREEAM and LEED are the most widely recognized ones as they are not limited to their places

of origin. BREEAM is seen as the first launched GBRS (Lee 2013, Awadh 2017) and LEED is the most widely used GBRS (USGBC 2018). These two systems represent the two mainstreams of GBRSs, and they have influenced the development of later GBRSs (Lee 2012), such as BEAM (Hong Kong), CASBEE (Japan), Green Star (Australia) and Green Mark (Singapore). These GBRSs usually have a similar coverage of sustainable assessment criteria, such as building energy efficiency, water efficiency, construction material and resources and indoor environmental quality. Meanwhile, these systems also vary due to different industry needs in their countries of origin as well as different performance levels achievable above local building regulations. In other words, GBRS can reflect the status of sustainable construction practices in different countries.

Many studies have been done to compare various GBRSs (Alyami and Rezgui 2012, Lee 2012, Lee 2013). However, Green Mark has seldom been discussed in previous comparative studies, since it is tailored for tropical and sub-tropical climates and thus it is regionally limited. Green Mark, launched in January 2005, was developed by the Building and Construction Authority (BCA) in Singapore. It aims at promoting sustainability in Singapore construction industry and raising environmental awareness among developers, designers and contractors (BCA 2017). This section, therefore, compared Green Mark with BREEAM and LEED, which can help understand the current sustainable construction practices in Singapore, as well as have an overview on the common features of GBRSs.

In order to conduct the comparison on the same basis, the latest versions of these methods were investigated, as summarized in Table 2-3. It can be observed that all the latest versions of these systems were released and updated within the past five years. This illustrates the active efforts made by these organizations in system revision and updating in order to enable the GBRSs to follow the changing trend of sustainable construction. All the rating systems have established assessment methods separately for new and existing buildings, as well as residential buildings, industrial and commercial buildings, and other specially-functioned buildings such as schools and healthcare, although applying different classification systems on building types. On the other hand, assessment structures of BREEAM and LEED are subdivided in

more detail. For instance, regarding assessment of existing buildings, BREEAM differentiates “In-Use” stage from “Refurbishment and Fit-Out” stage; the former evaluates the operational efficiency and the latter assesses sustainability-related impacts during the design and works of a refurbishment or fit out project. LEED develops a separate assessment scheme for interior design and construction, to stress the importance of indoor space quality.

In terms of rating approach, both Green Mark and LEED adopt simple additive points approach, in which points assigned to each performance aspect are summed up to calculate the final score without weighting process. As for BREEAM, each evaluation section has several sustainability-related requirements and corresponding credits. Percentage of credits achieved for each section is calculated depending on the number of requirements met. These percentages are then multiplied by the weights of corresponding sections, giving individual section scores. These scores are then added together to obtain the final BREEAM score.

Table 2-3 Basic features of Green Mark, BREEAM and LEED

	Green Mark	BREEAM	LEED
Organization	Singapore BCA (Government body)	UK BRE (Non-profit)	USGBC (Non-profit)
First & Latest Versions	2005 & 2015 (updated in 2018)	1990 & 2016	1998 & 2013 (updated in 2018)
Website	https://www.bca.gov.sg/GreenMark/green_mark_building.html	https://www.breeam.com/	https://new.usgbc.org/leed
Rating System Structure	New Buildings Existing Buildings	New Construction Refurbishment & Fit-out In-Use	Design and Construction Interior Design and Construction Building Operations and Maintenance Homes
Building Types	<ul style="list-style-type: none"> Residential buildings Non-residential buildings: commercial buildings (office, retail and hotel); industrial buildings; institutional buildings Others: schools, healthcare, landed houses, data centres, etc. 	<ul style="list-style-type: none"> Domestic buildings Non-domestic buildings: Industrial buildings (office, retail and industrial); public buildings (education, healthcare, courts and prisons); multi-residential accommodation; others 	<ul style="list-style-type: none"> Homes: single family homes, low-rise multi-family or mid-rise multi-family Industrial and commercial buildings Others: schools, healthcare, data centres, warehouses & distribution, hospitality
Rating Approach	simple additive points approach	additive pre-weighted credits approach	simple additive points approach
Rating Level	Platinum ≥ 70 Points Gold ^{PLUS} ≥ 60 Points Gold ≥ 50 Points (possible points: 140 points)	Outstanding ≥ 85 % Excellent ≥ 70 % Very Good ≥ 55 % Good ≥ 45 % Pass ≥ 30 % Unclassified < 30 %	Platinum ≥ 80 Points Gold ≥ 60 Points Silver ≥ 50 Points Certified ≥ 40 Points (possible points: 110 points)

To compare sustainable assessment criteria covered by different rating systems, this study investigates the latest versions for non-residential buildings, i.e., *Green Mark for New Non-Residential Buildings 2015* (BCA 2015), *BREEAM International New Construction 2016* (BRE 2016), and *LEED Version 4 for Building Design and Construction* (USGBC 2013), as summarized in Table 2-4. BREEAM has the most criteria, which gives the initial impression that BREEAM covers a wider assessment scope. As these methods apply different assessment structure, a set of re-organized categories was created to facilitate the comparison, and percentages of point/credits assigned in different systems were calculated.

Table 2-4 Assessment scope of Green Mark, BREEAM and LEED

	Green Mark	BREEAM	LEED
<i>Criteria Overview</i>			
- Sections	5	10	8
	Climate Responsive Design	Management Health & well-being	Location & Transportation
	Building energy performance	Energy Transport	Sustainable Sites Water Efficiency
	Resource Stewardship	Water Material	Energy & Atmosphere
	Smart & Healthy Building	Waste Land use & ecology	Material & Resources
	Advanced Green Efforts	Pollution Innovation	Indoor Environmental Quality
			Innovation
			Regional Priority
- Assessment issues	16	56	55
- Criteria/indicators	52	150	NA
<i>Re-organized categories & percentages of point/credits assigned</i>			
Energy	26%	17%	26%
Occupants' health and well-being	23%	14%	14%
Material & Resources	16%	15%	12%
Advanced Practices	11%	7%	4%
Management	10%	15%	6%
Water	6%	6%	10%
Land Use & Ecology	4%	7%	6%
Transportation	1%	7%	6%
Pollution	1%	9%	5%
Climate Change	1%	1%	3%
Community	-	2%	4%
Others	1%	-	4%
	(social well-being)		(regional priority)

As for Green Mark, *Energy*, *Occupants' health and well-being*, and *Material & Resources*, are assigned with the most points, which take up 65% of total points (140 pts). These three are also the top-three emphasized categories in LEED, but only take up 52% of total points (110 pts). While for BREEAM, *Energy*, *Material and Resources*, and *Management* are the most stressed criteria. Green Mark cares more for occupants' health and well-being compared with the other two systems; in addition, it stresses more in terms of *Advanced Practices*, which illustrates Singapore government's encouragement in applying advanced technologies/practices, such as use of 4D, 5D and 6D BIM and computation of carbon footprint for the entire development.

However, Green Mark lacks points for *Transportation* and *Pollution* compared with the others. Green Mark allocate 1.5 points under *Green Transport* regarding electrical vehicle charging and parking, car parking area reduction and bicycle usage promotion; however, a very common category, accessibility to public transportation, is not included. As for *Pollution*, other rating systems typically consider construction-related pollution, refrigerant management, nitrous oxides, stormwater management, light pollution and external noise attenuation, yet Green Mark only include stormwater and refrigerant management, with the latter treated as advanced effort. In addition, all three rating systems do not stress much on climate change issues and interaction with the community.

In summary, Green Mark, BREEAM and LEED provide a comprehensive environmental portfolio for environmental impact assessment. Their assessments focus on those common concerns of a building project development, including consumption of energy, materials and water, indoor environmental quality and waste management. Nevertheless, they do not emphasize pollutant and climate change despite of global significance and awareness. In terms of sustainability dimension coverage, as mentioned, most of the criteria are environmental related, while financial and social considerations are relatively weak. Percentages of points/credits assigned to life cycle cost planning and cost-effective design only range from 1% to 3%. As for social impacts, although occupant's health and comfort are well-addressed through criteria related to indoor air quality and spatial quality, well-being of other

stakeholders, such as workers and neighbourhoods, are neglected or not well-addressed.

From the perspective of rating approach (as shown in Table 2-3), GBRs do provide a simple and straightforward approach to integrating various sustainability-related practices into a common platform. They can serve as easy-to-adopt guides for planning and design. However, using scoring approach in assessing most of the impact categories, GBRs only provide a subjective rating scale of the examined built environment system or offer a qualitative evaluation, rather than an illustration of the actual performance, which makes their assessment results more of a declaration of sustainable practices. The effectiveness and the reliability of adopting GBRs assessment results as decision-making basis are thus questionable. In addition, it has been criticized that the point-based system of GBRs sometimes makes decision-makers focus merely on chasing the points and distracts their attention away from setting and achieving sustainability targets (Cole 2005, Wedding and Crawford-Brown 2007).

2.2.2 Quantitative Assessment Methods

Quantitative assessment methods overcome the shortcomings of GBRs in terms of assessment approach; they can provide relatively reliable quantitative information on project's sustainability performance. These methods vary in the assessment scope and intended application. Some of them are mono-indicator calculation methods, which quantify one aspect of sustainability, and present evaluation results as single measurement units, such as dollars, kWh and kg CO₂-equivalent. Cost might be the most frequently discussed aspect, and is always emphasized by a company together with quality and timely delivery (Asiedu and Gu 1998), regardless whether sustainable-related goals have been set. In addition, energy consumption and GHG emissions are the two common concerns regarding environmental aspects (Chau, Leung et al. 2015). In contrast to mono-indicator calculation methods, methods such as material flow analysis, cost-benefit analysis, environmental risk assessment and E-LCA are more systematic, among which E-LCA is the most widely applied method in the building-related sustainability assessment (Buyle, Braet et al. 2013).

E-LCA investigates life-cycle activities associated with a product system and quantifies relevant environmental impacts in terms of natural environment, human health and resource depletion, etc. (ISO 2006). As for a building project, life-cycle phases typically start from raw material extraction, followed by production of construction materials and components, construction, operation, maintenance and final demolition, which is illustrated by Figure 2-1. The “cradle-to-gate” approach of E-LCA makes it unique among other methods (Forsberg and Von Malmborg 2004, Finnveden, Hauschild et al. 2009), while other methods, when their evaluation scope is extended to the entire life cycle, can be a part or complement of E-LCA.

Figure 2-1 Concept of E-LCA and its relationship with LCEA and LCCEA

For instance, extending assessment scopes of the mono-indicator analyses as mentioned (i.e., cost, energy and GHG emissions calculation) gives rise to life-cycle based methods, that is, life cycle costing analysis (LCCA), life cycle energy analysis (LCEA) and life cycle carbon emissions analysis (LCCEA). LCEA calculates the energy inputs within the entire life cycle of a building, which includes (1) embodied energy referring to energy consumption during material manufacturing and construction processes, (2) operational energy referring to energy consumption for daily operations of HVAC systems, lighting, appliances, etc., and (3) energy consumptions for demolition, recycling and disposal processes, i.e., end-of-life phase (Chau, Leung et al. 2015). LCCEA considers all the CO₂-equivalent emission output

from the entire life cycle of a building, and similarly, it consists of embodied carbon emission, operational carbon emission and end-of-life carbon emission. A detailed review can be referred to Ramesh, Prakash et al. (2010), Cabeza, Rincón et al. (2014) and Chau, Leung et al. (2015). Both LCEA and LCCEA serve as a part of E-LCA, as indicated in Figure 2-1. LCCA, as an evaluation method for economic performance, can be seen as a complement to E-LCA aiming at evaluating environmental performance. A detailed review on life-cycle based methods will be provided in Chapter 3.

In summary, through taking different phases into consideration, life-cycle based method can avoid problem-shifting between different life-cycle phases, between regions and between environmental problems, and thus can help decision makers understand long-term impacts of a given technology under a certain regional condition (Bribián, Uson et al. 2009, Malmqvist, Glaumann et al. 2011, Basbagill, Flager et al. 2013). However, none of these methods, i.e., E-LCA for environmental assessment and LCCA for economic assessment, addresses all the dimensions of sustainability (Reijnders and Van Roekel 1999, Forsberg and Von Malmberg 2004, Haapio and Viitaniemi 2008, Berardi 2012, Khoshnava, Rostami et al. 2016). An integrated, life-cycle based approach is therefore needed. Many approaches have been discussed and developed in the literatures, among which life cycle sustainability assessment (LCSA) (Klöppfer 2003, 2008) that aims at comprehensively evaluating economic, environmental and social aspects from life-cycle perspective is one of the well-accepted approaches.

However, as a conceptual model, there are still many specific methodological issues to be solved. For one thing, there is no widely accepted method to assess life-cycle social impacts of building projects. Compared with E-LCA and LCCA that are relatively mature, S-LCA method is still under development. In addition, a proper sustainability assessment method is supposed to take multiple conflicting criteria into consideration and to make proper and informed decision in a structured, transparent and reliable manner (Cinelli, Coles et al. 2014). Such requirement can be achieved by multi-criteria decision analysis (MCDA), which was developed as effective decision support to address complex problems dealing with conflicting objectives and

interests (Martín-Gamboa, Iribarren et al. 2017). MCDA has proven its feasibility to be applied in sustainability-related studies, such as environmental management systems (Khalili and Duecker 2013) and green building material selection (Khoshnava, Rostami et al. 2016). A further review will be given in the following sections.

2.3 Multi-Criteria Decision Analysis for Sustainability Assessment

MCDA is a sub-discipline of operations research that is used to improve understanding of a complicated or uncertain decision-making problem (Linkov and Seager 2011). A typical MCDA requires decision problem to be firstly identified in order to specify analysis focuses and scope. A decision-making model should then be established; model parameters, including decision criteria and indicators, weights, alternatives and their performance on each criterion, and other constraints, should be prepared. Next, decision algorithm is applied to compare or rank among different alternatives, which lead to the result interpretation and final decision. These processes are connected closely, making backtracks and loops unavoidable before reaching a final decision. Criteria, alternatives, decision makers form the basic elements of MCDA problems, while decision algorithms are regarded as the centrepiece of MCDA (Linkov and Seager 2011).

Previous studies have proven the feasibility of MCDA methods in solving sustainability-related decision problems. MCDA can not only be used to provide solid and logical backbone for decision-making model (Khoshnava, Rostami et al. 2016), but also to address issues existing in sustainability-related decision-making problems, such as how to make trade-offs among socio-political, environmental and economic factors, and deal with both quantitative and qualitative data. There are various MCDA approaches that have been adopted in sustainability-related studies, such as AHP (Sambasivan and Fei 2008, Tseng, Lin et al. 2009, Ren, Manzardo et al. 2015, Thanki, Govindan et al. 2016), ELECTRE (Hatami-Marbini and Tavana 2011, Kaya and Kahraman 2011, Wen, Yu et al. 2016), TOPSIS (Kaya and Kahraman 2011, Kluczek and Gladysz 2015, Joshi and Kumar 2016), and PROMETHEE (Athawale and Chakraborty 2010, Ren, Xu et al. 2016, Arıkan, Şimşit-Kalender et al. 2017). These methods are either adopted solely or combined with other MCDM methods to take

full advantage of different methods (Kaya and Kahraman 2010, Kaya and Kahraman 2011, Kluczek and Gladysz 2015, Chauhan and Singh 2016, Joshi and Kumar 2016, Sánchez-Lozano, García-Cascales et al. 2016). A further review on these methods will be provided in Chapter 9 to serve as the basis for MCDA method selection in this study.

2.4 Summary

This chapter firstly examines existing concepts related to sustainable construction and proposes a definition for sustainable construction in this study, which is a holistic and balanced process that aims at meeting a building's functional requirement throughout its entire life cycle in a resource-efficient manner, and at the same time, minimizing negative environmental impact, achieving economic benefit, and improving human's well-being via protection of occupants' satisfaction and other stakeholder's rights.

This is followed by reviewing various sustainability assessment methods that are classified into two groups: GBRs as well as *quantitative assessment methods*. Through comparing Green Mark with BREEAM and LEED, current sustainable construction practices in Singapore and the common features of GBRs are discussed. In general, GBRs are easy to adopt and have broad coverage of criteria, but their qualitative nature makes the reliability of evaluation results questionable; on the other hand, quantitative assessment methods, such as E-LCA and LCCA, are more scientifically sound, yet an integrated quantitative assessment method is still under development. To this end, MCDA methods are briefly introduced, which will be extensively reviewed in Chapter 9. The basic procedure of conducting MCDA will serve as the skeleton for research design focusing on assessment method development.

Chapter 3 Review on Life-cycle Based Assessment Methods

In this chapter, a systematic review is conducted on four life-cycle based assessment methods, that is, LCCA, E-LCA, S-LCA and LCSA, in the context of the construction industry. As LCCA is assumed to be a maturely developed method, only basic concept and principles are introduced briefly. As for E-LCA, an overview is firstly given, followed by the review on the previous studies in the context of the building sector, based on which further research needs are discussed. At last, S-LCA and LCSA are reviewed. Considering their application in the construction industry is still in the early stage, the review is expanded to a more general application rather than only focusing on building-related studies.

3.1 Life Cycle Costing Analysis (LCCA)

LCCA is a technique to monitor the creation, operation and disposal costs of a selected alternative through its life cycle (New South Wales Treasury 2004). It was originally designed for procurement purpose in the US Department of Defence in the mid-1960s, and was further developed to be adapted to building investments since the mid-1980s (Gluch and Baumann 2004). The construction industry is one of the primary sectors that adopt LCCA, due to the long life span of buildings and high operating costs. In a review of published LCCA case studies (Korpi and Ala-Risku 2008), it is shown that 62% of the total case studies belong to the construction industry.

In the construction industry, LCCA is applied to quantifying life-cycle costs of whole buildings, systems and building components and materials. The technique can assist decision-making in building investment projects and offers a new angle to evaluate the cost of buildings. For instance, a building with better quality may cost less than those poor-quality buildings from life-cycle perspective, even though its initial construction cost may be higher.

Cost categories of LCCA for building projects are presented in Figure 3-1 as proposed by British Standards Institution (2008). A conceptual model for LCCA is given by Stanford University (Stanford University 2005), which is shown in the basic formula as follow:

$$LCC = C + PV_{\text{Recurring}} - PV_{\text{Residual Value}} \quad (3-1)$$

Where LCC is the life cycle costs, C is the year zero construction costs, $PV_{\text{Recurring}}$ is the present value of all recurring costs (including utilities, maintenance, replacement, service, etc.), and $PV_{\text{Residual Value}}$ is the present value of the residual value at the end of the study life.

Figure 3-1 Life cycle cost components of a building project

Construction costs (or capital costs) are further broken down into several categories according to different construction works, including substructure (including foundation, basement excavation and basement retaining wall) superstructure (including frame, stairs, upper floor, roof, external and internal walls, windows and doors), finishes (including ceiling finishes, wall finishes, floor finishes, fitting and furnishings), services, external works (including site works, drainage, external services, minor building works, and demolition and work outside the site), contingencies, preliminaries, and design fee (YUN 2013). In addition to the above-mentioned costs, residual value should also be considered. Residual value is the remaining value of a structure or a system at the end of the contract, or at the time when being replaced within the contract period (Langdon 2006). It can be calculated based on the value in place, salvage value, resale value or scrap value, net of any

selling, conversion or disposal costs. In general, residual value of a system with remaining useful life can be computed by linearly prorating its initial costs (Langdon 2006). Other cost variables considered include discount rate, inflation rate and taxes. Discount rate is a factor reflecting the time value of money and is usually adopted to convert cash flows occurring at different time to a common time.

It is also worth mentioning that the LCCA discussed in this study is financial LCCA, which is life cycle perspective financial economic analysis of a product and is presented as present value of all monetary costs for the studied building. However, there is another type of LCCA, called environmental LCCA, which is a newly developed method (Rebitzer and Hunkeler 2003). It is a weighting method of environmental impacts of an ELCA study in monetary terms. Environmental LCCA is a complement to financial LCCA and is a consecutive tool of E-LCA. There are some studies combining environmental LCCA with financial LCCA to address both environmental and economic aspects (Norris 2001, Reich 2005, Hoogmartens, Van Passel et al. 2014). However, in this study, only financial LCCA is considered considering the environmental aspects are addressed using E-LCA method.

3.2 Environmental Life Cycle Assessment (E-LCA)

3.2.1 Overview of E-LCA

E-LCA has been carried out in the construction industry since the 1990s. It is a method to quantitatively assess the environmental impacts of a product system over its life cycle (ISO 2006), usually including raw material extraction, transportation, manufacturing, use, end-of-life disposal and recycling. This “cradle-to-grave” approach avoids burden shifting from one environmental impact category to another and enables the identification of effective improvement strategies. Thus E-LCA has become an important decision-making tool today to facilitate companies to benchmark and optimize the environmental performance of products or to inform authorities to make policies in terms of sustainability (Hellweg and i Canals 2014). Current practices of E-LCA are executed based on the framework of the ISO 14040 series, which includes four iterative steps (ISO 2006): (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and

(4) interpretation of results. To avoid possible confusion, in the rest part of the thesis, the term, LCI and LCIA are replaced by E-LCI and E-LCIA, respectively.

Goal and scope definition phase states the intended application and audience of the study, the functional unit and system boundaries. Defining product systems based on their function rather than physical characteristics enables the comparison among inherently different products with similar function, for example, different construction materials. The system boundary defines the unit processes included in the E-LCA study, which is usually presented in a process flow map.

E-LCI analysis phase deals with the collection and synthesis of data related to the functional unit, that is, the inputs and outputs of the life cycle stages of a product system, including the use of raw material and energy, emissions, pollutants and wastes released to air, water and soil, etc. Typically, E-LCI analysis phase involves the quantification for several hundreds of emissions and resources (Hellweg and i Canals 2014), which makes it the most time-consuming stage of an E-LCA study. In order to facilitate E-LCI data collection and avoid duplication in data compilation, many databases have been established, including public national or regional databases, industry databases, and consultants' databases. These databases are often provided in combination with E-LCA software tools, such as SimaPro and Gabi (Finnveden, Hauschild et al. 2009).

E-LCIA phase evaluates potential environmental impacts using E-LCI data, which contains two mandatory steps, classification and characterization, as well as two optional steps, normalization and weighting. Classification is to assign the emissions and resources to different environmental impact categories, such as global warming potential (GWP), acidification potential (AP), ozone depletion potential (ODP), etc. Characterization is to calculate category indicator results using corresponding characterization factors, which convert different emissions and resources to the common impact units. Several E-LCIA methods that provide characterization factors for different impact categories have been developed to facilitate the calculation such as CML 2001, EDIP 2003, IMPACT 2002, and Eco-indicator 99 (Guinée 2002, Jolliet, Margni et al. 2003, Blengini 2009, Goedkoop, Heijungs et al. 2009).

Interpretation phase aims to answer the objectives of the study. It presents a complete and understandable presentation of the results of an E-LCA, from which conclusions and recommendations are provided accordingly.

Various E-LCA tools have been developed based on the methodology framework. Some of them are generic LCA software, such as SimaPro and Gabi, which is typically designed to compare different products including building products. There are also some E-LCA tools specific for building systems, such as BEES and Athena.

3.2.2 E-LCA Studies for Building Component and System

E-LCA studies in the context of the construction industry are generally classified into two categories: E-LCA for building materials and components (BMCs) and E-LCA for the whole building systems (WBSs) (Ortiz, Castells et al. 2009). Table 3-1 lists some of these cases studies, which highlight the choice in terms of life cycle phases, lifespan and E-LCIA indicators in different E-LCA case studies.

Table 3-1 E-LCA case studies of building components and building systems

Ref.	Description	System Boundary					Life Span (yrs)	Environmental Impacts Analysed													
		P	C;I	O&M	EoL	T		GWP	AP	POCP	EC	EP	T	RD	WC	WM	ODP	EE	Others	End-	
<i>Building Materials and Components</i>																					
(Citherlet, Guglielmo et al. 2000)	Window and advanced glazing system in Europe	×	×		×	×	30,45	×	×	×	×										
(Nicoletti, Notarnicola et al. 2002)	Flooring materials: ceramic versus marble tiles	×		×	×		40	×	×	×		×	×				×		×	×	
(Prek 2004)	HVAC systems: radiator heating, floor heating, and fan coil convector	×					-													×	
(Nyman and Simonson 2005)	Residential ventilation units in a cold climate (Finland)	×		×		×	50	×	×	×	×										
(Ardente, Beccali et al. 2005)	Solar thermal collector	×	×	×	×	×	15	×	×	×		×		×	×	×	×				
(Gustavsson and Sathre 2006)	Building materials: wood and concrete	×			×	×	100	×			×							×			
(Saiz, Kennedy et al. 2006)	Standard and green roofs of a residential building in Madrid	×		×			50	×	×	×		×	×	×			×				
(Nebel, Zimmer et al. 2006)	Wood Floor Coverings in German	×	×	×	×	×	50	×	×	×		×					×				

(Asif, Muneer et al. 2007)	Eight materials for a typical dwelling home in Scotland	×				-	×			×				×		
(Koroneos and Dompros 2007)	Brick production in Greece	×	×	×	×	80	×	×		×			×	×	×	
(Bribián, Capilla et al. 2011)	Most commonly used building materials in Europe	×	×		×	×	-	×		×			×		×	
(Reza, Sadiq et al. 2011)	Flooring systems: Concrete, Clay, Expanded polystyrene in Iran	×	×	×	×	30	×	×	×			×	×	×	×	×
(Menoufi, Castell et al. 2013)	Phase change materials for building envelope: esters, paraffin & salt hydrates	×			×		-	×	×			×	×	×		×
(Ximenes and Grant 2013)	Benefits of using wood products in two house designs in Australia	×	×	×	×	×	50	×								×
(Liu, Schulz et al. 2016)	Chilled ceiling system and VAV system in Singapore	×			×	×	×	20	×	×	×		×			×
Whole building systems																
(Adalberth, Almgren et al. 2001)	Four multi-family Dwellings in Sweden	×	×	×		×	50	×	×	×	×	×	×	×		
(Peuportier 2001)	Three types of single-family house in French	×	×	×	×		80	×	×	×	×	×	×	×	×	×
(Scheuer, Keoleian et al. 2003)	A new university Building in the US	×	×	×	×	×	75	×	×		×	×			×	×

(Junnila and Horvath 2003)	A new high-end office building in Finland	×	×	×	×	×	50	×	×		×		×
(Junnila, Horvath et al. 2006)	Office Buildings in Europe And the US	×	×	×	×		50	×	×		×		
(Kofoworola and Gheewala 2008)	A commercial office Building in Thailand	×	×	×	×		50	×	×	×			
(Bribián, Uson et al. 2009)	Simplified LCA study (single-family house)	×		×			50	×			×		×
(Blengini 2009)	Residential building in Turin	×	×	×	×	×	40	×	×	×	×	×	×
(Blengini and Di Carlo 2010)	Low energy building vs conventional building	×	×	×	×	×	35,70	×	×	×	×	×	×
(Asdrubali, Baldassarri et al. 2013)	Three conventional buildings in Italy: detached residential house, multi-family and multi-story office building	×	×	×	×	×	50	×			×		×
(Hossaini, Reza et al. 2015)	Six-storey wood frame and concrete frame building	×	×	×	×		60	×	×	×		×	×

P=Material Production; C=Construction; I=Installation; O&M=Operation and Maintenance; EoL=End-of-Life; T= Transportation
GWP=Global Warming Potential; AP=Acidification Potential; POCP= Photochemical Ozone Creation Potential; EC= Energy Consumption;
EP=Eutrophication Potential; T= Toxicity; RD=Resource Depletion; WC= Water Consumption; WM= Waste Management; ODP= Ozone Depletion Potential; EE= Embodied Energy

3.2.2.1 *E-LCA for building materials and components (BMC)*

Many studies have been conducted to make comparison among different materials and facilitate the selection of environmentally preferred ones. For example, Ximenes and Grant (2013) studied the environmental impacts of using wood products in buildings, in comparison with alternative materials. Results showed that replacing the original floor and sub-floor materials by timber wood led to better E-LCA results. Other similar studies include the comparison of floor coverings in Germany (Nebel, Zimmer et al. 2006), comparison of marble and ceramic tiles in Italy (Nicoletti, Notarnicola et al. 2002), and comparison of bamboo with wood and steel in Europe (Van der Lugt, Van den Dobbelsteen et al. 2006). BMC-related studies also aim to identify possible improvements during production process of the materials. For example, Koroneos and Dompros (2007) investigated the brick production process in Greece. Eco-indicator 95 results showed that acidification contributed over 50% of the total environmental impacts and using low-sulphur fuels was therefore recommended to diminish such impact.

While most of the above-mentioned studies exclude the operational energy of the use phase, studies on those with benefit in building climate control, such as glazing (Citherlet, Guglielmo et al. 2000) and roof systems (Saiz, Kennedy et al. 2006, Kosareo and Ries 2007), always consider the operational energy, due to their indirect influence on the energy consumption of the building. A comparative E-LCA study between standard and green roof showed that by substituting the common flat roof with a green roof, environmental impacts are reduced ranging from 1.0% to 5.3% (Saiz, Kennedy et al. 2006). Attention was also given to the use of phase change materials (PCM) (Aranda-Usón, Ferreira et al. 2013, Castell, Menoufi et al. 2013). It was shown that using PCM in buildings can reduce energy consumption during O&M phase and the overall environmental impacts. However, such reduction is highly influenced by PCM types and climate conditions (Aranda-Usón, Ferreira et al. 2013).

Besides the assessment of different materials, systems that directly influence the building energy consumption were also evaluated using E-LCA methodology, most of which focus on new or controversial green building techniques, such as solar PV systems (Kannan, Leong et al. 2006) and HVAC-related systems (Prek 2004, Shah,

Debella et al. 2008, Blom, Itard et al. 2010, Beccali, Cellura et al. 2012, Liu, Schulz et al. 2016). Shah et al. (2008) compared life-cycle impacts of three HVAC systems at four locations in the USA. The study discussed the effect of using high-efficiency equipment and the efficacy of renewable source replacement on the environmental impact and illustrated the relative environmental performance in a regional context.

An E-LCA case study on a chilled ceiling (CC) system and a VAV system will be present in Section 3.3 as an illustration of E-LCA studies on BMCs.

3.2.2.2 *ELCA for the whole building systems (WBS)*

WBSs can be regarded as the combination of different BMCs. However, E-LCA for WBSs is not merely a simple aggregation of assessments on individual products and components (Buyle, Braet et al. 2013). Compared with conventional applications of E-LCA to industrial products, WBS-related E-LCAs are more complicated, which is not only because of the involvement of numerous materials and processes, but also due to the specificity of building as a product. For one thing, the lifespan of an entire building is longer than BMCs, usually 50-100 years (Sartori and Hestnes 2007). Such long lifespan usually requires much more assumptions for the E-LCA, resulting in larger uncertainty and lower credibility of evaluation results (Radhi and Sharples 2013). Besides, construction process is less standardized than industrial processes since each building has its own function and characteristics, resulting in different construction techniques and schedules.

The main difference between E-LCA studies on BMCs and WBSs is the choice of the system boundary. Fig 3-2 illustrates the life cycle phases of the entire building. As previously discussed, most of the studies on BMCs mainly focus on the production phase, and sometimes also include the disposal phase to compensate for the production impact. Those with direct or indirect influence on operational energy consumption also take operational phase into consideration. However, most of these studies exclude construction or installation process from their assessment. WBS-related E-LCA studies include the above-mentioned phases, and tend to omit transportation and maintenance phase, which is also similar to the BMC-related studies. The main difference between E-LCA studies on BMC and WBS is the treatment of construction phase, that is, construction phase is more commonly

discussed in WBS-related studies. Construction phase can be regarded as “the production of the building”, involving the use of heavy construction equipment, such as excavator and bulldozer, and some additional materials and work such as formwork or connection elements to flanking walls.

Figure 3-2 Life-cycle phases of building system

In literature, many studies have been done to investigate the contribution of different life-cycle phases towards overall environmental impact. Most of the literatures show similar conclusion: operational phase contributes 80-85% to total life-cycle energy consumption of buildings (Junnila and Horvath 2003, Richman, Pasqualini et al. 2009, Ramesh, Prakash et al. 2010, Sharma, Saxena et al. 2011), and 60-90% to total environmental burdens, mainly to GWP (Adalberth 1997, Kofoworola and Gheewala 2008). The dominance of operational phase stresses the necessity of reducing energy consumption, especially those for HVAC systems, by improving envelope airtightness and insulation, and controlling ventilation (Buyle, Braet et al. 2013). However, a comparative E-LCA study showed that the overall environmental impact

of a low energy dwelling was only reduced by 50% compared with a reference conventional building, although its energy consumption was ten times lower (Blengini and Di Carlo 2010). This suggests that when energy consumption is pushed back, other life cycle phases are growing in relative significance, such as choice of construction methods, building materials and end-of-life scenarios. Similarly, it was concluded that embodied energy of building materials increases relatively when operational energy decrease (Huberman and Pearlmutter 2008).

While the two main phases that have greater impact on the environment are production and O&M phases, it does not mean that other phases can be ignored. Construction phase is always overshadowed by significantly larger operational-phase effects. However, as stated by Guggemos and Horvath (2006), construction impact of projects can be significant when scaling up to the national level. In their study, equipment usage takes up around 50% of total environmental impacts, while usage of temporary construction materials causes the second largest impacts. Impacts of end-of-life phase are also frequently discussed since waste management approaches can compensate the production impacts. It is concluded that reuse showed greater benefits than recycling (Blengini 2009), but the feasibility of reuse is still questionable considering its unclear profitability and it requires changes from present industrial practices.

On the other hand, transportation phase is always concluded to have minor importance. Although being considered in almost all the previous studies, impacts associated with the transportation phase are limited to around 1% or less since building products are often locally produced and delivered (Adalberth, Almgren et al. 2001, Ortiz-Rodríguez, Castells et al. 2010). Even when some parts are transported over a long distance, the associated impacts still play a minor role, as indicated in a case study on a low energy house that used windows and cork slab transported over long distances via truck and ship (Blengini 2009). Transportation might start to reveal a notable impact only when most of the building products are transported over a long distance, which can be seen in the study on office buildings in Hong Kong (Chen, Burnett et al. 2001), in which transportation contributed 7% to total environmental burdens. This is because the materials are mostly imported from overseas.

Considering the very similar situation in Singapore, where construction materials depend greatly on import, transportation seems necessary to be included in E-LCA studies of Singapore construction industry, which will be discussed in a case study as presented in Chapter 5.

3.2.3 Future Development in E-LCA

Improvement in term of E-LCA methodology is required to make E-LCA method tailored for building assessment. At first, inventory needs to be enhanced by including more relevant processes and more regional specific data. In the construction industry, regional electricity mix has a great influence on the environmental impacts of O&M phase (Adalberth, Almgren et al. 2001), as reflected in a study comparing two dwellings located in Spain and Colombia respectively. Due to the larger share of hydropower in Colombia electricity mix, environmental burden from electricity consumption is twice as large in Spain as in Colombia for most impact categories (Ortiz-Rodríguez, Castells et al. 2010). Therefore, E-LCI of different processes in the context of Singapore needs to be developed, especially considering the objective of this study is to evaluate buildings in Singapore. Besides, a more detailed system boundary needs to be investigated and adjusted based on the building practitioner's opinions.

Secondly, uncertainty analysis should be included in E-LCA analysis. E-LCA results have high uncertainty due to numerous measured or simulated data as well as the simplification of complex environmental cause-effect chains (Hellweg and i Canals 2014). Huijbregts et al. (1998, 2003) grouped the uncertainties in E-LCA studies into three categories: (1) parameter uncertainty, which arises from imprecise measurements, unrepresentative data and lack of data; (2) scenario uncertainty, which is due to the choices made for E-LCA, such as, functional units, system boundaries, product lifespan and impact categories; (3) model uncertainty, which refers to the uncertainty associated with the structure of the E-LCA model. Table 3-2 provides a summary of three categories of uncertainties associated with E-LCA modelling steps, which is adapted from previous studies (Björklund 2002, Huijbregts, Gilijamse et al. 2003, Geisler, Hellweg et al. 2005, Lloyd and Ries 2007, Williams, Weber et al. 2009, Clavreul, Guyonnet et al. 2012).

Table 3-2 List of uncertainties associated with E-LCA

E-LCA Step	Parameter Uncertainty	Scenario Uncertainty	Model Uncertainty
Goal and Scope Definition		choice of - functional unit - system boundaries	
LCI Analysis	- data collection errors in input parameters - inaccurate emission measurements - methods for estimating missing data - assigning quantitative parameter - estimates based on qualitative descriptors	choice of - allocation methods - inventory databases - waste handling method for long-life products	- ignoring nonlinear processes - complete lack of process data - no spatial details on emission - no temporal details on emissions
LCIA	imprecise knowledge on properties of substances and the environment (characterization factors)	choice of - number of impact categories - characterization method - time horizon of impacts - spatial horizon of impacts - normalization method & reference - weighting method & reference	- ignoring nonlinear processes - lack of information on substances' properties - ignoring interactions among different pollutants - no modelling of metabolites - assumption on uniform mixing of compartments

At last, there is an increasing demand for a broader sustainability assessment covering all the three dimensions of sustainability (Min and Kim 2012). It is exactly the main objective of this study, that is, to establish an approach to assessing the three aspects for building systems. Cost management is one of the most important concerns in the construction industry, and methods for life cycle cost analysis are quite mature. However, methods for social assessment are still in their infancy, and thus further studies are needed.

3.3 Social Life Cycle Assessment (S-LCA)

S-LCA is a relatively new technique. The discussion on how to incorporate social criteria in E-LCA began in the Society of Environmental Toxicology and Chemistry (SETAC) Workshop Report, *Conceptual Framework for Life Cycle Impact Assessment*, in which social welfare category was introduced into LCIA (SETAC 1993). The proposed social impact category called for a more comprehensive discussion on S-LCA development, and several methodologies have been created from 2006 (Brent and Labuschagne 2006, Dreyer, Hauschild et al. 2006, Hunkeler 2006, Norris 2006, Weidema 2006). Similar to E-LCA, S-LCA is a social impact assessment technique that aims to assess the social aspects of products and their potential positive and negative impacts along their life cycle (Chhipi-Shrestha, Hewage et al. 2015). It also includes four steps, i.e. goal and scope definition, S-LCI analysis, S-LCIA and interpretation (UNEP/SETAC 2009).

Although sharing very similar definition and methodology framework, S-LCA is different from E-LCA. When focusing on environmental impacts, there is a natural link between physical inputs or outputs of a process and change of environmental quality. Therefore, E-LCA is conducted at a process level. On the other hand, S-LCA is an analysis based on the way that business affects human well-being directly or indirectly. Thus, it usually focuses on those activities in the life cycle which affect people, and needs to create the link from the conduct of company to the social impact (Dreyer, Hauschild et al. 2006, Jørgensen, Le Bocq et al. 2008, UNEP/SETAC 2009).

Review on existing studies of S-LCA indicates that S-LCA is still in its infancy and many aspects of S-LCA remain unclear. It has been pointed out that there is no consensus on the selection of the impact categories in S-LCA (Jørgensen, Le Bocq et

al. 2008). There are two classification schemes for impact category selection, namely, impact category-based schemes in the early studies and stakeholder-based ones (Benoît-Norris, Vickery-Niederman et al. 2011), where the latter is preferable today. This is because social sustainability by nature involves multi-faceted social values, which are sequentially influenced by plentiful stakeholders (Almahmoud and Doloï 2015). In particular, a socially sustainable building project is supposed to respond to different requirements of multiple stakeholders involved in the whole process of building project development, including not only the final users but also construction personnel, suppliers and local communities (Valdes-Vasquez and Klotz 2012, Hussin, Rahman et al. 2013, Wong and Fan 2013).

Stakeholder-based approach is also suggested by UNEP/SETAC, and the corresponding framework is provided in *Guidelines for Social Life Cycle Assessment of Products* (hereafter referred to as the *Guidelines*) (UNEP/SETAC 2009). The *Guidelines* is seen as a significant step towards the standardization of S-LCA, which provides a general framework with methodological sheets for 31 social impact subcategories regarding different aspects of social concerns. As shown in Table 3-2, social impacts are observed in five stakeholder categories, namely, workers, local community, consumer, society and value chain actors; each of them is associated with several impact subcategories.

Table 3-3 Stakeholder categories and subcategories proposed in the *Guidelines*

Stakeholder categories	Impact subcategories
Worker	Freedom of Association and Collective Bargaining Child Labour Fair Salary Working Hours Forced Labour Equal opportunities/Discrimination Health and Safety Social Benefits/Social Security
Consumer	Health & Safety Feedback Mechanism Consumer Privacy Transparency End of life responsibility
Local Community	Access to material resources Access to immaterial resources Delocalization and Migration Cultural Heritage Safe & healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Society	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors (not including consumers)	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

The *Guideline* has been applied and tested in many case studies in various industrial contexts with different objectives, including some building-specific analyses, such as

in Hosseinijou, Mansour et al. (2014), Dong and Ng (2015). Franze and Ciroth (2011) developed a checklist method to compare the social impacts of rose production and cutting and packaging process in Ecuador and Netherlands considering 19 impact categories associated with five stakeholders. Traverso et al. (2012) compared social impacts of the production of three PV modules considering six impact categories related to workers. Foolmaun and Ramjeeawon (2013) proposed a scoring method for quantitative social impact assessment and conducted a comparative S-LCA study of four scenarios of disposing used PET bottles. Hosseinijou et al. (2014) performed a comparative assessment of life cycle social impacts of concrete and steel as building materials with the combination of material flow analysis. Some other studies aim to identify social hotspots of different products, such as laptop computers (Ciroth and Franze 2011, Ekener-Petersen and Finnveden 2013), palm oil biodiesel (Manik, Leahy et al. 2013) and fertilizers (Martínez-Blanco, Lehmann et al. 2014).

While using the *Guidelines* as the basis for their analysis, previous cases studies vary greatly regarding the detailed methodological choices to conduct S-LCA studies depending upon different purposes and application scenarios. This means the *Guideline* at this stage is still adopted as a methodological skeleton rather than a technical handbook (Macombe, Feschet et al. 2011, Reitingner, Dumke et al. 2011). Several key issues regarding methodological choices are identified from previous studies. The fundamental one is the identification of relevant stakeholders and social issues. Although the *Guideline* identifies hundreds of social issues, not all of them are directly relevant to the analysis. Social issues can be identified differently under different regional and industrial scenarios, and may change over time. Therefore, a set of social issues associated with various stakeholders related to different life cycle phases of building projects needs to be understood before conducting S-LCA. Sequentially, weights among the selected impact categories need to be determined properly instead of being assumed to be equally significant (Foolmaun and Ramjeeawon 2012, Aparcana and Salhofer 2013).

Another concern is associated with the social indicators to characterize the social issues identified. In S-LCA studies, data can be collected from either generic or site-specific sources, and the impacts can be captured through quantitative, semi-

quantitative or qualitative indicators. Parent et al. (2010) classified the LCIA in S-LCA studies (S-LCIA) into two types. Type 1 adopts taskforce approach, which uses performance reference points to evaluate the social impacts in either qualitative or semi-quantitative manner. On the other hand, Type 2 uses pathway approach that allows quantitative assessment of social impacts along the causal-effect chain. Both data source and indicator type, and even different policy or industrial requirement, may lead to different choices of indicator for a certain impact category, and further lead to different S-LCIA approaches. Hence, a specific set of indicators needs to be developed depending on the goal and scope definition as well as data accessibility. Besides, the choice of the reference performance for each indicator needs to be justified for quantitatively illustrating social performance. The reference performance could be determined based on the minimum legal requirements, industrial standards, as well as the average or best-expected practices within the industry (Revéret, Couture et al. 2015).

3.4 Life Cycle Sustainability Assessment (LCSA)

The idea to combine the three aspects of sustainability was firstly proposed by Klöpffer (Klöpffer 2003). He further developed this idea in 2008, and proposed two options of LCSA (Klöpffer 2008). One is to conduct separate LCAs with consistent and preferably identical system boundaries, while another option is to broaden the E-LCA in the LCIA phase, and to adopt only one LCI used for three impact assessments. Up till now, no agreement has been reached on which option should be adopted, but it seems the first option is more favorable in the previous studies (Foolmaun and Ramjeawon 2013, Hu, Kleijn et al. 2013, Dong and Ng 2015). This is also adopted in an instructional report developed by SETAC and UNEP, *Towards a Life Cycle Sustainability Assessment* (SETAC/UNEP 2012).

As an integrated tool, LCSA covers both strengths and shortages of all the three aspects. As for E-LCA, selection of E-LCIA methods is usually subjective without a reasonable judgment to support the decision. Data quality of E-LCI is always questionable, and a regionalized E-LCI is required. In terms of S-LCA, selection of impact categories and indicators is not consistent and the methods to quantify social impacts vary greatly in the previous studies. All these unsolved issues may cause

great uncertainty in LCSA and affect the reliability of LCSA. On the other hand, E-LCA has been standardized and applied by a variety of sectors for decision making, and LCCA has been adopted in practice for decades. The development status of E-LCA and LCCA enlightens the future development of LCSA.

There have been several case studies based on LCSA. Bozhilova-Kisheva et al. (2015) proposed an integrated LCI template to establish the connection among three assessment aspects. Hu et al. (2013) developed inventory through interviews and analyzed three dimensions separately. Foolmaun and Ramjeawon (2013) adopted the analytical hierarchy process to compare the LCSA results of alternatives. However, these studies were just case study-based while no commonly agreed method of LCSA has been developed. This study, therefore, aims to address this research gap and attempts to harmonize the three LCA tools into a holistic and consistent LCSA framework.

3.5 Summary

In this chapter, a systematic review is conducted on the four life-cycle based assessment methods, that is, LCCA, E-LCA, S-LCA and LCSA, in the context of the construction industry. As LCCA is assumed to be a maturely developed method, only basic concept and method principles are introduced briefly. As for E-LCA, an overview is firstly given, followed by the review on the previous studies in the context of the building sector, based on which further research needs are discussed. The review highlights the need to address uncertainties issues in E-LCA studies, which could also be crucial in other life-cycle based methods. S-LCA is also reviewed with a scope expanded to a more general application rather than focusing on building-related studies only. The review results identify several key issues to develop a building-specific S-LCA method.

Chapter 4 Research Methodology

The importance of research method selection on the possible outcomes of any research effort can never be overstressed. When conducting research, it is essential to choose suitable research methods, to ensure that the research aim and objectives can be met, and research outcomes can be validated. This chapter firstly discusses the research design, which is influenced by the nature of a research topic, aim and objectives. The choices of research methods are also explained and associated with different research tasks. Generally, this study adopts triangulation research approach, in which both qualitative and quantitative research methods are used.

4.1 Overview of Research Design

Research design is highly influenced by the research aim, which is to establish a building-specific LCSA model for decision-making. Such decision-making model can be established based on MCDA methods, as discussed in Chapter 2. Accordingly, the MCDA procedure can serve as the basis for the research design.

MCDA procedure typically consists of six steps as indicated in Figure 4-1: (1) problem identification, (2) assessment framework construction, which is constructed based on three life-cycle based assessment methods (i.e., LCCA, E-LCA and S-LCA) in this study, (3) establishment of decision-making model, during which main model parameters need to be prepared including alternatives and their performance on each criterion, and weights among criteria, (4) comparison or ranking among alternatives using a certain decision algorithm, (5) model quality assessment, and (6) result interpretation.

As indicated in Figure 4-1, eight tasks are needed to achieve the research aim. The entire study is based on an in-depth understanding of existing building-specific SA methods and life-cycle based assessment methods, which is achieved by literature review (Task 1) and a case study using E-LCA and LCCA to evaluate sustainability performance of building sub-systems (Task 2). Accordingly, three key research issues were identified, namely, lack of S-LCA method, chaos in method selection for uncertainty characterization and multi-dimension integration. Identification of these issues makes the research objectives clearly understood, and they are associated with MCDA procedure via five tasks. To develop an S-LCA method for buildings, social impact categories and criteria should be firstly identified (Task 3) and a social impact assessment approach is needed (Task 4). Social criteria, together with environmental and economic criteria based on E-LCA and LCCA respectively, will form a hierarchical sustainability assessment framework. Weights (Task 5) are necessary for integrating LCCA, E-LCA and S-LCA to establish a comprehensive LCSA model. Equipped with weights and impact assessment results of each alternative in terms of three dimensions of sustainability, a decision-making model can be established for further comparison or ranking process via a proper MCDA method (Task 6). In addition, information on uncertainties informs decision-makers about the robustness of evaluation results; hence this study will discuss parameter uncertainties in life cycle inventory analysis (Task 7) due to the limited scope. Finally, in Task 8, the applicability of the model will be demonstrated through a case study.

Figure 4-1 Illustration of research framework

4.2 Research Methods

Due to the complexity of tasks as shown in Figure 4-1, there could not be a single type and source of research data, and thus multiple research methods would be involved. Qualitative and quantitative research methods are usually combined in assessment framework development process, which is believed to be more powerful and effective than adopting a single approach (Moffatt, White et al. 2006). Application and combination of several research methods in one study is termed as triangulation approach, in which theories or models can be developed in a qualitative manner, while tested through quantitative studies or vice versa. Triangulation approach can improve the reliability and validity of research outcomes, and it also provides much more flexibility to researchers. Research methods adopted corresponding to different tasks are explained in detail in the next sections.

4.2.1 Literature Review

There are numerous literatures on the topic of sustainable construction and sustainability assessment. Reviews on these literatures were conducted throughout the entire process of the assessment model development; two methods for literature review were adopted, namely, archival analysis and content analysis. Archival analysis is an effective yet very cheap method for gathering existing literature on a certain topic to form a thorough understanding (Akadiri 2011). Information could be gathered from different sources including university and institutions databases, academic and industrial publications, webpages, workshops, seminars, and among many others. At the initial stage of this study, archival analysis was applied to extensive literatures, which provided a solid theoretical basis for establishing research aim and objectives, as well as study scopes. Later, archival analysis was conducted with a more narrowed scope at the early stage of every research sub-topic, such as literatures on building-specific sustainability assessment criteria, E-LCA methods, MCDA methods, uncertainty and sensitivity analysis methods, and so on, in order to identify research gaps and prepared for the subsequent studies. Content analysis was particularly adopted for social sustainability assessment criteria derivation, which is a set of procedures for converting textual information to numerical data. Through the classification of words, phrases, and other units of text

into several pre-defined categories, a comprehensive set of social criteria were established. The procedure and results of content analysis will be presented in Chapter 5.

4.2.2 Survey

Social assessment criteria were derived through content analysis, and weights among these pre-selected criteria were obtained through a questionnaire survey, which includes questionnaire design, pilot survey, main survey, as well as data analysis.

4.2.2.1. Questionnaire design

The questionnaire consists of four parts, as attached in Appendix 1. The first part is to collect respondents' general information, such as information on their job position and work experience. The second part is the main survey content, followed by an additional section that investigates various requirements associated with achieving healthy and comfortable living condition of building occupants. The last part is an explanatory section that clarifies the meanings of these criteria.

The main part of the questionnaire was designed based on analytic hierarchy process (AHP) method using consistent fuzzy preference relations (CFPR). AHP is one of the most commonly adopted methods to determine weights for different decision-making models (Sambasivan and Fei 2008, Tseng, Lin et al. 2009, Wang, Qin et al. 2009, Reza, Sadiq et al. 2011, Thanki, Govindan et al. 2016). It provides a more mathematical solution through pairwise comparisons compared with other weighting methods where weights are assigned subjectively (Reza, Sadiq et al. 2011). However, such pairwise comparison also brings some issues. In the traditional AHP, $n(n - 1)/2$ judgements need to be made in a group of n criteria. When there are too many criteria in a decision-making model, questionnaire has to be quite long, and experts usually do not have enough time or patience to complete such questionnaire. Furthermore, too many pairs of comparison may cause experts' mental confusion, resulting in inconsistent responses. In such case, the questionnaire needs to be checked and re-answered, leading to inefficiency of survey (Chen and Chao 2012).

To avoid the abovementioned problems, this study utilizes CFPR-based AHP method to obtain weighting matrix. Different from traditional AHP, in CFPR-based AHP, i th

criterion is only compared with $(i + 1)$ th criterion, which means only $(n - 1)$ judgments are involved, and consistency can also be guaranteed. Questionnaire is designed in a pairwise comparison manner, as illustrated in Figure 4-2, where linguistic terms are used, including equally important, weakly more important (or unimportant), strongly more important (or unimportant), absolutely more important (or unimportant), as well as intermediate values.

Please compare in pairs the relative importance between two impact categories regarding social evaluation of building projects.

Stakeholder Categories	Abso.		Strong		Slight		Equal		Slight		Strong		Abso.	Stakeholder Categories
Workers' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Occupants' Well-being
Occupants' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local Community's Well-being
Local Community's Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Development of Industry/ Society

Abso. – Absolutely more important Strong – Strongly more important
Slight – Slightly more important Equal – Equally important

Figure 4-2 Part of the questionnaire for pairwise comparison regarding social acceptability

4.2.2.2. Pilot Study

Pilot study is an essential step to check the quality of a questionnaire. It was conducted through face-to-face interviews with 20 industrial and academic experts. During the interviews, main focuses are on the suitability of proposed sustainability criteria, clarity of the question expression, as well as the usability of the questionnaire. According to the feedback from the interviewees, it took around 20 minutes to complete this questionnaire. Therefore, the length of the questionnaire was considered to be reasonable. However, although the initial questionnaire did provide an example illustrating how to conduct pair-wise comparison, many interviewees still felt confused as they have never seen such a question form before. Therefore, in the following main survey, face-to-face survey was mainly adopted, considering it would lead to a greater control of the interviewing situation. Not many suggestions were received from respondents in terms of proposed sustainability criteria, yet the expressions of some criteria seemed to be ambiguous, which were rephrased according to respondents' advices.

4.2.2.3. Main Survey

Survey was conducted through face-to-face interview with or e-mail distribution to experts representing different industrial stakeholders, including government agency, developer, designer, contractor, supplier/manufacturer, academic, sustainability consultant. As mentioned before, face-to-face interview was much more preferred, and thus e-mail distribution approach was applied only when the interviewees strongly preferred to do so. The sample size was determined using the following formula (Blair, Czaja et al. 2013, Hazra and Gogtay 2016):

$$N = \frac{z^2 \times p(1-p)}{E^2} \quad (4-1)$$

where N is sample size, z is the critical value for the confidence level, p is response distribution, and E is margin of error. In this study, confidence level was assumed to be 95%, which gave a z value of 1.96. Margin of error indicates the extent of deviation from the true result that can be tolerated. The smaller the margin of error, the closer it is towards having the exact answer at a given confidence level, yet, at the same time, the sample size will be much larger. Considering the relatively low response rate in the construction industry, margin of error was assumed to be 10% in this study to seek for a balance between the precision level and the efficiency of this survey. As for response distribution, it describes the values and frequencies associated with a particular question. Its value is usually estimated based on researchers' past experience and/or their knowledge of the target population. However, setting the response distribution to 50% is the most conservative choice, as it assumes a most heterogenous population and will return the largest sample size. Accordingly, the sample size was calculated to be 96. This number requires further correction for finite populations using Equation 4-2 (Blair, Czaja et al. 2013, Hazra and Gogtay 2016).

$$N' = \frac{N}{1 + \frac{N-1}{Pop}} \quad (4-2)$$

where Pop is the population size. According to Singapore Employment Statistics (MOM 2017), there are around 450,000 people working in the construction industry. Therefore, the sample size was calculated to be 97.

4.2.2.4. Calculation of criteria weights

For the main part of the questionnaire, comparison results were converted into corresponding numbers using Table 4-1, which is recorded as e_{ij}^k , indicating the relative importance of criterion C_i compared to C_j assessed by k th evaluator. Results were summarized in an evaluation matrix E^k , as shown in Equation 4-3, in which positions with symbol “×” will be filled in through further calculation process.

Table 4-1 Scale of relative importance

Linguistic variable	Scales (e_{ij})
Equally important	1
Weakly more important (unimportant)	3 (1/3)
strongly more important (unimportant)	5 (1/5)
absolutely more important (unimportant)	7 (1/7)
Intermediate values	2, 4, 6 (1/2, 1/4, 1/6)

$$E^k = \begin{matrix} & \begin{matrix} C_1 & C_2 & C_3 & \cdots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 1 & e_{12}^k & \times & \cdots & \times \\ \times & 1 & e_{23}^k & \cdots & \times \\ \times & \times & 1 & e_{34}^k & \times \\ \vdots & \vdots & \vdots & \ddots & e_{(n-1)n}^k \\ \times & \times & \times & \times & 1 \end{bmatrix} \end{matrix} \quad (4-3)$$

Individual evaluation results were then aggregated into group evaluation result using the geometric mean, that is,

$$E = (e_{ij}), \quad e_{ij} = \sqrt[K]{e_{ij}^1 \cdot e_{ij}^2 \cdot \dots \cdot e_{ij}^K} \quad (4-4)$$

where K is the number of experts.

To obtain the values for the positions marked with symbol “×” in Equation 4-3, a method proposed by Herrera-Viedma et al. (2004) was adopted, which utilizes additive transitivity property to establish pairwise comparison preference decision matrices. Based on their study, the expert’s preferences toward the set of criteria in

this case can be denoted by a fuzzy preference relation matrix $P = (p_{ij})$ with $p_{ij} \in [0, 1]$. p_{ij} is interpreted as the preference degree of criterion C_i over C_j : $p_{ij} = 0.5$ indicates indifference between C_i and C_j , $p_{ij} > 0.5$ indicates C_i is more important than C_j , and $p_{ij} = 1$ indicates that C_i is absolutely more important than C_j . P is assumed to be additively reciprocal, namely,

$$p_{ij} + p_{ji} = 1 \quad \forall i, j \in \{1, \dots, n\}. \quad (4-5)$$

A transformation function g can be developed to associate fuzzy preference relation matrix P with the evaluation matrix obtained in the first step, $E = (e_{ij})$ with $e_{ij} \in [\frac{1}{7}, 7]$, (Herrera-Viedma, Herrera et al. 2004), which is given as follows:

$$p_{ij} = g(e_{ij}) = \frac{1}{2} \cdot (1 + \log_7 e_{ij}), \quad (4-6)$$

where the base of logarithm is determined by the range of e_{ij} . If e_{ij} is between $\frac{1}{9}$ and 9, then the base should be 9.

Therefore, based on Equations 4-3 and 4-4, a new evaluation matrix P is given, which is

$$P = \begin{matrix} & \begin{matrix} C_1 & C_2 & C_3 & \dots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 0.5 & p_{12} & \times & \dots & \times \\ p_{21} & 0.5 & p_{23} & \dots & \times \\ \times & p_{32} & 0.5 & p_{34} & \times \\ \vdots & \vdots & \vdots & \ddots & p_{(n-1)n} \\ \times & \times & \times & p_{n(n-1)} & 0.5 \end{bmatrix} \end{matrix} \quad (4-7)$$

To obtain the remaining p_{ij} values, additive transitivity property is adopted, which characterizes the consistency of the fuzzy preference relations. The definition of additive transitivity property is given by,

$$\begin{aligned} (p_{ij} - 0.5) + (p_{jk} - 0.5) &= (p_{ik} - 0.5), \forall i, j, k, \text{ or equivalently,} \\ p_{ij} + p_{jk} + p_{ki} &= 1.5, \forall i, j, k. \end{aligned} \quad (4-8)$$

For a reciprocal fuzzy preference relation $P = (p_{ij})$, as concluded by Herrera-Viedma et al. (2004), the following statements are equivalent:

$$p_{ij} + p_{jk} + p_{ki} = 1.5, \forall i, j, k, \quad (4-8)$$

$$p_{ij} + p_{jk} + p_{ki} = 1.5, \forall i < j < k, \quad (4-9)$$

$$p_{i(i+1)} + p_{(i+1)(i+2)} + \dots + p_{(j-1)j} + p_{ji} = \frac{j-i+1}{2}, \forall i < j. \quad (4-10)$$

Therefore, the remaining p_{ij} values were calculated using Equations 4-5 and 4-10. If there is any p_{ij} values in this preference matrix that are not in the interval $[0, 1]$, but in an interval $[-\alpha, 1 + \alpha]$, where α indicates the absolute value of the minimum value in this preference matrix, a normalization process is needed to transform the values from $[-\alpha, 1 + \alpha]$ to $[0, 1]$. The transformation function is given by:

$$f: [-\alpha, 1 + \alpha] \rightarrow [0, 1], f(p_{ij}) = \frac{p_{ij} + \alpha}{1 + 2\alpha} \quad (4-11)$$

Finally, weighting matrix was derived based on the final fuzzy preference matrix P , from which the principal eigenvector, the eigenvector corresponding to the eigenvalue of largest magnitude, can be generated. The weights matrix $W = (w_i), i = 1, 2 \dots n$ was obtained through normalizing the principal eigenvector, that is, the weights of assessment criteria were obtained.

4.2.3 Case Study

Several case studies were conducted with different purposes under different tasks. The preliminary study that will be presented in Chapter 5 was used to give an illustration of how E-LCA and LCCA can be applied to a building sub-system evaluation, which led to a much in-depth understanding of these two assessment techniques. As for the investigation of different methods for quantifying parameter uncertainties, i.e., Task 5, a simplified case study was conducted for quantitative comparison, where only one environmental impact and several inputs were considered to focus particularly on method comparison. Case study was also conducted to demonstrate the applicability of the proposed S-LCIA method and LCSA model.

Data collection for these case studies could be different. Data could be broadly classified into primary and secondary data. Primary data refer to site-specific data that are obtained directly from project records or information provided by project direct stakeholders. Primary data are always desirable, yet they are not always

available; in that case, secondary data should be used, which could be obtained from database, public reports, statistics, journal papers, websites, and among many others. Detailed information on these case studies will be presented separately in the corresponding Chapters.

4.3 Summary

This chapter firstly introduces the overall research design, which is guided by the understanding of the research objectives and focuses. Following the procedure of conducting MCDA, entire study is conducted in a systematic manner, which can also be followed by other assessment model development studies. Research methods are then explained associated with different research objectives and tasks. Methods for literature review include archival analysis to identify research gaps of each sub-topics as well as content analysis for social assessment criteria generation. Survey is applied to generate weightings of social criteria. Case studies are conducted with different purposes, such as concept illustration, quantitative comparison, and demonstration of model applicability.

Chapter 5 Comparative E-LCA and LCCA Studies of Air-Conditioning Systems

Due to high temperature (between 23°C and 34°C) and high relative humidity (mean value of 84%) in Singapore (Liping and Hien 2007), there is a significant demand for air conditioning in buildings to provide optimal thermal comfort for building occupants. The energy consumed by air-conditioning (AC) systems comprises 40-50% of total energy consumption during the entire lifespan of buildings in Singapore, which causes major environmental impacts. In other words, AC systems play a significant role when evaluating the sustainability of the entire building project.

This chapter presents a case study, in which two air-conditioning (AC) systems, namely, a chilled ceiling (CC) system and a variable air volume (VAV) system, are compared in terms of their sustainability performances. Specifically, E-LCA and LCCA are presented to evaluate the life-cycle environmental and economic performance of two systems under tropical weather conditions. In the following sections, CC system is firstly introduced as it is relatively new, followed by the results of E-LCA and LCCA studies. This chapter is associated with the first research objective, which will lead to much more in-depth understanding of these two life-cycle based assessment techniques.

5.1 Description of the CC System

The CC system is regarded as an energy-efficient alternative to the conventional AC system (e.g. VAV system) due to its significant advantages, including lower energy consumption during operation, better thermal comfort, space saving, and sound level reduction (Hao, Zhang et al. 2007). Different from the all-air system, which transfers cooled air from a central plant and distributes it into building space, CC system cools the ceiling surface through the chilled water circulation and subsequently provides a combination of radiant and convective cooling to the room. With its significant advantages, including lower energy consumption during operation, better thermal comfort, space saving, and sound level reduction (Hao, Zhang et al. 2007), CC system has attracted extensive attention in recent years from both industry and academia.

In this case study, CC system combined with air handling units is installed and operated in a 420 m² office space of Energy Research Institute at NTU (ERI@N) located on the 6th floor of JTC Clean Tech One in Singapore, replacing the initial VAV system. As presented in Figure 5-1, the CC system consists of chilled ceiling panels, supporting components, and the air distribution system (including air ducts and pipes). CC panels are designed to provide an optimum indoor climate, which are the interface of the CC system with the occupant. Pipes lay in the panels cool the room space through radiation heat transfer and natural convection. The supporting components considered in this study include the air handling unit (AHU) for air distribution, the chiller for water cooling, and the pumps for water distribution. The AHU is used to clean and condition the outdoor air and then to distribute it through to the terminal devices. The chiller plant provides the chilled water for the whole system. For the AHU, the chilled water enters the cooling coil to dehumidify and precool the air, and then returns to the chiller plant through a heat exchanger. For the CC panels, chilled water with the temperature around 14-16 °C flows through the pipe in the panels and absorbs the convection heat and heat radiated from warmer surfaces, such as windows and walls. Pumps within a CC system (not shown in Figure 5-1) are used to pump the chilled water from the chiller through the system and back to the chiller.

Figure 5-1 Schematic view of the chilled ceiling system

5.2 Environmental Performance Analysis

5.2.1 E-LCA Model Establishment

In this study, eBalance was used to construct the E-LCA model and to carry out the assessment. Functional unit (FU) and system boundary are firstly defined in order to keep consistent and to make the comparison meaningful.

As the function of an AC system is to achieve a specific indoor climate in a particular space, FU is usually defined by a suitable combination of parameters such as heat and cooling loads, required airflow at a specific temperature and/or relative humidity, and required operating hours, etc. (Heikkilä 2008). In this study, FU is the whole technical system (CC or VAV system) operated and maintained in an office space. The lifespan of the system is assumed to be 20 years, which is based on the judgment from the engineers of the CC system in this case. The system operates from 8 a.m. to 6 p.m. every day and is assumed to meet the cooling demand and thermal comfort requirement based on ASHRAE Standard 55 and SS 553:2009 (SPRING Singapore 2009, ASHRAE 2010), as listed in Table 5-1.

Table 5-1 Thermal comfort parameters of the CC system

Thermal Comfort Parameters	Measured Value	Acceptable Range (SPRING Singapore 2009, ASHRAE 2010)
Dry-bulb Temperature (°C)	24.4	23 to 25
Operative Temperature (°C)	24.9	24 to 26
Relative Humidity (%)	45.1	< 65
PMV	-0.09	-0.5 to +0.5
PPD (%)	5.2	< 10

Phases that were taken into account when conducting the E-LCA include the production of materials that comprise the main components, the transportation of the materials imported from overseas to Singapore, the energy consumption (electricity) for the operation of the main components during the 20-year lifetime, as well as the end-of-life phase, including the solid waste treatment. The following stages were not taken into consideration because relevant data were not available and their impacts are negligible (Beccali, Cellura et al. 2012): manufacturing of the system components and their transportation to the building site, the installation and maintenance of the system at the site, the removal of the system components and the transportation of the dismantled system components to the disposal site.

5.2.2 Data Collection and E-LCI analysis

As mentioned, E-LCI analysis phase deals with the collection and synthesis of data related to the FU, that is, the inputs and outputs for the life cycle stages of a product system, including the use of raw material and energy, emissions, pollutants and wastes released to air, water and soil.

The production phase includes the production of materials that comprise the main components of CC system and VAV system. For both systems, the components considered include the AHU, the chiller plant and the air distribution system (air ducts and pipes). Furthermore, the CC system requires additional pumps and CC panels. In this study, the material used for the common components (the AHU, the chiller and the air distribution system) were assumed to be identical. That is because the installation of the CC system in this case is a retrofit project, that is, there is almost

no change made to the existing AHU, chiller and air distribution systems, which were meant for the conventional VAV system. For the case of installation of a CC system in a new building, these systems can be tailor-made with reduced size/capacity to enhance the energy efficiency and environmental performance, which is beyond the scope of this study and will be explored in the future.

The quantity of the materials used for the AHU was estimated according to the previous E-LCA studies (Legarth, Åkesson et al. 2000, Nyman and Simonson 2004). Data for the chiller plant was determined by approximations based on the cooling capacity and environmental product declaration documents. It is assumed that 0.5% of the total amount of refrigerant leaks every year and requires replenishment to maintain the refrigerant at its original level based on an environmental product declaration of a typical chiller (2015). Materials used for the CC panels and the pump were calculated from the suppliers' technical documents (ERI@N 2013). For the air distribution system, quantities of the materials used were estimated from their length according to the drawings. Table 5-2 gives the material composition of the components of the two systems.

Table 5-2 Material quantities of main components of CC and VAV systems

Materials (kg)	AHU	Chiller	Air Ducts	Pipes	Additional Pumps	CC Panels
Galvanized Steel, Sheet	922.20		585.66			878.85
Hot Rolled Steel	275.46	1275.58				
Chromium Steel	9.96			437.26		
Electro-zincd Steel	6.92	6.83				
Cast Iron		512.96			4.60	
Aluminium, Cast	32.41	38.47				
Aluminium, Sheet	87.62					
Copper	21.27	730.97				227.71
Graphite						226.42
Fiberglass	30.54		235.63			
Rock Wool	82.05					
Polyethylene	7.98					
Rubber	1.73					
Refrigerant (R123)		13.20				

Based on the Singapore context, most of the materials and products listed in Table 5-2 are imported from overseas. For the CC panels, the graphite parts were imported from Germany and the metal parts, including galvanized steel sheets and embedded copper tubes, were imported from China and Malaysia. The iron and steel products were primarily supplied from China (Kua and Wong 2012). For the rest of the materials, it was assumed to be imported from China, Malaysia, and the United States equally due to the lack of further detailed information. These three countries were selected based on the statistical data of the top import partners to Singapore (Chen and Holden 2017).

Material quantities of main components, together with their transportation means and distance, were used to obtain life cycle inventories. The inventory datasets were extracted from the Ecoinvent 3 database (Weidema, Bauer et al. 2013), which contains global datasets for different activities and reflects the average global production. As for the operational phase, data collection focuses on the electricity consumption, which was simulated using EnergyPlus IDF Editor as shown in Table 5-3. An assumption is made that the electricity consumption will remain constant for the entire lifespan of the system. For the detailed simulation process, please refer to the project report (ERI@N 2013).

Table 5-3 Annual electricity consumption for CC and VAV systems

Air-conditioning End-Use	Annual Electricity Consumption (kWh)	
	CC System	VAV System
Chiller Plant	41,762	55,049
AHU	8,000	13,039
Pump	816	-
Sum	50,578	68,088

The fuel mix for electricity generation in Singapore contains 95.3% natural gas, 0.9% petroleum products (mainly in the form of diesel and fuel oil) and 3.7% other energy products (e.g. municipal waste, coal and biomass) (Energy Market Authority of Singapore 2014). Referring to the calculation method illustrated in the previous study

of Tan et al. (2010), emissions for 1MWh of electricity generation were estimated as shown in Table 5-4.

Table 5-4 Emissions for 1MWh of electricity generation in Singapore

Emissions	Weight (kg)
CO ₂	463.78
CO	0.128
N ₂ O	3.687×10 ⁻³
NO _x	1.185
SO _x	0.114
VOC	3.634×10 ⁻³
PM	7.479×10 ⁻³

The environmental impact of disposal phase was calculated based on the inventory of the materials used. According to solid waste management policy in Singapore, waste will be either recycled or disposed. For the disposed waste, waste that cannot be incinerated goes straight to Semakau Landfill after it is appropriately treated, while incinerable waste is sent to four incineration plants. This process generates energy for the national grid and ash which is also sent to Semakau Landfill. Therefore, calculation of disposal phase in this study considers material recycling, incineration and landfilling. Percentages of different approaches to waste material disposal were assumed according to the latest statistics in Singapore (Ministry of the Environment and Water Resources 2014) and previous studies (Heikkilä 2008, Shah, Debella et al. 2008), which are summarized in Table 5-5.

Table 5-5 Percentages of different approaches to waste material disposal

Waste Category	Percentage of Waste Disposal Approach		
	Recycling	Incineration	Landfilling
Ferrous metal	97%	-	3%
Non-Ferrous metals	84%	-	16%
Plastics	11%	89%	-
Others	-	-	100%

5.2.3 Life Cycle Impact Assessment

E-LCIA phase aims at evaluating the potential environmental impacts using the E-LCI results. CML 2001 method (Guinée 2002) was adopted in this study for the classification and characterization steps, which uses the problem-oriented approach with impact categories defined at mid-point level. The following five indicators were taken into account: global warming potential for a 100-year time horizon (GWP100), ozone depletion potential in the steady state (ODP), photochemical ozone creation potential (POCP), acidification potential (AP), and eutrophication potential (EP). Baseline characterization method was selected as recommended by CML to reduce uncertainties in E-LCIA results. Toxicity-related impact categories (including human toxicity and ecotoxicity) and depletion-related categories were not calculated since the discussion on the characterization of these categories is not settled as stated in the CML method report (Guinée 2002), and this may cause a higher level of uncertainty.

5.2.3.1 *E-LCIA Results of the CC System*

Table 5-6 summarizes the E-LCIA results for four life cycle phases of the CC system, with reference to the functional unit defined before. The impact of end-of-life phase is expressed as a negative value to reflect a net environmental gain. As expected, operation phase of CC system contributes the most to all selected impact categories. It is also worth mentioning that the contribution of production phase is notable except for GWP100. On the other hand, contribution of transportation phase is negligible, although the transportation distance is quite far due to the import of materials and products from overseas.

Table 5-6 E-LCIA results for life cycle phases of CC system over a 20-year lifespan

Impact Indicator	Life Cycle Phases (Weight)				Total
	Production	Transportation	Operation	End-of-Life	
GWP100 (ton CO ₂ -eq)	24.93 (4.93%)	0.22 (0.04%)	484.90 (95.79%)	-3.83 (-0.76%)	506.23
ODP (g CFC-11-eq)	76.83 (14.01%)	0.03 (0.01%)	471.92 (86.05%)	-0.38 (-0.07%)	548.40
POCP (kg ethylene-eq)	5.12 (23.38%)	0.03 (0.13%)	17.08 (78.05%)	-0.34 (-1.56%)	21.88
AP (kg SO ₂ -eq)	190.20 (16.59%)	4.30 (0.38%)	971.20 (84.73%)	-19.52 (-1.70%)	1146.18
EP (kg PO ₄ -eq)	105.90 (31.64%)	0.47 (0.14%)	256.71 (76.71%)	-28.41 (-8.49%)	334.66

In practice, the system design process normally proceeds by system components. To understand the environmental impacts of different system components, i.e., chiller, AHU, pumps, air distribution system and CC panels, the life-cycle impacts of each component were calculated. As reported in Figure 5-2, chiller plant always plays a significant role, whose contribution varies from 71.7% to 94.5%. This is because chiller plant is most material and energy intensive compared with the other components (see Tables 5-2 and 5-3). To be specific, chiller plant consumes the majority of the electricity during the operational phase, which makes it the main contributor to the life cycle environmental impact for most of the selected environmental impact categories, except for ODP. For ODP, refrigerant production, leakage, and replenishment lead to the substantial results. In this study, the refrigerant emission and production (including replenishment) comprise 79.7% and 13.9% of the overall ozone depletion impacts, respectively. The impact of the pump is the lowest, which only accounts for 0.2% to 1.5%.

Figure 5-2 Environmental impacts of CC system by system components over a 20-year lifespan

As mentioned, the installation of the CC system in this study is a retrofit project. To save cost, there is almost no change made to the existing AHU, chiller and air distribution systems. However, for a CC system, the cooling demand is lower and the amount of air flow is reduced, which means there is more potential for both energy and material savings through using higher temperature chiller and smaller sized AHU. These measures, if adopted especially in the new building scenario, will make the contributions from chiller and AHU significantly lower, which will be explored in the future study.

5.2.3.2 Contribution of Materials and System Components to Production Phase

This part investigates the relative contribution of different materials to the impact of production phase, as illustrated in Figure 5-3. Steel production is the first contributor to global warming and photo-smog, while copper manufacturing is the main contributor to acidification and eutrophication. The results suggest that the same conclusion holds for CC system that steel and copper materials influence the

environment the most in AC systems (Heikkilä 2008). In addition, although the aluminium usage only takes up 2.4% of the total weight of the whole system, aluminium materials still account for a great portion of GWP, POCP and AP, ranging from 6.2% to 17.0%.

Figure 5-3 Contribution of materials to the production impact

The results shown in Figure 5-3 can be used to interpret the contribution of different components to the impact of production phase, as shown in Figure 5-4. In terms of ODP, as discussed before, chiller plant accounts for the most because of the refrigerant production and leakage. In term of GWP and POCP, chiller plant and AHU are the two main contributors because they utilize significant amounts of steel and aluminium materials, while for AP and EP, chiller plant and CC panels are the two main contributors due to the usage of copper materials.

Figure 5-4 Contribution of system components to the production impact

5.2.3.3 Comparison of CC System and VAV System

As calculated from Table 5-3, the reduction in annual electricity consumption of the CC system is 25.7%. Although requiring additional pumps, the electricity consumption for the pumps only takes up 1.6% of the total energy consumption. Therefore, the reduction in cooling demand and air flow in CC system leads to the substantial reduction in electricity consumption.

By substituting the traditional VAV system with CC system, environmental impacts are reduced in all categories by varying degrees between 6.4% and 24.7%, as shown in Figure 5-5, which means CC system performs better in all impact categories investigated.

Figure 5-5 Comparison of normalized environmental impacts of CC and VAV systems

Changes in environmental impact of different life cycle phases of CC system upon VAV system are summarized in Table 5-7. As expected, most of the reductions are in the operation phase since the main benefit of a CC system to a building is the reduction of the energy consumption during its service life.

Table 5-7 Changes in impact of different life cycle phases of CC system upon VAV system

Indicator	Life Cycle Phases				Net Gain (Δ %)
	Δ Production	Δ Transportation	Δ Operation	Δ End-of-Life	
GWP100	1.42	0.06	-166.83	-0.34	-166.85 (-24.8%)
ODP	3.66	0.01	-11.23	-0.07	-7.63 (-2.9%)
POCP	1.27	0.01	-5.89	-0.07	-4.68 (-17.6%)
AP	36.90	0.81	-334.80	-4.25	-301.34 (-20.8%)
EP	5.06	0.09	-46.78	-0.14	-41.78 (-11.1%)

The largest reductions are in the categories of global warming and acidification, while ODP is reduced by only 2.9%. The reductions are mostly due to the reduction in electricity consumption, and the difference of reductions among impact categories are a reflection upon the extent to which impacts are associated with inventory results of the electricity mix. For instance, GWP is largely associated with the CO₂ emission, which is the dominant emission in electricity generation process (see Table 5-4), thus the decreased electricity usage for CC system results in greatly reduced GWP. On the other hand, ODP is associated with refrigerant leakage, rather than electricity generation, therefore the reduction is the least.

5.2.3.4 Comparison of Different Electricity Mix Compositions

As discussed, electricity consumption is the largest contribution to four of five impact categories investigated. The type of electricity in the assessment affects the results of LCA results significantly, which is shown in the previous studies (Shah, Debelli et al. 2008, Blom, Itard et al. 2010). The electricity mix used for calculations in this study is the 2014 electricity mix in Singapore. In the last 15 years, the portion of natural gas has increased steadily in Singapore, from 74.4% (in 2005) to 95.3% (in 2014), while the portion of petroleum products has decreased from 23.1% to 0.9% (Energy Market Authority of Singapore 2014). Therefore, through comparison of the environmental impact of CC system based on the three different fuel mix scenarios in 2010, 2012 and 2014 (Table 5-8), the basic trend due to change of electricity mix can be identified as shown in Figure 5-6. Results are normalized to the impact for year 2010, which is equal to 1. With the increase of the portion of natural gas, which is regarded as the cleanest fossil fuel, all the indicators show a decreasing trend from 2010 to 2014.

Table 5-8 Compositions of fuel mix for electricity generation in 2010, 2012 and 2014

Energy Product	2010	2012	2014
Natural Gas	77.2%	84.3%	95.3%
Petroleum Products	20.2%	13.0%	0.9%
Others	2.6%	2.7%	3.9%

Figure 5-6 Comparison of the environmental impact based on three different fuel mix compositions for electricity generation

At the same time, the contribution of operation phase impact to the life cycle environmental impact also declined, as shown in Figure 5-7. However, as the portion of natural gas is very close to 100% in Singapore in 2014, there will be very little room to reduce the environmental impact through increasing the portion. Therefore, using more efficient or cleaner forms of energy, such as solar power and hydrogen from solar energy, to change the energy structure should be taken into consideration. It is also necessary to focus on the improvement in other life cycle phases, e.g. seeking for more environmental-friendly alternative materials.

Figure 5-7 Contribution of operation phase to the life cycle environmental impact in 2010, 2012 and 2014

5.3 Economic Performance Analysis

5.3.1 LCCA Model Establish and Data Collection

Capital cost, operational cost and decommissioning cost were taken into account when examining the economic performance of the two AC systems. Capital cost includes initial capital expense for system design, equipment, installation and testing. The initial cost (C_i) of the VAV system was estimated based on the previous LCCA study on VAV systems, in which the costs for VAV systems are about US\$ 78.2/m² (US\$ 1=SG\$ 1.37) (Aktacir, Büyükalaca et al. 2006). As for the CC system, there are extra costs due to the installation of CC panels and pumps, which are SG\$ 63,998.7 in total adopted from the actual project cost (ERI@N 2013). However, in this case study, CC panels replaced the original ceilings, while suspended ceiling costs are usually not included in the cost for VAV systems. Therefore, the extra cost is estimated as SG\$ 50,138.7, excluding the cost for the original suspended ceilings, which is estimated as SG\$ 33/m².

Operational cost refers to the cost incurred during the operational phase, which includes O&M cost and energy cost. O&M cost ($C_{O\&M}$) includes the maintenance

cost, replacement cost and labour cost. The overall O&M cost varies from 4.7% to 6% of the initial cost according to previous studies (Leigh and Won 2004, Stanford University 2005, Fuller 2010), thus 5.3% was adopted to estimate the annual O&M cost. The energy cost (C_e) was estimated based on the annual energy consumption as shown in Table 3.3, as well as the average electricity tariff from 2014 to 2016 in Singapore (Singapore Power 2016), which is SG\$ 0.232/kWh. In the decommissioning phase, costs are incurred in demolition and disposal of the system while the equipment can have some salvage value (S), thus decommissioning cost is the difference of the demolition and disposal cost (C_d) and the salvage value. C_d was assumed to be 3% of the capital while 5% of the capital was counted as the salvage value. All the costs are summarized in Table 5-9. Negative value means the cost saving. It was found that by paying an extra investment of SG\$ 50,138.7, it is possible to save SG\$ 3,973.7 each year from O&M costs.

Table 5-9 Summary of cost of CC system and VAV system

Cost (SGD)	CC System	VAV System	Difference
Capital Cost	95,135.0	44,996.3	50,138.7
Annual Energy Cost	11,734.1	15,796.4	-4,062.3
Annual Maintenance Cost	168.1	79.5	88.6
Decommissioning Cost	-1902.7	-899.9	-1,002.8

Note: Annual O&M Cost = Annual Energy Cost + Annual Maintenance Cost

5.3.2 LCCA Results

The system lifetime of the CC and VAV system was assumed to be the same, which is 20 years. Therefore, the present-worth cost technique was used to examine total cost of the two alternative systems over the analysis period. All the cost occurred over the entire operational phase need to be projected with an annual inflation rate (r), and to be reduced to their present value using discounting techniques. The discount rate (R) reflects the effect of the real earning power of money invested over time. The operational cost can be calculated using Equation 5-1.

$$\text{Operational Cost} = \sum_{i=1}^n (C_{O\&M} + C_e)_i \left(\frac{1+r}{1+R} \right)^i \quad (5-1)$$

An LCCA can be performed in constant dollars or current dollars. However, a constant dollars approach is commonly recommended, especially in the comparative analyses (Wong, Tay et al. 2003), in which future prices and costs are expressed in dollars of constant purchasing power. The discounting method provides an equivalent basis for the alternatives to be compared. This method may be defined as “the application of a selected rate of interest to adjust the values of the cost distribution to a common reference point in time”, which is in general the present time of making decisions (Wong, Tay et al. 2003). An average statistics data of prime lending rates for the past ten years can be taken as the discount rate (Trading Economics 2016), which is 5.37% for this analysis.

Similarly, the decommissioning cost should also be discounted to the present value using the discount rate (5.37%), and can be calculated using Equation 5-2.

$$\text{Decommissioning Cost} = (C_d - S) \left[\frac{1}{(1+R)^n} \right] \quad (5-2)$$

Therefore, LCC can be calculated by Equation 5-3.

$$\text{LCC} = C_i + \left[\sum_{i=1}^n (C_{O\&M} + C_e)_i \left(\frac{1+R}{1+R} \right)^i \right] + (C_d - S) \left[\frac{1}{(1+R)^n} \right] \quad (5-3)$$

Table 5-10 summarizes the LCCA results of the CC and VAV system, as well as net present worth cost of three cost categories. Operational cost is the main contributor of the LCC for both AC systems due to electricity consumption. Although LCC results of the two systems did not show much difference, it is worth mentioning that the portions of the capital cost and the operational cost are quite different. This is also clearly revealed by Figure 5-8, at the beginning, the costly CC panels in this case study double the capital cost for CC system when compared to VAV system. During the operational phase, the difference between the two systems decreases gradually due to the significant energy savings of the CC system. However, at the end of the lifetime (20 years), the cumulative net present cost, namely LCC, of the CC system is still higher than that of the VAV system. Further calculation found that the payback period of the CC system with respect to the VAV system is approximately 21.4 years. Usually, an investment is considered as a “good” investment if the payback period is less than one-half of the lifetimes. Therefore, from this perspective, CC system does not show economic benefit compared to the VAV system within the 20-year lifespan.

Table 5-10 LCCA results of the CC system and VAV system

	CC System	VAV System
Capital Cost	95,135.0 (39.9%)	44,996.3 (19.0%)
Operational Cost	143,782.6 (60.3%)	191,605.3 (81.0%)
Decommissioning Cost	-668.4 (-0.3%)	-135.1 (-0.1%)
Life Cycle Cost	238,249.3	236,466.5

Figure 5-8 Cumulative net present cost of CC system and VAV system

5.4 Summary

In this chapter, an E-LCA and LCCA of two AC systems are presented. E-LCA results show CC system performs better in all five impact categories investigated when compared to the conventional VAV system which is widely used in Singapore. This means that CC system is viable in tropical conditions from the life cycle environmental impact perspective. Operation phase of CC system contributes the most to all the impact categories investigated; while transportation phase has a negligible contribution, although the transportation distance is quite far due to the import of materials and products from overseas. As for production phase, chiller plant and AHU are the two main contributors in term of GWP and POCP, while for AP and

EP, chiller plant and CC panels are the two main contributors. Chiller plant causes the highest environmental burden due to the high material content and the great annual electricity consumption. The study also verifies that steel and copper materials contribute the most to the environmental impact in air-conditioning systems.

While the CC system is a good choice compared to the VAV system from the environmental perspective, life cycle cost of a CC system is not comparable with that of VAV system, which is mainly because of the high cost for the chilled ceiling panels. With large-scale application, higher market adoption rate and more competition, this situation may be changed in favour of CC system.

This chapter is associated with the first research objective, which will lead to much in-depth understanding of these two life-cycle based assessment techniques, namely, E-LCA and LCCA. With conflicting results when attempting to choose a better-performed option from two AC systems, this study highlights the need to integrate two, or even more dimensions in sustainability assessment, in order to make a better decision.

Chapter 6 Conceptual Framework for LCSA

This chapter aims to develop a comprehensive model for building sustainability assessment that encompasses three-dimension and long-term impacts. As discussed in previous Chapters, an LCSA model proposed by Klöpffer (2003, 2008) can be adopted, as it conceptually integrates three life-cycle based assessment methods (i.e., LCCA, E-LCA and S-LCA), which ensures the consideration of long-term impacts and a comprehensive coverage of environmental, economic and social aspects. This chapter, as the first step for assessment model development, extracts assessment criteria from these three methods, and constructs a hierarchical framework for sustainability assessment. Discussions in this chapter focus on E-LCA and S-LCA, which are presented in sections 6.1 and 6.2, respectively. Environmental criteria and their weightings were extracted based on a selected E-LCIA method, and social criteria were extracted from previous studies through content analysis.

6.1 Selection of Environmental Assessment Criteria

Environmental impacts are evaluated through E-LCA, which involves four steps including goal and scope definition, E-LCI analysis, E-LCIA and interpretation, as introduced in detail in Section 3.2. Within these four steps, E-LCIA process is regarded as the core of E-LCA, leading to the results of environmental impacts through converting E-LCI results into various category indicators. E-LCIA normally involves six parts as indicated by ISO 14040 (2006), among which selection of impact categories and indicators, classification and characterization are mandatory, while normalization, grouping and weighting are optional. Impact categories represent environmental concerns that need to be addressed, such as climate change; category indicators are the substances for impact category description, such as CO₂ equivalent (CO₂-eq) for climate change. E-LCI results are classified to corresponding impact categories and are converted to the result of a certain impact category through characterization model. As for the optional parts, normalization is to convert indicator results to a normalized value based on a reference system, grouping process is to further group impact categories to several more straightforward categories, such as impacts to human health and ecosystems, and weighting is usually adopted to obtain a single score of environmental performance.

E-LCIA is a very data-intensive process; to save time and efforts for E-LCA practitioners, several E-LCIA methods have been developed, such as Eco-indicator 99 (Goedkoop and Spriensma 2000), CML 2001 (Guinée 2002), IMPACT 2002+(Humbert, Margni et al. 2005), TRACI 2 (Bare 2002) and ReCiPe 2008 (Goedkoop, Heijungs et al. 2009). These E-LCIA methods vary in impact categories and corresponding characterization, normalization, and/or weighting factors. Therefore, the selection of environmental assessment criteria could be based on the selection of a suitable E-LCIA method, whose impact categories can be used as environmental assessment criteria and their predefined factors can be applied to calculate environmental performance. In this study, seven commonly adopted E-LCIA methods were compared in terms of their basic characteristics and coverage of impact categories, as summarized in Table 6-1.

Table 6-1 Comparison of commonly used E-LCIA methods

E-LCIA Methods	Eco-indicator 99	CML 2001	IMPACT 2002+	TRACI 2 (2003)	EDIP 2003	EPD 2008	ReCiPe 2008
Basic Information							
Organization & Country	Pre Consultants, (Netherlands)	CML, Leiden University, (Netherlands)	Quantis, (Switzerland)	EPA, (US)	DTU, (Denmark)	SEMCo, (Sweden)	Pre Consultants, CML, RUN, RIVM (Netherlands)
Characterization Approach	Endpoint	Midpoint	Midpoint & Endpoint	Midpoint	Endpoint	Midpoint	Midpoint & Endpoint
Normalization	√	√	√	--	√	--	√
Weighting	√	--	√	--	√	--	√
Category number	11	51	14	12	18	6	18
Application	Europe	Europe & Worldwide	Europe	US	Europe	Worldwide	Europe & Worldwide
Coverage of Main Impact Categories							
Climate Change	√	√	√	√	√	√	√
Acidification	√	√	√	√	√	√	√
Ecotoxicity	√	√	√	√	--	--	√
Eutrophication	√	√	√	√	√	√	√
Ozone Depletion	√	√	√	√	√	√	√
Energy	√	--	√	--	--	√	√

The comparison started from the coverage of impact categories. It was found that these methods adopt different ways to classify impact categories, resulting in numbers of categories varying from 6 to 51. Considering this study focuses on building-specific analysis, the selected E-LCIA methods should at least include those impact categories that are relevant to the construction industry. Buildings are very energy intensive, and thus relevant impact categories should be included, such as fossil fuels as in Eco-indicator 99 and ReCiPe, and non-renewable energy as in IMPACT 2002+ and EPD. Besides, production of main building materials, such as steel and cement, may cause ecotoxicological risks (Kobetičová and Černý 2017). However, EDIP and EPD do not include impact category related to ecotoxicity. Therefore, from the perspective of impact category coverage, Eco-indicator 99, IMPACT 2002+ and ReCiPe are relatively better choices.

These three methods were further compared regarding methodological characteristics. As for characterization model, there are usually two approaches available, namely, midpoint and endpoint approaches. Midpoint approach translates impacts into environmental themes such as climate change and acidification; while endpoint approach converts environmental impacts into areas of protection (AoPs), such as human health, natural environment and natural resources (Hauschild, Goedkoop et al. 2011). Midpoint E-LCIA methods provide evaluation results as a set of indicators for numbers of impact categories. However, such detailed results make it difficult to be interpreted (Yi, Kurisu et al. 2011, Dong and Ng 2014). In contrast, endpoint E-LCIA methods convert impact indicators into only three or four damage categories (i.e., AoPs), which are more straightforward and thus can be more easily interpreted. Therefore, endpoint approach was selected in this study, which means Eco-indicator 99, IMPACT 2002+ and ReCiPe are all acceptable as they all provide characterization factors at endpoint level. In addition, all the methods provide normalization factors and weights. However, ReCiPe provides normalization factors and weights at the worldwide scale, while Eco-indicator 99 and IMPACT 2002+ only provide Europe-specific ones. As there is no Singapore or Asian specific factors, it seems better to adopt a set of world scale factors, which makes ReCiPe a most suitable method in this study.

Based on the above discussion, ReCiPe was selected. As indicated in Figure 6-1, 17 impact categories are defined to cover a large variety of impacts at the midpoint level, and three AoPs are considered at the endpoint level including: 1) protection of human health, which is described by the disability-adjusted loss of life years (DALY) considering the year of life lost and the year of life disabled due to environmental interventions; 2) protection of ecosystem diversity, which is described by local species lost in a predefined period as a result of emissions to terrestrial, freshwater, and marine systems; and 3) protection of resources availability, which is calculated as the economic loss caused by the marginal increase in costs due to the extraction of a resource (Goedkoop, Heijungs et al. 2009). Midpoint and endpoint categories are linked through endpoint characterization model in ReCiPe. Such calculation process can be conducted with the help of E-LCA software, such as SimaPro, and ReCiPe endpoint results will serve as the input for the LCSA model or decision-making model.

Figure 6-1 Schematic representation of ReCiPe (Goedkoop, Heijungs et al. 2009)

In addition to the characterization model as indicated in Figure 6-1, ReCiPe also provides weightings, which will be used in the decision-making process presented later in Chapter 9. In ReCiPe, different choices or assumptions are grouped into three

perspectives, which are individualistic, hierarchism and egalitarian perspectives, based on cultural theory (Goedkoop, Heijungs et al. 2009). Weights are different for these perspectives, as summarized in Table 6-2; however, it is recommended to employ the average weighting in ReCiPe report, and thus this study adopted weighting factors of 0.4, 0.4 and 0.2 for *protection of human health*, *protection of ecosystem diversity*, and *protection of resource availability*, respectively.

Table 6-2 Summary of three perspectives in ReCiPe and their corresponding weighting sets (Goedkoop, Heijungs et al. 2009)

Perspective	Ecosystems	Human health	Resources
Individualist	<i>“based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation”</i>		
	0.25	0.55	0.20
Hierarchism	<i>“based on scientific consensus with regard to the time frame and plausibility of impact mechanisms”</i>		
	0.40	0.30	0.30
Egalitarian	<i>“the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available”</i>		
	0.50	0.30	0.20
Average Weighting	0.40	0.40	0.20

6.2 Selection of Social Assessment Criteria

As discussed in Section 3.3, *Guidelines for Social Life Cycle Assessment of Products by UNEP/SETAC Life Cycle Initiative (the Guidelines)* serves as a methodological skeleton for the development of social assessment method in this study. Therefore, consistent with the stakeholder-based approach in *the Guidelines*, the selection of social assessment criteria should start from the selection of stakeholder categories, that is, to identify groups of people that are potentially affected by life-cycle activities. This is followed by the selection of social subcategories under each stakeholder category to illustrate different aspects of social concerns.

6.2.1 Selection and Definition of Stakeholder Categories

In this study, four main life-cycle phases of building projects were considered, including raw material extraction, building material or products manufacturing, on-site construction, and operation and maintenance (O&M). Activities within different life cycle phases are linked to different stakeholder categories, as illustrated in Figure 6-2. For raw material extraction and manufacturing phase, a number of materials or products are required; hence, various organizations are involved and cause different impacts due to different regional context and organizational conduct. Consequently, assessment should be performed separately by organizations. As for the construction and O&M phase, although several companies representing owners, contractors, designers, etc. are involved, only one integrated organization, i.e., project team, will be assessed. That is because building projects are delivered through a temporary and dynamic team. Stakeholder category “society” is not directly linked to any life-cycle phase; it is how the development of a certain building project causes the change of industrial environment or society (specifically Singapore in this study) that will be examined.

Figure 6-2 Relationship between life-cycle phases and stakeholder categories

In summary, four stakeholder categories were identified, including:

- workers, which refer to people working in manufacturing plant or on mining/construction site;
- occupants of the building;
- local communities, which refer to those who live in the close proximity to a production site or construction site, and thus directly affected by the production or construction activities; and
- society, which refers to the general public in the region where the building project is located and is indirectly affected regarding acknowledged social values (Manik, Leahy et al. 2013, Siebert, Bezama et al. 2016).

Other value chain actors were excluded since their identification is quite ambiguous and data collection from them are quite difficult, if not impossible, in the building supply chain (Dong and Ng 2015).

6.2.2 Selection of Social Impact Subcategories

Social impact subcategories were selected through content analysis, which is a systematic and qualitative method for literature review. Particularly, *the Guidelines* and 15 previous studies that developed building-specific criteria for social impact assessment (Shen, Li Hao et al. 2007, Chan and Lee 2008, Ali and Al Nsairat 2009, Alwaer and Clements-Croome 2010, Bragança, Mateus et al. 2010, Chen, Okudan et al. 2010, Shen, Tam et al. 2010, Andrade and Bragança 2011, Dave 2011, Nguyen and Altan 2011, Yunus and Yang 2011, Pan, Dainty et al. 2012, Valdes-Vasquez and Klotz 2012, Almahmoud and Doloi 2015, Kamali and Hewage 2015) were carefully reviewed. It is worth mentioning that previous building-specific studies usually only focus on construction and O&M phases, while enlarged boundary in this study, i.e., including four main life-cycle phases, leads to a broader set of impact categories.

Two-phase selection was conducted. Initial selection was based on *the Guidelines* and previous S-LCA case studies that adopted *the Guidelines'* framework disregarding their case scenarios (Wang, Hsu et al. 2016, Chen and Holden 2017). Subcategories irrelevant to our study were excluded, such as delocalization and migration issues, and prevention of armed conflicts and corruption. Secondly,

building-specific criteria (which refers to subcategories in the context of S-LCA) for social impact assessment proposed in the 15 studies were reviewed to refine the selection, which were then classified into stakeholder categories. In addition, the initial list of social criteria was reviewed by experts during the pilot survey process, as described in Section 4.2.2. Finally, after revising based on experts' opinions, social impact categories were obtained as summarized in Table 6-3.

Table 6-3 Selection of stakeholder categories and subcategories

Social Impact Category		Source	
Stakeholder Category	Subcategory	<i>the Guideline</i> (original expression if any change)	Papers (count of papers mentioning a certain subcategory)
Worker	Health and safety of workers	√	√ (8)
	Fair Salary	√	×
	Working Hours	√	×
	Discrimination	√	×
	Forced Labour	√	×
	Child Labour	√	×
Occupant	Functionality and Usability	√ (safety & health)	√ (8)
	Health and Comfort	√ (safety & health)	√ (14)
	Accessibility	×	√ (6)
	Feedback Mechanism	√	×
Local Community	Safety and Health	√ (safe, healthy and secure living conditions)	√ (9)
	Accessibility	√ (access to material resources)	√ (6)
	Integration and Interaction	√ (local engagement; cultural heritage)	√ (7)
	Local Employment	√	√ (6)
Society	Technology development	√	√ (3)
	Public commitments to sustainability issues	√	×

For category “workers”, *safety and health* is the only aspect discussed in previous papers. It evaluates the quality and efficiency of safety management within an organization, mainly including the provision of necessary and enough safety measures, equipment, facilities, information and trainings to the workers. Apart from safety and health protection, *the Guidelines* also highlights the importance of protecting human rights, particularly workers’ rights here, in achieving social sustainability, which is seldom included in previous building-specific criteria. Therefore, five subcategories, including *fair salary*, *working hours*, *discrimination*, *forced labour*, and *child labour*, are added to consider human rights including right to free choice of employment, right to equal pay for equal work without any discrimination, right to just remuneration and right to rest brought by reasonable working hours and periodic holidays with pay.

Category “occupants”, named “consumer” in *the Guidelines*, is most frequently discussed in building-specific studies as it is about the core function of buildings. *Safety and health* in *the Guidelines* are fitted into two subcategories, *functionality and usability*, and *health and comfort*. *Functionality and usability* assesses how well the project meets its functional needs and provides building facilities and features depending on different usage purposes. Particularly, it focuses on the provision of essential amenities such as drinking water, toilet, rest area, first aid, etc., as well as safety and security issues, including building's ability to protect the residents from external harm events (such as weather, home invasion, etc.), provide safe internal installations (such as appliances, stairs, etc.) and security measures to avoid risk of harm due to intentional criminal acts such as assault, burglary or vandalism. *Health and comfort* basically assesses indoor environmental quality (IEQ). IEQ is regarded to directly influence the comfort, health and well-being of occupants (De Giuli, Da Pos et al. 2012), which is illustrated by several aspects such as indoor air quality, hydrothermal comfort, visual comfort and acoustic comfort.

Accessibility is another essential factor in improving social sustainability through increasing occupants’ satisfaction. People are always willing to live in a place that can access to certain places in their daily lives properly and conveniently (Chan and Lee 2008); thus they care about how building is linked to places such as public

transport nodes, daily use shops, health facilities, open spaces, etc. Aesthetic options and beauty of the building is also a frequently mentioned aspect in previous studies (Chen, Okudan et al. 2010, Andrade and Bragança 2011, Yunus and Yang 2011, Kamali and Hewage 2015). However, considering the ambiguity to define beauty, this aspect is excluded from our framework to avoid excessive subjective evaluation. The last subcategory is *feedback mechanism*, which is tightly related to the occupants' satisfaction related to building services. Efficient feedback mechanism should at least make sure any complaints concerning the building normal operation can be solved within a reasonable time.

As for category “local community”, *safety and health* assesses whether production activities in factories or on-site construction work have a good control of noise generation, pollution and dust emission as well as a good waste management to avoid harming neighbours' health and comfort. It also evaluates whether there is any safety risk around construction site, such as falling objects, uncovered holes in the road or pavement, poor lighting and uneven surfaces, etc. *Accessibility* for the surroundings means differently for different phases. During construction phase, accessibility assesses how construction works affect people's daily travel time and distance and decrease the mobility of daily life (Andersson and Johansson 2012); while during O&M phase, surrounding residents see accessibility as whether the project respects, protects, provides or improves community access to infrastructures, such as roads, facilities, electrical grids, drainage, and even open spaces, parking areas, green areas, etc.

Integration and Interaction is to assess how a project is integrated into the local community, and how it interacts with community stakeholders. As for a building project, it is supposed to enhance such practices proactively as it is principally an integral part of the local community (Almahmoud and Doloi 2015). This subcategory, therefore, requires a project to respect the social value of a community, to preserve the local characteristics (including both natural and cultural heritage), to engage community stakeholders in relevant decision-making processes and listen to their voices, to respond to communities' concerns and perceptions effectively, as well as to establish a communication path to encourage such interaction and integration. The

last subcategory, *local employment*, investigates both direct and indirect influence of a project on local employment. Local hiring preferences provide important income and training opportunities to community members. Furthermore, developing relationships with locally-based suppliers will further encourage local employment and development.

For category “society”, *technology development* examines technology development strategies of an organization. It may include involvement in technology transfer program, partnerships in research and development, or investments in technology transfer or technology development regarding building products, systems, construction methods, services, techniques, or management models. Another category, *public commitments to sustainability issues*, is related to the broader meaning of organizational social responsibility. It assesses whether an organization prepares publicly available documents as promises or agreements on sustainability issues to its customers, shareholders, local community or the public.

6.3 Conceptual Framework for LCSA Model

In the previous sections, selection of environmental and social assessment criteria was explained. As for economic assessment, LCCA was adopted and its results can be reported using several indicators, such as net present value (NPV), equivalent annual cost (EAC) and internal rate of return (IRR) (Hossaini, Reza et al. 2015). NPV, as a commonly adopted indicator, was selected in this study, which refers to the sum of present values of cash flows occurring at different stages of building. Usually, the estimation of costs for different life cycle phases of buildings can be obtained through Bill of Quantity documents and simulation results regarding energy consumption during operational phase, among many others.

With impact categories identified based on LCCA, E-LCA and S-LCA methods, an LCSA model for building evaluation can be constructed. To make it more straightforward and prepared for further MCDA modeling process, this model was presented as a hierarchical decision-making model, as demonstrated in Figure 6-3, where goal, criteria and alternatives are arranged similar to a family tree. The top level indicates the overall goal of the decision-making problem, which is to select the alternative with highest level of sustainability. Intermediate levels show multiple

criteria that define alternatives. The first level of criteria indicates the three pillars of sustainability, i.e., economic optimization, environmental protection and social acceptability. Environmental protection is subdivided into three AoPs, and social acceptability is subdivided into four stakeholder categories and subcategories under each stakeholder category. Lowest level is composed of all the alternatives to be compared or ranked, and alternatives here can be building components or entire building system. Indicators for economic and environmental assessment are all quantitative ones, which are NPV (unit: Singapore dollar), disability-adjusted loss of life years (unit: year), time-integrated species loss (unit: species year) and surplus costs (unit: dollar); while social impact assessment involves both quantitative and semi-quantitative indicators, which will be explained in Chapter 7 as a part of the proposed social impact assessment method.

Figure 6-3 Hierarchical structure of LCSA model

6.4 Summary

This chapter aims at establishing a conceptual framework for sustainability assessment through extracting impact categories from three life-cycle based methods. Economic aspect is evaluated through LCCA, whose results are reported by NPV. Environmental impacts are calculated through E-LCIA process in E-LCA studies, and thus impact categories were extracted from a selected E-LCIA method, that is, ReCiPe endpoint approach in this study. Accordingly, three environmental (endpoint) impact categories were included in the conceptual framework, which are protection of human health, protection of ecosystem diversity and protection of resource availability. As for social impact assessment, impact categories were selected using stakeholder-based approach according to *the Guidelines*. Four groups of stakeholders were firstly identified, which are worker, occupant, local community and society. This was followed by identification of impact subcategories through content analysis of *the Guidelines* and fifteen previous studies that proposed social criteria. This chapter addresses the issue of selecting social impact categories; however, what indicators should be used to characterize these impact categories and how to conduct social impact assessment are still unclear, which will be explained in the next chapter.

Chapter 7 Development of Social Life Cycle Impact

Assessment Method for Building Projects

As discussed in Section 3.3, S-LCA is still in its infancy and many aspects of S-LCA remain unclear, such as selection of impact categories and characterization of social issues. A set of social impact categories has been proposed in Chapter 6, and this chapter presents a building-specific social life cycle impact assessment (S-LCIA) method, including indicators selection, weights determination and calculation of social impact scores. The proposed method will be illustrated by a case study that compares social performance of CC and VAV systems.

7.1 Overview of the Proposed S-LCIA Method

This chapter addresses the issues related to social impact assessment, which are illustrated by Figure 7-1. One or more social indicators were selected to characterize each impact subcategory (as listed in Table 6-3), and the justification for indicator selection is provided in Section 7.2. Three groups of indicators were used in this proposed method and they applied different scoring methods, which are explained separately in Section 7.3. To integrate these social performance scores (SPS), weights among life-cycle phases and impact categories were generated, which are presented in Section 7.4. Accordingly, SPS for each social impact subcategory can be obtained by integrating SPS for each indicator of each phase and phase weights. Furthermore, an integrated SPS or SPS for each stakeholder category can be obtained using subcategory weights.

Figure 7-1 Methodological framework for social impact assessment

7.2 Indicators Selection

Indicator selection is influenced by the nature of the assessment objective and data availability. As discussed in previous S-LCA studies (Dreyer, Hauschild et al. 2006, Jørgensen, Le Bocq et al. 2008, Kruse, Flysjö et al. 2009), site-specific data obtained by investigating organizational operation are more favourable to evaluate social

impact compared with generic statistical data. However, such information is not always available. From life cycle perspective, main activities of a project team lie in construction and O&M phases, and the building evaluation is always conducted during the design phase, or before buildings being put into operation. The availability of detailed information will be lower if the activities are located farther from the centre, as indicated in Figure 7-2. It is impossible to trace back where a certain raw material was extracted exactly, not to mention to know which specific company it is from. As for manufacturing phase, more specific information may be obtained from first-tier supplier of building material or components, however, most of information regarding organizational-level management is still lacking or out of the control of those who conduct social assessment. Therefore, considering data availability, this study uses both generic and site-specific data, as shown in Figure 7-2, which influences the indicator selection.

Figure 7-2 Data specificity change along life cycle phases and their corresponding data sources and indicator types

To obtain quantitative results, indicators can be quantitative or semi-quantitative. Quantitative indicators describe assessed issues using specific values, for instance, number of work accidents per unit process. Semi-quantitative indicators are quantification of qualitative indicators which usually use a scoring system or a yes/no form, for example, giving score for company performance regarding human rights protection using a scale of 1 to 5. Quantitative indicators can be directly related to the unit process output as it is the case in E-LCA. However, the representativeness of quantitative indicators for the real case situation is sometimes questioned compared

to the qualitative ones that are based on the site-specific evaluation (Dreyer, Hauschild et al. 2010). An example that illustrates the shortcoming of quantitative indicators is about the measurement of the efficiency of dealing with consumer's complains in a company. It seems reasonable to use "average time in dealing with complains" as the indicators, but this indicator may also be a poor one when a company does not have strict requirement on recording complaining cases and custom service staffs only record those cases that can be easily solved. Semi-quantitative indicators, by contrast, allow site-specific evaluation and, at the same time, make it possible to express in quantitative terms, which is suitable to be aggregated into our LCSA model.

In summary, as shown in Figure 7-2, for the analyses based on the generic data, indicators are all quantitative since statistical data at the country and industry level are used. As for site-specific analyses, both quantitative and semi-quantitative indicators are involved, considering quantitative indicators sometimes cannot properly describe the real case situation (Dreyer, Hauschild et al. 2010). Indicators selected for generic analysis and site-specific analysis are summarized in Table 7-1 and Table 7-2, respectively. As generic analysis is associated with raw material extraction and manufacturing phases, only impact subcategories related to 'worker' and 'local community' are considered (as shown in Figure 6-2); while site-specific analysis is conducted to all the stakeholder categories.

Table 7-1 Selection of indicators for generic analysis

Impact Subcategory	Indicators	Sources
Health and safety (worker)	Non-fatal and fatal occupational injuries per 100,000 workers	(Hämäläinen, Takala et al. 2006)
Fair Salary	Ratio between average sector wage and living wage	(Communities 2009, ILO 2017)
Working Hours	Excessive weekly working hours per employed person compared with 48 hours	(ILO 2017)
Discrimination	Gender inequality index	(Selim Jahan, Eva Jespersen et al. 2016)
Forced Labour	Proportion of population in modern slavery	(WalkFree 2016)
Child Labour	Percentage of children 5-14 years old involved in child labour	(UNICEF 2017)
Safety and Health (Local community)	Reliability of police services	(Klaus Schwab, Xavier Sala-i-Martin et al. 2018)
	Burden of disease	(WHO 2015)
	Dealing with construction permits	(WorldBank 2017)
Accessibility (Local community)	Percentage of population with access to improved water source and improved sanitation facilities	(WorldBank 2016)
	Quality of road	(Klaus Schwab, Xavier Sala-i-Martin et al. 2018)
Integration and Interaction	Transparency of government Policymaking	(Klaus Schwab, Xavier Sala-i-Martin et al. 2018)
	Public trust in politicians	
Local Employment	Unemployment rate	(WorldBank 2016)
	Local supplier quantity	(Klaus Schwab, Xavier Sala-i-Martin et al. 2018)

Table 7-2 Selection of indicators for site-specific analysis

Subcategory	Indicators	Sources
Health and safety (worker)	<ul style="list-style-type: none"> ○ Status of managerial practices ● Accident frequency rate 	On-site observation Workers' feedback Human resources and management records Project management records ...
Fair Salary	<ul style="list-style-type: none"> ○ Status of managerial practices ● Percentage of workers whose wages meet at least legal minimum wage/sectorial standard 	
Working Hours	<ul style="list-style-type: none"> ● Percentage of workers who are paid a living wage. ○ Status of managerial practices ● Contractual working hours 	
Discrimination	<ul style="list-style-type: none"> ○ Management of overtime ○ Status of managerial practices ● Numbers of incidents of discrimination 	
Forced Labour	<ul style="list-style-type: none"> ○ Status of managerial practices ● Numbers of forced labour 	
Child Labour	<ul style="list-style-type: none"> ○ Status of managerial practices ● Numbers of child labour 	
Functionality and Usability	<ul style="list-style-type: none"> ○ Status of design consideration ○ Performance regarding meeting functionality needs and provision of essential amenities and building equipment 	On-site observation and audit Design document and parameters Occupants' feedback managerial records ...
Health and Comfort	<ul style="list-style-type: none"> ○ Status of design consideration ○ Performance regarding indoor air quality, acoustic comfort, hydrothermal comfort and visual comfort 	
Accessibility (occupants)	<ul style="list-style-type: none"> ○ Status of design consideration ○ Performance regarding proximity to public transportations and amenities 	
Feedback	<ul style="list-style-type: none"> ○ Status of managerial practices 	
Mechanism	<ul style="list-style-type: none"> ○ Performance regarding efficiency of dealing with fault reporting and general enquiries 	

Table 7-2 (Continued)

Safety and Health (Local community)	<ul style="list-style-type: none"> ○ Status of managerial practices ○ Performance regarding controlling disturbance to surroundings regarding dust emission, noise emission, and preventing safety issues 	
Accessibility (Local community)	<ul style="list-style-type: none"> ○ Status of managerial practices ○ Performance regarding preventing mobility disturbance (construction phase) ○ Status of design consideration ○ Performance regarding providing open places, paths and facility for public (O&M phase) 	On-site observation Feedback of neighbourhoods and pedestrian project records
Integration and Interaction	<ul style="list-style-type: none"> ○ Status of managerial practices ○ Performance regarding the preservation of local characteristics, and involvement of neighbourhoods into project-related activities, such as design and construction process planning, knowledge sharing and skill transfer 	...
Local Employment	<ul style="list-style-type: none"> ○ Status of managerial practices ● Percentage of workforce hired locally ● Percentage of spending on locally-based suppliers. 	
Technology development	<ul style="list-style-type: none"> ○ Status of managerial practices ○ Performance regarding technology development strategies 	Organization and project report
Public Commitment to Sustainability Issues	<ul style="list-style-type: none"> ○ Status of managerial practices ○ Performance regarding public sustainability reporting 	...

- Quantitative indicator using site-specific data
- Semi-Quantitative indicator using site-specific data

7.3 Scoring of Indicators

As listed in Tables 7-1 and 7-2, three groups of indicators are involved, including quantitative indicators in generic analysis, as well as quantitative and semi-normalized to a range of -2 to +2 in order to be further integrated to single social performance scores. With different forms and actual meanings, these indicators vary greatly on scoring and normalization process, which will be explained in the following parts.

7.3.1 Quantitative Indicators in Generic Analysis

Before conducting generic analysis, country-level performance scores regarding each impact indicator need to be prepared using national statistical data. Statistical data were collected from several online databases or international reports, as indicated in Table 7-1, and were normalized to a range of -2 to +2. Typically, positive values represent above-average or favourable social performance, while negative ones show poor social performance or negative impact. For example, country-level statistics regarding non-fatal occupational injuries rate (Hämäläinen, Takala et al. 2006) were normalized between -2 to +2 where country with lowest injuries rate was assigned a score of 2, and country with the highest injuries rate was assigned a score of -2. As mentioned, the normalization rule is based on the actual social meaning of the indicator, rather than all being normalized according to maximum and minimum values. For example, most of the countries do not have issues of child labour according to the statistics (UNICEF 2017); thus countries with 0% were scored as 2, while others are normalized to -2~0. Figure 7-3 shows an example of normalized country-level social performance score for several impact subcategories.

	Health and safety of workers	Fair Salary			Working Hours			Discrimination	Forced Labor	Child Labor
		Mining	Prod.	General	Mining	Prod.	General			
Australia	1.80	1.80			0.62		1.75	1.55	2.00	2.00
Brazil	0.66	0.56			0.77		1.13	-0.15	1.94	-0.33
Cambodia	-0.34	-0.42		-0.42	0.38		0.38	-1.03	0.50	-0.79
Canada	1.53	1.31			1.50		1.50	1.65	2.00	2.00
China	1.17	-0.29	-0.37		0.31	-0.14	0.13	1.28	1.79	2.00
France	1.81	0.89			1.08		1.50	1.65	2.00	2.00
Germany	1.76	1.13			1.08		1.63	1.81	2.00	2.00
India	1.09	0.19		0.19	0.00		0.00	-0.85	0.73	-0.48
Indonesia	0.29	-0.19		-0.19	0.46		0.88	-0.38	1.75	-0.28
Iran	0.64	0.05		0.05	0.00		0.00	-0.62	1.44	-0.47
Italy	1.48	0.74			1.23		1.50	1.70	1.82	2.00
Japan	1.80	1.52	1.31		1.08	1.00	1.13	1.57	1.81	2.00
Korea, Republic of	0.73	1.49			0.77		0.50	1.82	1.65	2.00
Malaysia	0.51	0.05	0.05	0.05	-0.31	0.14	0.38	0.60	1.63	2.00
Poland	1.22	0.48			1.08		1.00	1.43	1.58	2.00
Russia	1.13	-0.13			1.38		1.25	0.64	1.34	2.00
Singapore	1.24		0.11			0.43	0.50	1.79	1.86	2.00
South Africa	0.44	2.00		2.00	0.31		0.63	-0.01	1.60	2.00
Turkey	0.44	0.34		0.34	-0.31		0.13	0.29	1.44	-0.24
Ukraine	0.60	0.21		0.21	1.23		1.13	0.55	1.59	-0.10
USA	1.63	0.91			1.13		1.13	1.00	2.00	2.00
Vietnam	-0.23	0.34		0.34	0.15		0.50	0.40	1.88	-0.67

Figure 7-3 Example of normalized country-level social performance score for various impact subcategories

With country-level performance scores prepared, data collection for generic analysis focuses on the identification of main countries involved in certain phases (particularly raw material extraction and production phase), and the activity contribution of these countries. In this study, weight proportions of building materials serve as the basis for calculation, as adopted in previous studies (Ekener-Petersen and Finnveden 2013, Gould, Missimer et al. 2017); while activity contributions of countries are connected to these materials through worldwide extraction statistics and export or import data.

For raw material extraction phase, weights of raw materials are estimated based on the quantity of building materials that can be identified using Bill of Quantity or other project records. These materials can be split into raw materials based on general production information of a certain material. For example, integrated steelmaking route requires 1.4 kg of iron ore, 0.8 kg of coal, 0.3 kg of limestone and 0.12 kg of recycled steel to produce 1 kg of crude steel (Worldsteel 2018). Such information indicates the extraction forms of raw materials and allows the conversion to percentage composition of all the raw materials involved. For each raw material, main extraction locations and percentage of extraction from each country can be obtained from the statistics. In this study, Mineral Commodity Statistics (USGS 2017) and

World Mineral Production (Brown, Wright et al. 2014) were used to identify dominant countries that contribute around 90% of total world extraction, which are then used to represent all contributing countries for simplification.

For manufacturing phase, indicators are scored following the similar process. Differently, the activity contribution of each country could be calculated based on more specific and accurate information, such as project purchasing or supplier records, showing actual origins of a certain building material or product. Alternatively, for building materials or products that are directly related to assembly or construction activities in Singapore, country activity distribution can be determined using Singapore-specific statistical data, such as import statistics (COMTRADE 2017, Simoes 2017), instead of using worldwide statistical data. For example, considering sand usage in Singapore relies greatly on import, country activity contribution for sand was estimated using import data, according to which Malaysia (65.3%), Vietnam (20.4%) and Cambodia (14.3%) are the top three contributors for sand mining.

Accordingly, the contribution of activities in j th country (activity contribution, AC_j) involved in a certain life cycle stage can be obtained through integrating quantity proportion of k th material (quantity proportion, QP_k) and country activity contributions regarding individual materials (AC_{jk}), as indicated by Equation 7-1.

$$AC_j = \sum QP_k \times AC_{jk} \quad (7-1)$$

With the normalized social performance score of j th country for i th indicator (country-level performance score, CPS_{ij}), and the activities contribution occurred in each country (AC_j), the integrated normalized social performance score of i th indicator (social performance score, SPS_i) can be obtained by,

$$SPS_i = \sum CPS_{ij} \times AC_j \quad (7-2)$$

7.2.2 Site-Specific Analysis

Site-specific analysis focuses on the analysis on the project-specific social performance regarding each impact subcategories, as well as organizational efforts in management practices to improve or prevent certain social issues. There are some

previous studies (Dreyer, Hauschild et al. 2010, Wang, Hsu et al. 2016) that developed site-specific assessment methods or models; however, these studies only focus on organizational operations to indirectly identify the risk of violation incidents, while direct social performances regarding certain impact subcategories were not investigated. In this study, site-specific analysis covers both organizational managerial practices and direct social performance.

7.3.2.1 Evaluation of organizational performance

For organizational performance, Deming Cycle, also known as PDCA Cycle, was used as a reference to develop evaluation framework. Four aspects relevant to plan (P), do (D), check (C) and action (A) are to be investigated. Please note that in below discussion an organization refers to a building project team, instead of a single company.

For *plan* aspect, it evaluates whether an organization plans or designs properly based on legislation and sustainability principles, establishes organizational sustainability policy, and clearly communicates to relevant managers and employees. For *do* aspect, it evaluates whether organizational practices are complied with legislation and whether there is any sustainable practice to prevent violation or achieve improvement. *Check* aspect is about whether an organization monitor, audit or benchmark social related performance and/or establish a system to receive complaints/feedbacks, and whether it records properly. *Act* aspect is closely related to the *Check* results. On one hand, it evaluates whether organization responses properly if there is any violation incidents or complaints/feedbacks; on the other hand, it evaluates whether organization reviews problems in practice and determines whether any changes or revisions are needed in strategy and practices.

Scores for organizational performance, using semi-quantitative indicators, are obtained based on experts' verbal and qualitative assessments and their further conversion to numbers. The assessment is based on the performance reference scales (PRS), including five performance levels, namely, very poor (VP), poor (P), fair (F), good (G), very good (VG), and corresponding performance descriptions of each level. An example of the performance reference scale is provided in Table 7-3.

Table 7-3 Example of performance reference scale: managerial practices
regarding workers' safety and health

Scales	Description
P	<p>VG</p> <ul style="list-style-type: none"> Aware local regulation on worker's health and safety, here refers to Singapore Workplace Safety and Health (Construction) Regulations 2007. Have clear strategy to comply with regulation and achieve goals regarding safety and health Completely inform relevant stakeholders (managers, supervisors and on-site workers) <p>F</p> <ul style="list-style-type: none"> Aware local regulation on worker's health and safety, here refers to Singapore Workplace Safety and Health (Construction) Regulations 2007. Have corresponding strategy to comply with regulation No particular actions to achieve complete communication. <p>VP</p> <ul style="list-style-type: none"> No strategy is established; or even unaware local regulation
D	<p>VG</p> <ul style="list-style-type: none"> Adequate measures, such as protective equipment, are fully implemented to protect the health and safety of workers. Necessary training or explanation are actively provided to make sure the personnel aware of health and safety issues and steps/protocol to follow in case of emergency/ accidents Take measures to prevent workers from dangerous working condition through advanced techniques or construction methods <p>F</p> <ul style="list-style-type: none"> Adequate measures, such as protective equipment, are implemented to protect the health and safety of workers. Training and explanation are provided as requirement <p>VP</p> <ul style="list-style-type: none"> Insufficient measures or no measures
C	<p>VG</p> <ul style="list-style-type: none"> Occupational health of the personnel is monitored, recorded and managed. System for Receiving complaints or feedbacks from the personnel is well-established <p>F</p> <ul style="list-style-type: none"> Occupational health of the personnel is monitored, recorded & managed <p>VP</p> <ul style="list-style-type: none"> Occupational health of the personnel is not monitored or/and not recorded
A	<p>VG</p> <ul style="list-style-type: none"> Deal with complains, violation incidents, etc., if any, properly as requirement Review problems exist in practice and determine whether any changes or revisions are needed in strategy and practices <p>F</p> <ul style="list-style-type: none"> Deal with complains, violation incidents, if any, properly as requirement; or no violation incidents with no action <p>VP</p> <ul style="list-style-type: none"> Do not take action when complains/violation incidents occur

* Poor and good are the intermediate levels and therefore are not provided with corresponding descriptions

Management team members, such as engineers and project managers, are required to carefully check the descriptions provided and select the suitable performance level

based on their opinion. Assessment results are then converted into triangular fuzzy numbers $\tilde{x}_i^m = (a, b, c)$ using Figure 7-4 to represent m th evaluator's assessment regarding i th indicator, where a , b , and c are the membership function parameters. Adoption of fuzzy numbers can address the imprecision and uncertainty that is inherent to the human judgments in the decision-making process (Ren, Manzardo et al. 2015). Later, all the assessment results are aggregated into group evaluation results by applying the fuzzy averaging operator, which is defined by:

$$\tilde{x}_i = \frac{1}{M} [\tilde{x}_i^1 (+) \tilde{x}_i^2 (+) \dots (+) \tilde{x}_i^M], \quad (7-3)$$

where M is the number of experts.

Figure 7-4 Membership function of linguistic terms

Note: Linguistic scales and their corresponding fuzzy numbers adopt the definition of (Hsieh, Lu et al. 2004) which is proportionally transformed between -2 and 2.

Finally, fuzzy evaluation results are then defuzzified based on centroid of area (COA) method, as indicated by Equation 7-4, which are the scores for semi-quantitative indicators.

$$x'_i = \frac{a+b+c}{3} \quad (7-4)$$

7.3.2.2 Evaluation of direct social performance

Indicators of direct social performance could be both quantitative and semi-quantitative, as indicated in Table 7-2. For semi-quantitative indicators, scoring process is similar to the process to evaluate organizational performance, which is also obtained from evaluators' verbal and qualitative assessments based on PRS and their further conversion to numbers using fuzzy numbers. Differently, evaluators should

be multi-stakeholder, which may include occupants, local community, workers, and so on, depending on their relevancy.

Scores for quantitative indicators are obtained using performance reference values (PRVs), which can be country and/or sector average performance values. Specific calculation depends highly on the actual meaning of the indicators. For instance, to score performance regarding local employment, percentage of local workforce in a project is selected as indicator, and both sector and country statistical data were used as PRVs, being 14% and 63% respectively. 63%, rather than 100%, is given the score of +2, considering 63% is seen as the optimistic (best) performance in the context of Singapore; 14% is given the score of 0, indicating the standard and average performance level. Accordingly, performance score is obtained through normalizing project-specific percentage of local workforce, e.g. project with 20% being local workforce obtains the score of 0.24 ($= (20\% - 14\%) / (63\% - 14\%)$).

Another example is evaluating worker's health and safety using accident frequency rate (AFR, calculated by 1,000,000 times the ratio of the number of workplace accidents to the number of man-hours worked). Country-level statistics is selected as PRV, which is 1.50 in Singapore (MOM 2016). Score of +2 is assigned if no injury occurs, indicating best performance; score of -1 is assigned if AFR is identical to statistical (average) value, i.e., 1.5. Other values are normalized within the range of -2 to 0 based on PRVs, e.g., for a project with 2 minor injury cases and 164,500 man-days (averagely, 9.5 hours per man-day) recorded, its AFR is calculated as 1.28; accordingly, performance score is -0.85 ($= -1 * 1.28/1.50$).

7.4 Weights

Weights among social impact subcategories were obtained through questionnaire survey. As introduced in Section 4.2.2, the main part of the questionnaire was designed based on CFPR-based AHP. Questionnaires, including respondents' basic information, main pairwise comparison part and corresponding explanations, were delivered via face-to-face distribution or e-mail to local construction experts. In total, 103 feedbacks were collected with a response rate of 71.03%, which is enough for this study according to the minimum sample size of 97 as calculated in Section 4.2.2.

The respondents covered various stakeholders as shown in Figure 7-5. Based on the questionnaire survey results, weights were derived as summarized in Table 7-4.

Figure 7-5 Distribution of responses of questionnaire survey

Table 7-4 Weights of social impact categories

Stakeholder Category	Subcategory	Local weights	Global weights
Worker		0.273	
	Health and Safety	0.254	0.069
	Fair Salary	0.233	0.064
	Working Hours	0.186	0.051
	Discrimination	0.175	0.048
	Forced Labour	0.085	0.023
	Child Labour	0.067	0.018
Occupant		0.283	
	Functionality and Usability	0.312	0.088
	Health and Comfort	0.307	0.087
	Accessibility	0.209	0.059
Local Community		0.243	
	Safety and Health	0.343	0.083
	Accessibility	0.191	0.046
	Integration and Interaction	0.170	0.041
Society		0.201	
	Local Employment	0.296	0.072
	Technology development	0.621	0.125
	Public Commitment to Sustainability Issues	0.379	0.076

Another set of weights are weights among life cycle phases. Previous studies usually use activity variables to “reflect the share of a given activity associated with each unit process” and to describe the relevance of impacts caused by a process in a life cycle. Currently, the most common activity variable is worker hours, that is, the time workers spend to produce certain amount of products in the given process. However, strictly speaking, worker hours are only associated with stakeholder category “workers” (Ciroth and Eisfeldt 2017), which is very relevant in previous studies that only discuss topics regarding labour conditions. In this study, worker hours, however, may not be a suitable activity variable as this study includes multiple stakeholders.

This study indicatively estimated the relative importance of each phase based on two considerations, as shown in Table 7-5. One is the degree of possibility to place control. As indicated in Figure 7-2, data specificity is lower if the activities are located farther from the centre phases; so is the control possibility. Therefore, the possibility to control is ranked from high to low as follows: construction phase, use phase, production phase, and raw material extraction phase. Use phase is weaker than construction phase due to its longer time span (around 50 years). Another aspect is level of concern of construction practitioners, whose focus is on construction and use phase; raw material extraction was given a relatively higher score, since mining industry is believed to have much severer negative social impact compared with manufacturing industry. A total score of 100 was allocated to four phases for each aspect of consideration, and for each phase mean of two scores was calculated and converted to weight.

Table 7-5 Weights of life cycle phases

	Raw Material Extraction	Production	Construction	Use
Control	5	15	50	30
Concern	25	5	30	40
Weighting	0.15	0.10	0.40	0.35

7.5 Illustrative Case Study on CC and VAV Systems

In this section, the proposed S-LCIA method is illustrated by a case study comparing life-cycle social performance of CC and VAV systems, whose basic information has

been presented and adopted for environmental and economic analysis in Chapter 5. Assessment scope was set to include raw material extraction, manufacturing and O&M phases. Accordingly, well-beings of worker, local community and occupant were evaluated. Stakeholder category “society” was excluded, considering AC system is just a small-scale system in a building project, and thus it is hard to judge how an AC system could influence the social value.

7.5.1 Generic Analysis

Generic analysis was conducted for raw material extraction and manufacturing phases. Activity contributions of countries involved in these two phases are shown in Table 7-6 and were obtained based on material quantity information (as listed in Table 5-2) and material extraction or import statistical data. It is found that most of the activities were carried out in Chile, Peru, China and Australia for both systems in raw material extraction phase. That is because Chile and Peru are actively-involved as the main extraction locations for copper ore, which takes up around 60% of the total raw material; China is the main provider of crude steel and coal; and Australia is for its provision of crude steel and copper ore. For manufacturing phase, most of the activities occurred in China, followed by Malaysia and the US. In addition, part of CC panels (i.e., the graphite part) was manufactured in Germany, taking up 3.4% of total activities.

Social performance scores, summarized in Table 7-7, were then obtained using information on activity contribution of countries, together with country-level social performance score for different impact subcategories. For raw material extraction phase, VAV system performs better in most indicators; while for manufacturing phase, CC system is relatively better. As mentioned in Chapter 5, the main difference in terms of material usage is the extra CC panels and additional pumps installed in the CC system. Raw materials associated with these components, such as copper ore, iron ore, limestone and coal, are common for other AC system components as well, which do not cause significant difference regarding percentage composition of raw materials. As a result, differences between two systems are not significant.

Table 7-6 Activity contribution of countries involved in raw material extraction and manufacturing processes

	Raw Material Extraction		Manufacturing	
	CC System	VAV System	CC System	VAV System
Australia	11.07%	11.17%		
Brazil	5.75%	5.79%		
Canada	5.66%	5.59%		
Chile	25.66%	25.27%		
China	11.73%	12.33%	74.05%	76.07%
Germany	0.26%	0.27%	3.41%	
India	1.31%	1.38%		
Indonesia	6.55%	6.47%		
Malaysia			12.17%	12.96%
Mexico	3.39%	3.34%		
Mongolia	3.21%	3.16%		
Peru	17.41%	17.14%		
Russia	0.95%	1.00%		
South Africa	0.60%	0.64%		
Spain	2.31%	2.28%		
Ukraine	0.32%	0.34%		
USA	3.80%	3.83%	10.37%	10.97%

Table 7-7 Social performance score of CC and VAV systems in raw material extraction and manufacturing phases

	Raw Material Extraction		Manufacturing	
	CC System	VAV System	CC System	VAV System
Health and safety (workers)	0.93	0.94	1.16	1.14
Fair Salary	0.13	0.13	0.21	0.21
Working Hours	0.17	0.18	0.08	0.03
Discrimination	0.59	0.60	1.18	1.16
Forced Labour	0.74	0.76	1.80	1.79
Child Labour	0.35	0.37	2.00	2.00
Health and safety (Local Community)	0.71	0.71	0.75	0.74
Local Employment	0.59	0.59	1.15	1.14
Integration & Interaction	-0.17	-0.17	0.38	0.36
Accessibility	1.04	1.04	1.16	1.15

Note: The higher the score, the better the social performance

7.5.2 Site-Specific Analysis

Site-specific analysis was conducted to investigate social performance in O&M phase. As a case study on AC systems for a 400 m² office space, the author assumed that local community was not affected, and thus only stakeholder category “occupants” was evaluated with two subcategories considered, that is, *functionality and usability* and *health and comfort*. Information regarding design consideration was collected from project management team and facility management team. Sources of information on direct social performance include project records or design parameters for quantitative indicators (as shown in Table 5-1), as well as on-site observation and interview with staffs working in this office for semi-quantitative indicators.

Direct social performance in terms of *health and comfort* were characterized using two thermal comfort-related indicators, which are predicted mean vote (PMV) values and operative temperature. PMV values of CC and VAV systems are -0.09 and -0.12, respectively, and operative temperature of the two systems are 24.9 °C and 24.5 °C, respectively. As listed in Table 5-1, acceptable range for PMV is -0.5 to +0.5, and zero is the ideal value. As mentioned previously, all the actual performance values should be normalized to the range of -2 to +2. The ideal value should be assigned by the highest score, i.e., +2, and threshold values should be assigned by 0, indicating a minimum requirement. Accordingly, as for PMV, the normalized values are 1.64 and 1.52 for CC and VAV systems, respectively. As for operative temperature, the acceptable range is between 24 and 26°C, and 25°C was set as the ideal value for a similar normalization process. Indicators for other impact categories are all semi-quantitative, which were calculated using Equations 7-3 and 7-4. The normalized values are further integrated via averaging of two aspects (managerial practices/design consideration and direct social performance). The results are presented in Table 7-8.

Table 7-8 Social performance score of CC and VAV systems in O&M phase

Impact Category	Design consideration		Direct social performance		Integrated score	
	CC System	VAV System	CC System	VAV System	CC System	VAV System
Functionality & Usability	1.23	1.23	1.73	1.73	1.48	1.48
Health and Comfort	1.23	1.23	1.71	1.26	1.47	1.25

7.5.3 Integrated Social Sustainability Performance

Based on the performance scores and weighting sets, single social performance scores were calculated as 0.953 and 0.914 for CC and VAV systems, respectively. This indicates an overall better social performance of CC system from life-cycle perspective. Detailed comparison results were summarized in Figure 7-6. As indicated in Figure 7-6, CC system performs significantly better in *occupant's health and comfort* due to better thermal comfort performance; while for other impact categories, only slight differences can be observed. Together with the results in Chapter 5, comparison of normalized sustainability performance of CC and VAV systems are summarized in Figure 7-7. It is found that CC system performs better in social aspects compared with VAV system, and the main advantage of CC system is still in environmental aspects, which is because of its significant reduction of energy consumption during operational phase.

Figure 7-6 Scores of social impact subcategories for CC and VAV systems

Figure 7-7 Comparison of normalized sustainability performance of CC and VAV systems

(Note: for S-LCA, larger value indicates a better performance; while for E-LCA and LCCA, smaller value illustrates a better performance)

7.6 Summary

This chapter presents a building-specific social life cycle impact assessment method, which applies multi-stakeholder approach and includes several life-cycle phases in the analysis which enables the investigation on potential transfer of impacts between life-cycle phases. Specifically, three groups of indicators are involved, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis. Each type of indicators adopts different scoring methods.

For generic analysis, SPS were obtained by integrating country activity contribution and normalized country-level performance scores, which were calculated from different sources of statistics. For site-specific analysis, SPS were the average of scores for organizational managerial practices and direct social performance. Organizational managerial practices adopted semi-quantitative indicators and their scores were obtained based on performance reference scales (PRS). The PRS scales are constructed based on PDCA Cycle theory, aided by fuzzy theory for the conversion of qualitative evaluation results. As for direct social performance, score for semi-quantitative indicators were also obtained using PRSs and fuzzy numbers. Score for quantitative indicators were calculated using actual performance data and performance reference values (PRVs), which can be country and/or sector average performance values. In addition, weights among life-cycle phases were determined considering the degree of possibility to place control as well as level of concern of construction practitioners.

The proposed method was then applied to an illustrative case study, comparing social performance of CC and VAV systems. Single SPSs of two projects indicated that CC system outperformed VAV system in terms of social sustainability, which is mainly caused by its better thermal comfort level. Together with previous conclusions in terms of environmental and economic performance presented in Chapter 5, it is proved that overall CC system is a better choice. On the other hand, this case study serves illustration purpose only. Considering AC system is just a part of the entire building project, some phases and impact categories were not included in the evaluation, which may limit the applicability of the conclusions. Case study on a large-scale building project will be presented in Chapter 10.

Chapter 8 Dealing with Parameter Uncertainties in E-LCA

With various uncertainties existing, the reliability and transparency of E-LCA results are questionable, and inappropriate decisions may be made. In current LCA practices, there are numbers of methods to address the issue of uncertainties yet the reasoning for choosing a particular method is not always plausible. This chapter, therefore, provides a comparative analysis on those commonly used methods and discusses advantages of each method, based on which suggestions on method selection could be given. This chapter starts from an overview of uncertainty issues in E-LCA and approaches to dealing with uncertainties. Next, methods to be compared are introduced in terms of their main characteristics, followed by a detailed case study. Finally, results are presented and discussed, and guidelines were given as to the proper choice of various methods.

8.1 Overview of Approaches to Treating Uncertainty in E-LCA

It is evident that there are considerable uncertainties involved in each phase of E-LCA (Ciroth, Fleischer et al. 2004), which could be classified into parameter, scenario and model uncertainties, as proposed by Huijbregts et al. (2003). Parameter uncertainties reflect insufficient knowledge about the true value of parameters, which may be caused by the inherent data variability, inappropriate measurements or estimation, or data unavailability (Heijungs and Huijbregts 2004, Lloyd and Ries 2007). Scenario uncertainties are related to the normative choices made in modelling process, such as choice for system boundary, allocation, inventory data sources representing different geographical or temporal situations, and characterization methods (Clavreul, Guyonnet et al. 2012). Model uncertainties stem from the model structure and mathematical equations used, which cannot perfectly represent the real-world situation due to assumptions and simplifications involved, such as ignoring nonlinear processes.

Without taking these uncertainties into account, the reliability and transparency of E-LCA results are questionable, and inappropriate decisions may be made. For instance, significant differences between product systems may turn out statistically insignificant due to existing uncertainties (Huijbregts, Gilijamse et al. 2003). Therefore, it is necessary to investigate the impacts of these uncertainties in order to help decision makers understand the quality of E-LCA models, identify the most significant factors and recognize how they influence the results (Bisinella, Conradsen et al. 2016, Khang, Tan et al. 2017), all of which could guide further studies on uncertainty reduction.

Although it is widely recognized that uncertainties are significant and need to be made explicit, a standardized approach to addressing uncertainty issues is still lacking. In general, uncertainty and sensitivity analysis are recommended in ISO 14040 (2006) as additional data quality analyses in E-LCA, yet no specific techniques are provided. As defined by ISO 14040 (2006), uncertainty analysis is to determine how uncertainties in model input parameters propagate in the calculation and how they affect the reliability of E-LCA results; while sensitivity analysis is to study how changes in data and methodological choices affect E-LCA results. Ideally,

uncertainty and sensitivity analysis should be conducted in tandem to describe model quality comprehensively (Song, Zhang et al. 2015); however, in the current E-LCA practices, these two are usually conducted separately (Bisinella, Conradsen et al. 2016).

Before conducting uncertainty analysis, or uncertainty propagation, uncertainties should be characterized using probability distributions, possibility distributions, numerical forms or statistical parameters (Lloyd and Ries 2007). Generally, there are two main approaches to characterizing uncertainties in E-LCA studies, which are statistical and data quality indicator (DQI) methods. Statistical methods fit data samples with the goodness-of-fit test to characterize data range with probabilistic distributions if enough data samples are available (Wang and Shen 2013). Usually information can be obtained from product reports, relevant studies or experimental data (Lloyd and Ries 2007). DQI, on the other hand, estimates the reliability and uncertainty of data based on the descriptive metadata and expert knowledge regarding data age and source (Yu, Liu et al. 2018). It can be applied in both qualitative (Junnila and Horvath 2003) and quantitative (Guo and Murphy 2012) manners in E-LCA studies. When used quantitatively, DQI can be converted into Beta functions for further uncertainty propagation process. The statistical method is desirable when high accuracy is required, while DQI is more favourable when the high accuracy of uncertainty estimate is not critical, or the data sample size is not large enough for meaningful statistical analysis (Wang and Shen 2013).

As for methods for uncertainty propagation, sampling methods are very commonly used in E-LCA. Particularly, Monte Carlo sampling (MCS) method is the most commonly used method, and it has been built into some commercial E-LCA software such as SimaPro (Lloyd and Ries 2007, Bisinella, Conradsen et al. 2016). MCS method transforms deterministic E-LCA model to a probabilistic one through repeated calculation of model output using randomly sampled input parameters. It can reveal true uncertainty of model output as long as enough runs are performed (typically over 10,000 times) (Ciroth, Fleischer et al. 2004, Imbeault-Tétreault, Jolliet et al. 2013).

However, as E-LCA model usually involves numerous parameters, simulating all the input parameters may exceed available computer resources and time. In addition, MCS requires well-defined distribution for all input uncertainties, which may not be possible in many cases (Lo, Ma et al. 2005, Venkatesh, Jaramillo et al. 2010). Therefore, some variants of MCS method have been explored and applied, such as Latin hypercube sampling (Helton and Davis 2002, Basson and Petrie 2007), in order to reduce computation efforts. In addition to sampling methods, analytical method and fuzzy set method have also been implemented (Björklund 2002, Lloyd and Ries 2007). These methods show great advantages when limited information on input parameters is available for further processing (Tan, Briones et al. 2007), yet require more complex mathematical expressions (Heijungs 1996) and provide less directly usable information compared to sampling methods (Groen, Heijungs et al. 2014).

As for sensitivity analysis, one-at-a-time (OAT) analysis, also called local sensitivity analysis or perturbation analysis, is the most common practice (Huijbregts, Norris et al. 2001, Björklund 2002). In OAT analysis, each of the selected input parameters is changed by a small amount from a reference value and the corresponding change in the model output is computed. A variant of OAT analysis is scenario analysis, where scenarios have different values for several parameters (Mutel, de Baan et al. 2013, Cucurachi, Borgonovo et al. 2016). OAT approach has advantage of easy conduct and straightforward results interpretation (Groen, Heijungs et al. 2014). On the other hand, this approach have also been widely criticized for being inefficient for a large system, depending highly on practitioners' choices as to which model input parameters to be changed and by which amount, ignoring the probability distribution and expected ranges of parameters in the presence of uncertainty. Other reasons include ignoring interaction effects between parameters and assuming all parameters have strictly linear effects (Mishra, Deeds et al. 2009, Saltelli and Annoni 2010, Saltelli and D'Hombres 2010, Mutel, de Baan et al. 2013, Groen, Heijungs et al. 2014, Cucurachi, Borgonovo et al. 2016).

In order to overcome these limitations of local sensitivity analysis, another type of sensitivity analysis technique called global sensitivity analysis (GSA) has been identified as the best practice (Saltelli, Ratto et al. 2008). This new technique can also

address issues caused by separated execution of sensitivity and uncertainty analysis. For instance, parameters with low sensitivity but high uncertainty would usually not be considered (Bisinella, Conradsen et al. 2016). GSA is to investigate how uncertainty in model output can be apportioned to different sources of uncertainties in model input parameters (Saltelli, Tarantola et al. 2004). It has been increasingly applied in E-LCA studies, appearing with different terms, such as uncertainty contribution/importance analysis (Malça and Freire 2010, Röös, Sundberg et al. 2010, Hoxha, Habert et al. 2014) and key issue analysis (Heijungs, Suh et al. 2005, Groen, Bokkers et al. 2017).

Common methods to conduct GSA in E-LCA studies include regression-based methods (Basset-Mens, Kelliher et al. 2009), correlation-based methods (Chen and Corson 2014, Ross and Cheah 2017), variance-based methods (Padey, Girard et al. 2013, Kiese, Ventura et al. 2017), analytical methods (Hoxha, Habert et al. 2014, Groen, Bokkers et al. 2017), among many others. Furthermore, there are also some building-specific E-LCA studies. Hoxha et al. (2014) proposed a simplified analytical method based on Taylor series expansion to identify the relative contribution of different building materials to the variability of building's environmental impact considering three parameter (i.e., elementary impact, service life and quantity) of each material. Kiese et al. (2017) presented a method combining Morris' screening method with Sobol's method and applied to a case study of hemp-base building insulation material.

Facing with many methods available in the literature, however, reasoning for choosing a certain method is not always well explained (Saltelli, Ratto et al. 2008, Mishra, Deeds et al. 2009, Mutel, de Baan et al. 2013, Bisinella, Conradsen et al. 2016). Therefore, this chapter aims to provide a comparative assessment on methods for addressing parameter uncertainties in LCA studies and to determine the relative advantages of each method, which would lead to a reasonable selection of method in the future study. In the next section, methods to be compared will be introduced in terms of their main characteristics, followed by the description of a hypothetical case study.

8.2 Description of Methods to Be Compared

As mentioned before, this study aims to investigate sampling-based GSA methods applied in E-LCA studies. While a traditional E-LCA usually lead to a deterministic result, as indicated in Figure 8-1, an E-LCA model with sampling-based GSA can provide statistical result and sensitivity information, which typically consists of three steps. Firstly, an E-LCA model is constructed and model input parameters are determined with probability distributions assigned. Secondly, uncertainty propagation is performed using sampling methods, which leads to a distribution function of model output. Finally, GSA is conducted to obtain sensitivity indices for each input parameter, providing quantitative information on contribution of each input parameter to output variance.

Figure 8-1 Illustration of process of LCA with GSA and its difference compared with traditional LCA

Both sampling process and GSA have multiple method choices, which are independent from one another. Therefore, this study firstly compared three sampling methods (as described in Section 8.2.1), among which a relatively better one was selected to be applied in GSA. Four GSA methods, as introduced in Section 8.2.2, were then compared, which provided suggestion regarding selection of GSA methods in E-LCA. All the computations were done in MATLAB®.

8.2.1 Sampling Methods

This study compared regular MCS with its two other variants, namely, Latin hypercube sampling (LHS) and low-discrepancy sampling (LDS). The typical practice of MCS in E-LCA is to use random or pseudo-random numbers drawn from probability distributions of input parameters to estimate uncertainty in model output. For each parameter that is selected to be sampled, a probability distribution should be given, such as lognormal, normal and uniform distributions, which is usually determined by a-priori information (Marino, Hogue et al. 2008). Although it can be straightforwardly applied, traditional MCS is always criticized by its heavy computational burden, especially considering an E-LCA model usually involves numerous input parameters. Researchers have developed numerous techniques to increase computational efficiency, in which LHS and LDS have seen increasing popularity recently.

LHS is one of the popular variance reduction sampling techniques, which adopts stratified sampling procedure (Dai and Wang 2009). In LHS process, the selection of sample values is greatly controlled yet still allowed to vary. The probability distributions of input parameters are firstly divided in equally stratified subgroups; random numbers are subsequently picked from these subgroups, which are then combined randomly (Helton and Davis 2003). LHS performs the sampling independently for each parameter and each subgroup or interval is sampled exactly once without replacement, which provides more uniform space-filling coverage of the parameter space (Marino, Hogue et al. 2008, Mishra, Deeds et al. 2009).

Different from LHS's stratification manner, LDS speeds up MCS by improving sampling generator itself. It replaces the pseudo-random numbers in regular MCS by quasi-random ones; hence LDS method is also called quasi-Monte Carlo sampling

method. As indicated by its name, LDS employ low-discrepancy sequences, which are deterministic sequences without random component. It is believed that low-discrepancy sequences could yield precise integral estimates as they are more uniformly distributed than pure random numbers (Wang and Sloan 2008, Dai and Wang 2009). There are several known low-discrepancy sequences, such as Faure, Halton, Niederreiter and Sobol' (Wang and Sloan 2008, Tarantola, Becker et al. 2012). Among these methods, Sobol' sequences have been proven to be superior to the others in many aspects, especially in efficiency (Tarantola, Becker et al. 2012, Glasserman 2013, Kucherenko, Albrecht et al. 2015), and thus Sobol's LDS was selected for further investigation in this study.

Two aspects were considered for comparison, which were convergence rate and computation time. Theoretically, MCS has a convergence rate of $O(1/\sqrt{N})$ (where N refers to the sample size), while a much better rate of $O(1/N)$ can be achieved by LHS and LDS. Convergence rate of a sampling method can be measured by empirical standard error of the mean (SEM) for an increasing sample size, which describes how much variation is expected around the sample mean for a specific sample size (Groen, Heijungs et al. 2014). Smaller SEM value indicates a more accurate reflection of the true mean when comparing various sampling methods with the same N value. In this study, SEM was plotted against N , which was assigned with values ranging from 32 to 2048. With each N value, the mean was calculated and iterated for 50 times. These fifty mean values were used to calculate the SEM value. The actual convergence rate can be observed based on the slope of the line and will be compared with the theoretical one. As for computation time, information was directly derived from log of MATLAB calculation.

8.2.2 GSA Methods

The comparison of GSA methods focuses on two aspects. One is the performances of different GSA methods on explaining the total output variance, and another one is the ranking of variance contributions of individual input parameters obtained based on different GSA methods. Considering a generic model $y = f(x_1, x_2, \dots, x_k)$, in which each x has a non-null range of variation. The total output variance is given by

$$\text{Var}(y) = \text{Var}\left(E(y|x_j)\right) + E\left(\text{Var}(y|x_j)\right) \quad (8-1)$$

$\text{Var}\left(E(y|x_j)\right)$ is the conditional variance of parameter x_j , which is the resulting variance of y when x_j is fixed; while $E\left(\text{Var}(y|x_j)\right)$ is the residual term, which should ideally be zero. A large conditional variance indicates that x_j is an important factor. Accordingly, the variance contribution of each parameter is given by a ratio,

$$S_j = \frac{\text{var}\left(E(y|x_j)\right)}{\text{var}(y)}, S_j \in [0,1] \quad (8-2)$$

which is the sensitivity index of x_j on y . A high value of S_j signals an important variable. For an in-depth explanation, please refer to (Saltelli, Ratto et al. 2008). The sum of sensitivity indices of all the variances x (S_{sum}) shows the percentage of output variance that can be explained using different GSA methods. Through comparing sensitivity indices, this study investigates four sampling-based GSA methods, which belong to two groups, that is, regression-based and variance-based methods.

Regression-based method has been commonly used for GSA due to its simplicity and fast computation (Tian 2013, Song, Zhang et al. 2015). Principally, regression-based method estimates the relationship between an output and the input parameters through the following equation.

$$y_i = b_0 + \sum_j b_j x_{ij} + \varepsilon_i \quad (8-3)$$

where $j = 1, 2, \dots, k$ refers to the j th parameter, $i = 1, 2, \dots, N$ indicates the times of model runs; b_0 is a constant, b_j is the regression coefficient and ε_i is an error term.

The standardized regression coefficients (SRCs) are derived as $\frac{b_j \hat{s}_j}{\hat{s}}$, and sensitivity indices are determined using squared SRCs, as indicated in Equation 8-4 (Groen, Bokkers et al. 2017).

$$S_j^{SRC} = \left(\frac{b_j \hat{s}_j}{\hat{s}}\right)^2 = (b_j)^2 \frac{\text{Var}(x_j)}{\text{Var}(y)} = \frac{(\sum_{i=1}^N (x_{ij} - \bar{x}_j)(y_i - \bar{y}))^2}{\sum_{i=1}^N (x_{ij} - \bar{x}_j)^2 \sum_{i=1}^N (y_i - \bar{y})^2} \quad (8-4)$$

where $\text{Var}(x_j) = \sum_{i=1}^N \frac{(x_{ij} - \bar{x}_j)^2}{(N-1)}$ and $\text{Var}(y) = \sum_{j=1}^N \frac{(y_j - \bar{y})^2}{(N-1)}$. b_j is determined by

least square fitting, which equals to $\frac{\sum_{i=1}^N (x_{ij} - \bar{x}_j)(y_j - \bar{y})}{\sum_{i=1}^N (x_{ij} - \bar{x}_j)^2}$.

While SRC is suitable for linear model, its rank transformation, standardized rank regression coefficients (SRRC), can be used for non-linear but monotonic models. Input parameters x_{ij} is rank-transformed to $x_{(i)j}$, and y_i is rank-transformed to $y_{(i)}$. Similarly, sensitivity indices using SRRC are calculated as

$$S_j^{SRRC} = \frac{(\sum_{i=1}^N (x_{(i)j} - \bar{x}_j)(y_{(i)} - \bar{y}))^2}{\sum_{i=1}^N (x_{(i)j} - \bar{x}_j)^2 \sum_{i=1}^N (y_{(i)} - \bar{y})^2} \quad (8-5)$$

Another group of methods discussed in this study is variance-based methods, which estimate the importance of input parameters based on the decomposition of model output variance. Variance-based method has advantages of model independence (that is, it works fine for non-linear models, non-monotonic models and models with parameter interaction) and its capability to capture parameter interaction. However, it is often very computational expensive. Variance decomposition can be carried out using many techniques such as Sobol's method, the Fourier Amplitude Sensitivity Test (FAST), and their extended versions.

In general, the attribution of total output variance to each input parameter and interactions between input parameters can be expressed as follows (Sobol 1993).

$$Var(y) = \sum_j^k V_j + \sum_{j < l}^k V_{jl} + \dots + V_{12\dots k} \quad (8-6)$$

where $V_j = Var(E(y|x_j))$, $V_{jl} = Var(E(y|x_j, x_l)) - V_j - V_l$, and so on for higher order interactions. Accordingly, sensitivity indices, also called Sobol indices, are obtained using Equation 8-7, which can be interpreted as the percentage of the output variance attributed to individual input variables x_j , or the combinations of several input variables.

$$S_j = \frac{V_j}{Var(y)}, S_{jl} = \frac{V_{jl}}{Var(y)}, \dots, S_{12\dots k} = \frac{V_{12\dots k}}{Var(y)} \quad (8-7)$$

Where S_j refers to the first-order or main-effect Sobol index, S_{jl} represent the second-order interactions, and so on.

Sobol's method has a drawback of high computational cost since the number of Sobol indices increases exponentially with the number of input parameters (d), that is, there will be $(2^d - 1)$ Sobol indices. Therefore, it is suggested not to estimate indices with order higher than two (Iooss and Lemaître 2015). Such limitation can be addressed by considering total-effect indices of individual input parameters, as shown in Equation 8-8, which were introduced by Homma and Saltelli (1996).

$$S_{T-j}^{Sobol} = S_j + \sum_{j \neq l} S_{jl} + \sum_{j \neq l, j \neq p, l < p} S_{jlp} + \dots S_{jlp \dots k} \quad (8-8)$$

S_{T-j}^{Sobol} estimates that how much of the output variance can be attributed to input parameter j , including all possible interactions with other parameters. In this study, S_{T-j}^{Sobol} , together with main-effect indices S_j^{Sobol} , is calculated to provide information on model sensitivities.

Another variance-based method discussed is FAST method. According to the theory of Fourier series, any function can be written as a sum of wave functions. Model output is expanded using discrete Fourier transform, expressed as:

$$y(x_\omega) = \frac{1}{N} \sum_{i=0}^{N-1} g(x_{ij}) e^{-\sqrt{-1} \pi \omega i / N} \quad (8-9)$$

where ω is the frequency domain, which is divided in equally spaced segments from 1 to $(N - 1)$, while N represents the size of the equally spaced periodic function. Sensitivity index is given by:

$$S_j^{FAST} = \frac{\text{var}\left(E_{x \sim j}(y|x_j)\right)}{\text{var}(x)} = \frac{2(\sum_{\omega=1}^M |y^j(x_\omega)|)^2}{(\sum_{\omega=1}^{N-1} |y(x_\omega)|)^2} \quad (8-10)$$

where M equals to the maximum oscillation frequency. For more details on the sensitivity index shown in Equation 8-10, please refer to Groen et al (2017).

8.3 Case Study

The comparison was performed based on an artificial case study on concrete with four scenarios combining different distributions and variation levels. The greenhouse

gas (GHG) emissions, expressed in kilograms of CO_2 equivalents ($kg\ CO_{2-eq}$), which are associated with the manufacturing and placement of $1\ m^3$ concrete in structure, were investigated. The overall GHG emissions were estimated as indicated in Equation 8-11, which is the sum of emissions from the production of raw materials, as well as concrete batching, transportation and placement.

$$GHG_{total} = GHG_{prod} + GHG_{trans} + GHG_{batch} + GHG_{place} \quad (8-11)$$

$$= \sum Q_i * EF_{prod_i} + D * V_{concrete} * EF_{trans} + V_{concrete} * EF_{batch} + V_{concrete} * EF_{place}$$

where Q_i refers to the quantity of each concrete constituent. Quantities were determined based on a mix-design for a type of fly ash concrete (Kishore 2006), which uses 337 kg of ordinary Portland cement, 636 kg of fine aggregate, 1060 kg of coarse aggregate and 145 kg of fly ash. EF s refer to GHG emission factors, which were extracted from previous studies, as summarized in Table 8-1. D is the transport distance from concrete batching plant to the construction site and $V_{concrete}$ refers to the volume of concrete, which is $1\ m^3$ in this study.

Table 8-1 Emission factors for main activities associated with concrete production and placement

Activity		Emission Factor	Unit	Source
Raw material Production	Cement	8.20E-01	$ton\ CO_{2-e}/t$	*
	Fine Aggregates	1.39E-02	$ton\ CO_{2-e}/t$	*
	Coarse Aggregates	3.57E-02	$ton\ CO_{2-e}/t$	*
	Fly Ash	2.70E-02	$ton\ CO_{2-e}/t$	*
Concrete Batching		3.30E-03	$ton\ CO_{2-e}/m^3$	*
Concrete Transportation (concrete mixer truck)		6.74E-04	$ton\ CO_{2-e}/m^3 \cdot km$	**
Concrete Placement		9.00E-03	$ton\ CO_{2-e}/m^3$	*

Source: * (Flower and Sanjayan 2007) ** (Cho and Chae 2016)

All the input parameters in Equation 8-11 were assumed to be represented by the same probability distribution. Two types of distribution, log-normal and normal

distributions were discussed, which aims to investigate whether difference in distribution type will influence the comparison result on the performance of different methods. Normal distribution is the most popular form for uncertainty characterization according to a previous literature review (Lloyd and Ries 2007). Lognormal distribution was selected in line with Ecoinvent database, in which lognormal is the predominant distribution chosen to model uncertainties due to the advantage of being closer to the real life situation and not being defined in the negative domain (Weidema, Bauer et al. 2013).

The uncertainty of input parameter can be indicated by coefficient of variance (i.e., $CV = \sigma/\mu$). Large and small input uncertainties were discussed separately to see whether they will influence the comparison results. For log-normal distribution, CV values of 5% and 30% were assumed, representing small and large uncertainties respectively; while for normal distribution, CV value of 5% was assumed to represent small uncertainty and 20%, instead of 30%, was assumed to represent large uncertainty considering large CV may reverse the sign of input parameters.

In summary, there are four scenarios with the combination of two distribution types and two uncertainty levels, which are denoted in the following sections as N_S (normal distribution with small uncertainties), N_L (normal distribution with large uncertainties), LOGN_S (lognormal distribution with small uncertainties) and LOGN_L (lognormal distribution with large uncertainties).

8.4 Comparison Results and Discussion

The case study investigated GHG emissions associated with the manufacturing and placement of 1 m^3 concrete in structure. Results are summarized in Figure 8-2, indicating the contribution of each of the activities to the total GHG emissions, which is $348.7\text{ kg CO}_2\text{-e}$. Portland cement is the most significant contributor to the total emissions, followed by coarse aggregates. In the following sections, results of comparison among three sampling methods and four GSA methods are presented and discussed. Recommendations on method selection based on the characteristics of input parameters are also discussed.

Figure 8-2 Breakdown of GHG emissions generated by 1 m^3 concrete in structure

8.4.1 Comparison Results of Sampling Methods

Results obtained from three sampling methods, i.e., MCS, LHS and LDS, are presented in Table 8-2. Mean (i.e., GHG emissions) and standard deviation (SD) values were generated from 50 independent runs, with a sample size of 2048 for each run. It is observed that different sampling methods can generate almost the same result in each scenario. However, the mean value obtained in scenario LOGN_L is much larger than the others, which is due to the asymmetric nature of lognormal distribution.

Table 8-2 Mean and standard deviation values (SD, shown in brackets) obtained from MCS, *LHS* and *LDS* in four scenarios (unit: $ton CO_2-e$)

	N_S	N_L	LOGN_S	LOGN_L
MCS	0.3494 (0.025)	0.3637(0.118)	0.3504 (0.026)	0.4123 (0.193)
LHS	0.3495 (0.026)	0.3638(0.117)	0.3503 (0.026)	0.4121(0.194)
LDS	0.3494 (0.026)	0.3639 (0.117)	0.3503 (0.026)	0.4121(0.193)

Sampling methods were firstly compared with respect to SEM and convergence rate. For each method, SEM was plotted with reference to sample size (N), which ranges from 32 to 1024. As can be seen in Figure 8-3, four scenarios were plotted separately

for comparison. Slope of the line illustrates the convergence rate. In addition, reference lines were drawn based on the theoretical convergence rate for MC ($SD/\sqrt{N}$) and approximate theoretical convergence rate for LHS and LDS (SD/N), where N equals to 2048 and SD is standard deviation.

Generally speaking, samples generated based on LHS and LDS methods always have smaller SEM values than MCS, which suggests that they are more accurate representation of the true mean value. It seems that the distribution type does not influence the comparison results while uncertainty level does lead to obvious difference. When uncertainty of input parameters is small, both LHS and LDS follow the reference line, showing very similar SEM values and convergence rates regardless of the distribution type. When uncertainty of input parameters is large, LDS shows the fastest convergence rate and lowest SEM value, but slightly worse than approximate theoretical performance as indicated by the reference line. As for LHS, it shows a similar convergence rate as MCS, yet with better accuracy.

Figure 8-3 Relationship between standard error of the mean (SEM) and sample size for MCS, LHS and LDS in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty

As for computational efforts, time required for the calculation was derived directly from the log of MATLAB, as shown in Figure 8-4. Similar trends are observed in four scenarios, regardless of distribution type and uncertainty level. Calculation time of LDS increases exponentially with sample size. When the sample size is 2048, LDS took more than twice of the time compared with MCS and LHS. However, LDS show great advantage regarding SEM and convergence rate when input parameters have large uncertainty, which means that it requires smaller sample size to achieve the same SEM. For example, for scenario N_L, while LHS method requires a sample size of 2048 to obtain SEM of 4.88×10^{-4} , LDS method requires only a sample size of 512 (see Figure 8-3c), which lead to the corresponding calculation time of 3.2 and 2.4

seconds for LHS and LDS respectively (see Figure 8-4c). In summary, MCS, LHS and LDS methods perform differently with different uncertainty level of input parameters. When uncertainty is small, LHS is recommended as it can achieve higher accuracy with lower computational effort. When uncertainty is large, LDS seems to be a better choice.

Figure 8-4 Calculation time of MCS, LHS and LDS in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty

8.4.2 Comparison Results of GSA Methods

GSA methods were compared on their performance on explaining the total output variance, as well as the ranking of variance contributions of individual input parameters (i.e., sensitivity index). As the methods in question (i.e., SRC, SRRC,

FAST and Sobol's) are sampling-based ones, sampling process is required. According to discussion in section 8.4.1, LHS was adopted to generate random numbers and to compute output variance with a sampling size of 2048 and 50 repetitions. This was followed by output variance decomposition process using four GSA methods.

Table 8-3 presents the output variance generated and the percentage of total output variance explainable by different methods. Being closer to 100% explainable variance indicates a better performance in variance decomposition. Generally, all the methods performed better in small-uncertainty scenarios compared to the large-uncertainty ones, which can also be observed in Figure 8-5. Different methods performed differently depending on the uncertainty level. When uncertainty of input parameters is small, SRC outperforms the others as over 99.8% of the total variance can be explained in both normal and lognormal cases. When uncertainty is large, SRRC and Sobol's methods show similar results that are relatively better than the others.

Table 8-3 Output variance (unit: ton^2) and variance explainable (shown in brackets) for different GSA methods in four scenarios

GSA methods	N_S	N_L	LOGN_S	LOGN_L
SRC	6.76×10^{-4} (99.85%)	1.29×10^{-2} (90.14%)	6.73×10^{-4} (99.88%)	3.63×10^{-2} (88.02%)
SRRC	6.77×10^{-4} (94.72%)	1.28×10^{-2} (93.61%)	6.74×10^{-4} (95.06%)	3.62×10^{-2} (91.34%)
FAST	6.80×10^{-4} (95.08%)	1.31×10^{-2} (89.17%)	6.76×10^{-4} (94.77%)	3.65×10^{-2} (86.46%)
Sobol_Main	6.77×10^{-4} (97.51%)	1.33×10^{-2} (93.16%)	6.74×10^{-4} (96.30%)	3.67×10^{-2} (91.17%)
Sobol_Total	6.78×10^{-4} (101.67%)	1.32×10^{-2} (104.39%)	6.74×10^{-4} (101.13%)	3.69×10^{-2} (107.94%)

Contribution of input parameters to output variance computed from different GSA methods are compared in Figure 8-5, in which only those with sensitivity index higher than 0.5% are presented. These results indicate that the three most predominant parameters are Q1 (quantity of cement), Q2 (quantity of coarse aggregates) and EF1 (emission factor of cement production). While Q1 is always the top contributor, ranging from 37% to 49%, differences exist in the ranking between Q2 and EF1, as

well as EF2 (emission factor of coarse aggregates production) and D (transportation distance). However, such slight differences were ignored as it may be caused by the randomness during sampling process and it does not affect the conclusion on identifying main uncertainty contributors in this case study. In summary, different GSA methods, though with different capability to explain output variance, do not show much difference in identifying the most significant input parameters.

Figure 8-5 Contribution of each parameter uncertainty to the output variance computed from different GSA methods in four scenarios: (a) normal distribution with small uncertainty, (b) lognormal distribution with small uncertainty, (c) normal distribution with large uncertainty, (d) lognormal distribution with large uncertainty. To sum up, through comparison among three sampling method and four GSA methods, suggestion on method selection can be given in Table 8-4. It was found that distribution type did not influence the performance of methods in question, while uncertainty levels indeed led to different results. In case of input parameters with

small uncertainty, LHS was recommended for uncertainty propagation process and to apply SRCs for the calculation of contribution to output variance. In case of input parameters with large uncertainty, LDS for uncertainty propagation, and SRRC or Sobol's Method for GSA are suggested.

Table 8-4 Suggestion on method selection based on uncertainty levels of input parameters

	Uncertainty Propagation	Global Sensitivity Analysis
input parameters with small uncertainties	Latin Hypercube Sampling (LHS)	Standardized Regression Coefficients (SRCs)
input parameters with large uncertainties	Low-Discrepancy Sampling (LDS)	Standardized Rank Regression Coefficients (SRRC) or Sobol's Method
input parameters with both small & large uncertainties	Latin Hypercube Sampling (LHS)	Sobol's Method

In addition, considering input parameters with small and large uncertainties usually exist simultaneously in reality, the author also tries to provide rough guidance for such case here, although such case has not been tested in this study. LHS is recommended for uncertainty propagation as it has some advantages from the practical point of view such as relatively easy application, acceptable SEM with reasonable computational cost. As for output variance decomposition, Sobol's Method is recommended since it is the second-best choice when input uncertainty is small and one of the best choices when input uncertainty is large. This makes it a safer choice when there is no significant pattern regarding parameter uncertainty levels. Nevertheless, one should exercise precaution and test it out with such case in the future before any conclusion can be made.

8.5 Summary

To address the issue of uncertainty of E-LCA studies, and more specifically the uncertainty induced by input parameters, this chapter provide a comparative assessment on global sensitivity analysis methods in terms of uncertainty propagation

efficiency and output variance accountability, which would lead to a reasonable selection of method in the future study. Focusing on sampling-based GSA methods, the comparison started from comparison among three sampling methods (i.e., MCS, LHS and LDS) regarding convergence rate and computation effort. This was followed by the comparison of four GSA methods (i.e., SRC, SRRC, FAST and Sobol's methods), which evaluated the capability of each method in explaining total output variance as well as the ranking of variance contributions of individual input parameters.

It was found that distribution type did not influence the performance of compared methods, while uncertainty levels did have significant impact. Accordingly, suggestions on method selection were given. In case of input parameters with small uncertainty, LHS is recommended for uncertainty propagation and SRCs for the calculation of contribution to output variance. In case of input parameters with large uncertainty, LDS is suggested for uncertainty propagation, and SRRC or Sobol's Method for GSA.

Chapter 9 Establishment of LCSA Model Based on MCDA

Methods

LCSA model is conceptually a combination of LCCA, E-LCA and S-LCA, and a conceptual framework for LCSA has been established in Chapter 6. However, in order to make proper and rational decisions, especially for the decision-making problems with multiple alternatives that have conflicting results regarding economic, environmental and social performance, a solid and logical backbone should be embedded in this model. As discussed in Section 2.3, MCDA methods can be adopted for this purpose; specifically, fuzzy ELECTRE III method was employed for this model. This chapter firstly discusses the reasons for adopting ELECTRE method in this study and introduces the fuzzy extension of ELECTRE III method. Procedures to conducting sustainability assessment and making sustainability-oriented decisions using LCSA model are then provided, which will facilitate the application of this model in building project evaluation.

9.1 Overview of MCDA Methods

Facing with decision-making problems that involve multiple alternatives and multiple criteria, decision-makers are eager to know how to make trade-offs among different aspects and how to deal with indicators with different forms and units. MCDA methods are developed to address these concerns. Various MCDM methods have been adopted in various decision-making situations, such as AHP (Sambasivan and Fei 2008, Tseng, Lin et al. 2009, Ren, Manzardo et al. 2015, Thanki, Govindan et al. 2016), ELECTRE (Hatami-Marbini and Tavana 2011, Kaya and Kahraman 2011, Wen, Yu et al. 2016), TOPSIS (Kaya and Kahraman 2011, Kluczek and Gladysz 2015, Joshi and Kumar 2016), and PROMETHEE (Athawale and Chakraborty 2010, Ren, Xu et al. 2016, Arikan, Şimşit-Kalender et al. 2017). These methods are either adopted solely or combined together with other MCDM methods to take full advantage of different methods (Kaya and Kahraman 2010, Chauhan and Singh 2016, Sánchez-Lozano, García-Cascales et al. 2016). In sustainability-related studies, utility-based methods and outranking methods are the most widely adopted ones (Pohekar and Ramachandran 2004, Cinelli, Coles et al. 2014).

Multi-attribute utility theory (MAUT) method is a typical utility-based method, which represents decision-makers' preference for each assessment criterion using a utility function. Direct comparison is then conducted when applying utility functions to the performance data of each alternative (Lai, Lundie et al. 2008, Martín-Gamboa, Iribarren et al. 2017). Another type of utility-based method is analytical hierarchy process (AHP), which may be the most popular method among MCDA methods (Sambasivan and Fei 2008, Tseng, Lin et al. 2009, Thanki, Govindan et al. 2016). It adopts pairwise comparison to determine relative importance of the criteria in a hierarchical structure, based on which ranking of alternatives can be derived using simple additive weighting method. While it is very popular due to its ease of use, it is also criticized for possible inconsistencies between judgment and ranking criteria that lead to rank reversal. AHP is more often adopted together with other MCDA methods. In a survey of 150 MCDA case studies, 81 studies used hybrid approaches, in which 58 studies applied AHP or fuzzy AHP together with other MCDA methods (Mahase, Musingwini et al. 2016).

As for outranking methods, binary relations are firstly established within a set of alternatives based on the intra-criterion preferences of decision-makers, which are then synthesized over all the criteria with the consideration of criteria weights. Different from utility-based methods, outranking methods make comparisons between pairs of alternatives to provide evidence on whether ‘an alternative A is at least as good as alternative B’ (Roy 1990), rather than trying to provide a single score for each alternative. This makes outranking methods favourable when some information is insufficient or missing. Two most well-known outranking methods are the elimination and choice expressing reality (ELECTRE) (Hatami-Marbini and Tavana 2011, Kaya and Kahraman 2011, Wen, Yu et al. 2016) and preference ranking organization method for enrichment of evaluation (PROMETHEE) (Athawale and Chakraborty 2010, Arıkan, Şimşit-Kalender et al. 2017). These methods vary in how outranking preference are measured; ELECTRE adopts concordance indices while PROMETHEE adopts preference indices (Mahase, Musingwini et al. 2016).

Compared with other MCDA methods, ELECTRE methods show great advantages in terms of compensation degree (Cinelli, Coles et al. 2014). The application of indifference and preference thresholds limit the compensation and tolerate vagueness or ambiguity. In addition, “very bad” performance in one criterion cannot be offset by good results in other criteria due to the use of veto threshold (Infante, de Mendonça et al. 2013). Such characteristics is quite important for sustainability-oriented decision-making problems, especially for building-specific ones, as a building should firstly meet those requirements related to its basic function, which is to provide structurally-sound and environmentally-controlled spaces to accommodate and shelter occupants and contents, before it can be considered as a sustainable building. From this perspective, using veto threshold seems quite important and should be included in the decision-making process. In addition, ELECTRE method is able to deal with the mix of both quantitative and qualitative information and to consider indicators with different units, which is also a very important consideration when choosing a suitable MCDA method for this LCSA model.

9.2 Fuzzy ELECTRE III

Up till now, many versions of ELECTRE methods have been developed, including four basic versions, ELECTRE I, II, III, IV, and their extended versions. These versions of ELECTRE can be employed to address mainly three types of problems namely choosing, ranking and sorting problems, as illustrated in Figure 9-1.

Figure 9-1 Problem types and their corresponding ELECTRE versions (adapted from (Majdi 2013))

Considering the target application of LCSA model, which is to rank alternatives in terms of sustainability performance, ELECTRE II, III and IV can be adopted. ELECTRE III was selected in this study, as it is based on pseudo-criteria and thus the outranking relations can be expressed using fuzzy relations. Introducing fuzzy relations could be a great advantage when there are subjective opinions involved (Zadeh 1965). ELECTRE III is also recommended in many sustainability-related studies, such as Rogers and Bruen (1998), Shanian et al. (2008) and Infante (2013). Detailed description of fuzzy ELECTRE III is provided as follows.

Let $A = \{A_k | k = 1, 2, \dots, m\}$ be the set of alternatives. The first step is to evaluate the alternatives with respect to each criterion $C_i (i = 1, 2, \dots, n)$. In LCSA model, indicators of criteria can be both quantitative (such as operational temperature and costs) and semi-quantitative (such as managerial performance). As for quantitative indicators, the evaluation result of k th alternative A_k with respect to i th criterion C_i is expressed as x_{ik} . As for semi-quantitative indicators, instead of using crisp number,

fuzzy numbers are adopted in this study, which allow the translation of verbal expressions into numerical ones, thereby dealing quantitatively with imprecision or vagueness within the expressions. Usually, triangular or trapezoidal fuzzy numbers are adopted. Trapezoidal fuzzy numbers can be defined as $\tilde{x}_i^m = (a, b, c, d)$, while triangular fuzzy numbers are given when $b=c$. Evaluation on qualitative indicators usually relies on experts' opinions. Their individual opinions, as introduced in Section 7.2.2, should be converted into fuzzy numbers based on the membership function of linguistic terms (as illustrated in Figure 7-4), and are aggregated into group evaluation results by applying the fuzzy averaging operator, which is defined by:

$$\tilde{x}_{ik} = \frac{1}{M} [\tilde{x}_{ik}^1 (+) \tilde{x}_{ik}^2 (+) \dots (+) \tilde{x}_{ik}^M], \quad (9-1)$$

where M is the number of experts.

Fuzzy evaluation results are then defuzzified using Equation 9-2

$$x'_{ik} = \frac{a+2(b+c)+d}{6} \quad (9-2)$$

Defuzzified values x'_{ik} for qualitative indicators, together with x_{ik} for quantitative indicators form a decision matrix denoted by $X = (x_{ik})_{n \times m}$. Before further ranking process, this decision matrix needs to be normalized using Equation 9-3,

$$r_{ik} = \begin{cases} \frac{x_{ik}}{\sqrt{\sum_{i=1}^n x_{ik}^2}}, & \text{if } x_{ik} \text{ is a benefit index} \\ \frac{1/x_{ik}}{\sqrt{\sum_{i=1}^n (1/x_{ik})^2}}, & \text{if } x_{ik} \text{ is a cost index} \end{cases} \quad (9-3)$$

where r_{ik} represents the normalized evaluation results.

The second step is to obtain the fuzzy outranking relation. The outranking relation of alternative A_k to A_l means that even though these two alternatives do not dominate each other mathematically, the decision maker accepts the risk of believing that A_k is better than A_l . To be specific, A_k outranks A_l means that A_k is at least as good as A_l , i.e., A_k is indifferent from or preferred to A_l . A_k does not outranks A_l indicates that A_l is preferred or incomparable to A_k .

Degree of concordance and discordance is used to derive fuzzy outranking relations, which is proposed by Roy (1977). The degree of concordance, $t_i(k, l)$, which expresses the credibility of proposition “ A_k over A_l ” with respect to C_i , is defined as:

$$t_i(k, l) = \begin{cases} 1, & r_{il} \leq r_{ik} + I_i \\ \frac{r_{il} - (r_{ik} + P_i)}{I_i - P_i}, & r_{ik} + I_i \leq r_{il} \leq r_{ik} + P_i, \\ 0, & r_{il} \geq r_{ik} + P_i \end{cases} \quad (9-4)$$

where I_i refers to the indifferent threshold for the criterion C_i , beneath which the decision maker feels indifferent to two alternative valuations regarding C_i . P_i refers to the preference threshold for the criterion C_i , above which the decision maker show a clear preference of one alternative over the other (Rogers and Bruen 1998).

The degree of concordance, $t_i(k, l)$, which is defined for each single criterion, are then aggregated into a unified concordance relation $T(k, l)$ as:

$$T(k, l) = \sum_{i=1}^n w_i \times t_i(k, l), \quad (9-5)$$

where w_i refer to the weights of criteria assigned by the decision makers, which are obtained through CFPR-based AHP process as explained in Section 4.2.2.

Similarly, the degree of discordance, $d_j(k, l)$, which expresses the credibility of the proposition “ A_k is not at least as good as A_l ” with respect to C_i , is defined as:

$$d_i(k, l) = \begin{cases} 0, & r_{il} \leq r_{ik} + P_i \\ \frac{r_{il} - (r_{ik} + P_i)}{V_i - P_i}, & r_{ik} + P_i \leq r_{il} \leq r_{ik} + V_i, \\ 1, & r_{il} \geq r_{ik} + V_i \end{cases} \quad (9-6)$$

where V_i refers to the veto threshold for the criterion C_i , where a “discordant difference” in favour of one option greater than this value will require the decision maker to negate any possible outranking relationship indicated by other criteria (Rogers and Bruen 1998), in other words, the “very bad” performance in one criterion cannot be offset by good results in other criteria.

Given single criterion discordance relations $d_i(k, l)$, together with concordance relation $T(k, l)$, an aggregated discordance relation $D(k, l)$ is obtained:

$$D(k, l) = \frac{1}{n} \sum_{i=1}^n f(d_i(k, l), T(k, l)), \quad (9-7)$$

where,

$$f(d_i(k, l), T(k, l)) = \begin{cases} 1, & d_i(k, l) < T(k, l) \\ \frac{1-d_i(k, l)}{1-T(k, l)}, & d_i(k, l) > T(k, l), T(k, l) \neq 1 \end{cases} \quad (9-8)$$

The concordance relation, $T(k, l)$, and the discordance relation, $D(k, l)$, are then combined to derive the fuzzy outranking relation $F(k, l)$ as defined by:

$$F(k, l) = T(k, l) \cdot D(k, l), \forall k, l \quad (9-9)$$

The last step is to utilize the fuzzy outranking relation to rank the alternatives. A fuzzy dominance relation is characterized by a membership function $\mu(k, l)$ to indicate the outranking intensity, which is computed as (Kaya and Kahraman 2011):

$$\mu(k, l) = \begin{cases} F(k, l) - F(l, k), & \text{if } F(k, l) > F(l, k) \\ 0, & \text{otherwise} \end{cases} \quad (9-10)$$

For a specific alternative A_k , $\mu(k, l)$ shows its degree of dominating other alternatives, on the contrary, $\mu(l, k)$ show its degrees of being dominated by other alternatives. The maximum degree of being dominated limits A_k 's dominance capability to the others, thus can be used to represent the degree of dominance of A_k , $\varphi(A_k)$, that is,

$$\varphi(A_k) = \max[\mu(l, k)] \quad (9-11)$$

Alternatives can be then ranked based on their $\varphi(A_k)$ values and the evaluation goal of the decision making problem. If the evaluation goal is presented as a benefit index, such as level of sustainability, alternative with lowest $\varphi(A_k)$ value means this alternative has the lowest level of being dominated by the others regarding a benefit index, thus it is the best alternative. For the rest alternatives, lower $\varphi(A_k)$ value means a better performance. On the contrary, as for the cost indexes, such as the risk of violating sustainability requirements, higher $\varphi(A_k)$ value is what decision makers want.

9.3 LCSA Model for Sustainability-Oriented Decision-Making

9.3.1 Procedure to Conducting LCSA

In summary, the proposed LCSA model was established based on a combination of AHP and ELECTRE methods, as demonstrated in Figure 9-2. Based on the establishment of assessment framework (as proposed in Chapter 6) and definition of alternatives, the methodology framework comprises the following parts:

- Evaluation of the performance of each alternative on each criterion, which is basically to conduct LCCA, E-LCA and S-LCA;
- Assignment of weightings among the criteria using CFPR-based AHP process, which was introduced in Chapter 4 as a methodological basis for conducting survey;
- Generation of alternatives' rankings regarding sustainability performance using fuzzy ELECTRE III method presented in this chapter.

Figure 9-2 Methodological frameworks for LCSA model based on MCDA methods

9.3.1 Preparation of Background Data

In this model, the most data-intensive part is the evaluation of alternatives with respect to each criterion. Cost information is usually relatively easy to be obtained. Estimation of initial costs usually starts from the very early stage of a project development and will be repeated throughout the design process. Once the design is completed, detailed costs can be calculated using cost databases, such as RSMeans Construction Cost Database (RSMeans 2012). Operational costs can be estimated based on the predicted energy/water consumption and local energy/water prices. Energy consumption can be obtained from simulation software such as eQuest and EnergyPlusTM. Costs for maintenance, repair and replacement are not always investigated in practice, which can be estimated according to operating schedules, standards of maintenance and repair, assumed service life and historical statistical data.

As for E-LCA part, impact assessment results can be calculated based on E-LCI database of E-LCA, such as Ecoinvent, with the help of E-LCA software tools, such as Simapro and Gabi. However, conducting E-LCA could still be quite complicated for the lay people. Therefore, a set of pre-calculated environmental impacts were prepared for energy, commonly used building materials, construction equipment and trucks, as summarized in Table 9-1. These impacts values were calculated using Ecoinvent database and endpoint characterization factors of ReCiPe method, and were then exported from SimaPro. Through collecting relevant project data, including quantity of building materials, waste rate, energy consumption for on-site work and building operation, construction equipment operation schedule for different parts of work (such as groundwork, structural work, surface and external work) transportation mode and distance, and among many others depending on evaluation goal and scope.

Table 9-1 Background data on endpoint environmental impacts

Items		Description	FU	Human Health DALY	Ecosystems species.yr	Resources \$
Energy	Diesel		1L	2.23E-06	3.59E-09	1.78E+01
	Electricity	Singapore electricity mix *	1 kWh	1.04E-06	6.45E-09	4.47E+00
	Gasoline		1L	1.99E-06	3.21E-09	1.59E+01
Material	Acoustic board	Gypsum fibre board, at plant/CH S	1 kg	6.45E-07	2.58E-09	1.60E+00
	Aluminium	Aluminium, primary, at plant/RER S	1 kg	2.71E-05	1.03E-07	4.88E+01
	Aluminium	Window frame, aluminium, U=1.6 W/m2K, at plant/RER S	1 m2	1.04E-03	4.21E-06	2.25E+03
	Aluminium	Aluminium, secondary, from old scrap, at plant/RER S	1 kg	3.38E-06	1.23E-08	7.52E+00
	Block	Concrete block, at plant/DE S	1 kg	2.12E-07	1.09E-09	2.32E-01
	Brick	Brick, at plant/RER S	1 kg	4.06E-07	2.02E-09	9.09E-01
	Cast Iron	Cast iron, at plant/RER S	1 kg	4.81E-06	1.29E-08	8.37E+00
	Cement	Cement, unspecified, at plant/CH S	1 kg	1.21E-06	6.16E-09	1.04E+00
	Cement	Portland cement, strength class Z 42.5, at plant/CH S	1 kg	1.31E-06	6.65E-09	1.11E+00
	Cement	Portland cement, strength class Z 52.5, at plant/CH S	1 kg	1.33E-06	6.73E-09	1.13E+00
	Copper	Copper, primary, at refinery/GLO S	1 kg	3.34E-04	5.52E-08	1.91E+01
	Door	Door, inner, wood, at plant/RER S	1 m2	8.51E-05	1.73E-06	2.18E+02
	Foam glass	Foam glass, at regional storage/AT S	1 kg	1.42E+00	1.65E-01	1.34E+00
	Galvanized steel	Galvanized steel sheet, at plant/RNA	1 kg	4.52E-06	2.15E-08	1.06E+01
	Glass	Flat glass, coated, at plant/RER S	1 kg	2.36E-06	9.76E-09	5.01E+00
	Glass	Flat glass, uncoated, at plant/RER S	1 kg	2.08E-06	8.61E-09	4.44E+00
	Glass	Glass fibre, at plant/RER S	1 kg	6.60E-06	2.20E-08	1.39E+01
	Glass wool	Glass wool mat, at plant/CH S	1 kg	3.10E-06	1.38E-08	1.08E+01
	Mortar	Lime mortar, at plant/CH S	1 kg	9.64E-07	5.17E-09	9.91E-01

	Paint	Alkyd paint, white, 60% in solvent, at plant/RER S	1 kg	6.33E-06	3.94E-08	2.74E+01
	Plaster	Clay plaster, at plant/CH S	1 kg	3.70E-08	1.75E-10	1.04E-01
	Plaster board	Gypsum plaster board, at plant/CH S	1 kg	7.70E-07	3.43E-09	1.91E+00
	Plywood (indoor)	Plywood, indoor use, at plant/RER S	1 m3	1.38E-03	1.11E-04	3.26E+03
	PVC	Window frame, plastic (PVC), U=1.6 W/m2K	1 m2	5.65E-04	2.29E-06	1.74E+03
	PVC	Polyvinylchloride, at regional storage/RER S	1 kg	3.41E-06	1.60E-08	1.84E+01
	Ready mix concrete	C35	1 m3	4.29E-04	2.18E-06	4.13E+02
	Ready mix concrete	C40	1 m3	4.75E-04	2.40E-06	4.71E+02
	Rebar	Reinforcing steel, at plant/RER S	1 kg	3.96E-06	1.25E-08	7.79E+00
	Resin	Polyester resin, unsaturated, at plant/RER S	1 kg	1.32E-05	6.13E-08	4.10E+01
	Steel	Steel, converter, chromium steel 18/8, at plant/RER S	1 kg	1.37E-05	3.87E-08	2.19E+01
	Steel	Steel, converter, low-alloyed, at plant/RER S	1 kg	5.87E-06	1.77E-08	1.06E+01
	Steel	Steel, converter, unalloyed, at plant/RER S	1 kg	4.21E-06	1.39E-08	8.34E+00
	Stone	Natural stone plate, cut, at regional storage/CH U	1 kg	5.88E-07	1.99E-09	1.25E+00
	Tile	Ceramic tiles, at regional storage/CH S	1 kg	3.87E-06	7.49E-09	4.63E+00
	Water	Tap water, at user/CH S	1 L	4.12E-10	1.99E-12	6.59E-04
	Wood	Fibreboard hard, at plant/RER S	1 m3	1.07E-03	1.12E-05	3.58E+03
	Wood	Plywood, outdoor use, at plant/RER S	1 m3	1.68E-03	1.12E-04	4.13E+03
Plant	Air compressor	-	1h	6.18E-05	1.84E-07	6.59E-02
	Concrete pump	-	1h	2.39E-04	7.10E-07	2.55E-01
	Excavator	Small Excavator	1h	4.08E-05	1.21E-07	4.34E-02
	Excavator	Medium Excavator	1h	8.43E-05	2.50E-07	8.98E-02
	Excavator	Large Excavator	1h	2.41E-04	7.16E-07	2.57E-01
	Forklift	Forklift	1h	5.78E-05	1.71E-07	6.15E-02
	Generator	-	1h	4.27E-06	1.45E-08	6.63E-03
	Hoist	3200kg/36person	1h	8.90E-05	3.83E-07	1.84E+02

	Hoist	5000kg/60person	1h	2.54E-04	1.09E-06	5.25E+02
	Loader	Small wheel loader	1h	7.54E-05	2.24E-07	8.04E-02
	Loader	Midsized wheel loader	1h	1.07E-04	3.19E-07	1.14E-01
	Loader	Large wheel loader	1h	3.18E-04	9.44E-07	3.39E-01
	Mobile Crane	Crane, 25 ton	1h	7.61E-05	2.26E-07	8.11E-02
	Mobile Crane	Crane, 55 ton	1h	2.01E-04	5.97E-07	2.14E-01
	Mobile Crane	Crane, 90 ton	1h	2.26E-04	6.72E-07	2.41E-01
	Rebar bender	-	1h	1.59E-06	6.84E-09	3.28E+00
	Rebar cutter	-	1h	1.59E-06	6.84E-09	3.28E+00
	Tower Crane	Crane, 79.4m/80m/25t	1h	1.75E-04	7.52E-07	3.61E+02
	Tower Crane	Crane, 98m/80m/50t	1h	2.86E-04	1.23E-06	5.91E+02
	Tower Crane	Crane, 104m/85m/80t	1h	2.86E-04	1.23E-06	5.91E+02
	Vibrator	-	1h	3.18E-06	1.37E-08	6.57E+00
Truck	Lorry >32 t	Transport, lorry >32t, EURO5/RER S	tkm	1.98E-07	9.38E-10	6.59E-01
	Lorry 16-32 t	Transport, lorry 16-32t, EURO5/RER S	tkm	3.07E-07	1.47E-09	9.94E-01
	Lorry 3.5-7.5 t	Transport, lorry 3.5-7.5t, EURO5/RER S	tkm	8.81E-07	4.27E-09	2.75E+00
	Lorry 7.5-16 t	Transport, lorry 7.5-16t, EURO5/RER S	tkm	4.08E-07	1.99E-09	1.31E+00
	Passenger car	Transport, passenger car, diesel, EURO5/CH S	persons km	2.84E-07	1.48E-09	8.99E-01
	Passenger car	Transport, passenger car, petrol, EURO5/CH S	persons km	2.94E-07	1.54E-09	9.43E-01
	Truck mixer	Transport, lorry 16-32t, EURO5/RER S	tkm	3.07E-07	1.47E-09	9.94E-01

* Calculated based on Singapore electricity mix proportion in 2017. Natural gas accounted for 95.2% of fuel mix; petroleum products, mainly in the form of diesel and fuel oil, made up 0.8% of the fuel mix; 1.1% was from coal; while other energy products (e.g. municipal waste, coal and biomass) accounted for 2.9% (MEA 2017).

As for S-LCA, two sets of background data associated with the generic analysis were prepared. Country-level social performance scores were collected and normalized to -2 to +2 for all the indicators of generic analysis. Such information was obtained from different sources as indicated in Table 7-1. An example of *working hours* is illustrated in Figure 9-3. In addition, percentages of extraction or production from different countries were collected for raw materials (such as iron ore) or building products (such as cement) that are associated with those commonly used building materials as listed in Table 9-1. Figure 9-4 shows part of the prepared data. Extraction information was mostly extracted from Mineral Commodity Statistics (USGS 2017) and World Mineral Production (Brown, Wright et al. 2014). Product trade statistics information was collected from an online database developed by MIT Media Lab (MIT 2018).

Country	Mining & Quarrying	Manufacturing	Construction	General (others)	Normalized Value			
					Mining & Quarrying	Manufacturing	Construction	General (others)
Albania	43	45	38	39	0.77	0.43	1.54	1.13
Algeria	45	40	41	42	0.46	1.14	1.08	0.75
Argentina	54	43	40	39	-0.92	0.71	1.23	1.13
Armenia	45	46	48	38	0.46	0.29	0.00	1.25
Australia	44	37	38	34	0.62	1.57	1.54	1.75
Austria	39	38	38	36	1.38	1.43	1.54	1.50
Azerbaijan	36	37	37	37	1.85	1.57	1.69	1.38
Bangladesh	49	49	46	45	-0.15	-0.14	0.31	0.38
Belarus	35	34	36	36	2.00	2.00	1.85	1.50
Belgium	38	38	42	37	1.54	1.43	0.92	1.38
Belize	59	47	48	46	-1.69	0.14	0.00	0.25
Bosnia and Herz	41	42	43	41	1.08	0.86	0.77	0.88
Brazil	43	40	39	39	0.77	1.14	1.38	1.13
Brunei Darussal	49	52	52	47	-0.15	-0.57	-0.62	0.13
Bulgaria	40	40	41	40	1.23	1.14	1.08	1.00
Cambodia	-	49	53	45		-0.14	-0.77	0.38
Canada	-	40	40	36		1.14	1.23	1.50
Cayman Islands	42	44	44	42	0.92	0.57	0.62	0.75
Chile	48	41	42	41	0.00	1.00	0.92	0.88
China	46	49	50	47	0.31	-0.14	-0.31	0.13
Colombia	46	43	44	42	0.31	0.71	0.62	0.75
Costa Rica	47	46	49	44	0.15	0.29	-0.15	0.50
Croatia	43	39	40	38	0.77	1.29	1.23	1.25
Cyprus	-	38	35	38		1.43	2.00	1.25
Czech Republic	39	39	42	39	1.38	1.29	0.92	1.13
Denmark	43	37	39	35	0.77	1.57	1.38	1.63
Dominican Repu	44	45	42	42	0.62	0.43	0.92	0.75
Ecuador	46	41	41	39	0.31	1.00	1.08	1.13
Egypt	49	55	50	53	-0.15	-1.00	-0.31	-0.63
El Salvador	40	43	43	42	1.23	0.71	0.77	0.75
Estonia	38	39	40	38	1.54	1.29	1.23	1.25
Ethiopia	36	37	42	33	1.85	1.57	0.92	1.88
Falkland Islands	43	42	46	45	0.77	0.86	0.31	0.38
Finland	40	38	39	36	1.23	1.43	1.38	1.50
France	41	37	38	36	1.08	1.57	1.54	1.50
Gambia	43	61	53	50	0.77	-1.86	-0.77	-0.25
Germany	41	38	39	35	1.08	1.43	1.38	1.63
Ghana	46	44	46	41	0.31	0.57	0.31	0.88
Greece	42	42	36	41	0.92	0.86	1.85	0.88

Fair Wage Working Hrs Health and Safety Discrimination Forced Labor Child Labor Local Employment

Figure 9-3 Screenshot of normalized country-level social performance scores prepared in Excel

Country	Bauxite	Iron Ore	Pig Ore	Clay Bentonite	gypsum	Cement(no limestone)
Algeria					0.9%	
Argentina					0.6%	
Australia	31.3%	37.0%			1.0%	
Brazil	13.2%	18.7%	2.2%	2.5%	1.3%	1.73%
Canada		2.2%	0.7%		0.6%	
Chile		0.6%				
China	24.8%	16.1%	59.6%	22.5%	49.4%	57.38%
Czech Republic				2.3%		
Dominica Replublic	0.5%					
France			1.0%		1.3%	
Germany			2.4%	2.2%	0.7%	
Greece	0.7%			7.4%		
Guinea	7.5%					
Guyana	0.6%					
India	9.5%	7.2%	5.4%	6.8%	1.3%	6.90%
Indonesia	0.8%					1.50%
Iran		1.2%	1.4%	3.7%	6.1%	1.26%
Italy			0.5%		3.3%	
Jamaica	3.2%					
Japan			7.0%		1.8%	1.33%
Kazakhstan	1.8%	1.7%				
Korea			3.9%			1.31%
Mexico		0.8%	0.9%	3.1%	2.1%	
Oman					2.5%	
Pakistan					0.6%	
Russia	2.1%	4.5%	4.5%		1.5%	1.33%
Saudi Arabia	1.5%				0.7%	1.45%
Sierra Leone		0.5%				
South Africa		2.8%	0.5%			
Spain				0.7%	2.7%	
Suriname	0.6%					
Sweden		1.1%				
Taiwan			1.2%			
Thailand					4.6%	
Turkey			1.3%	7.4%	4.9%	1.83%
UK			0.8%	3.0%	0.5%	
Ukraine		2.6%	2.1%	1.3%		
USA		1.9%	2.0%	23.5%	5.9%	2.05%
Venezuela	0.9%					
Vietnam	0.6%					1.67%
Others	0.5%	1.3%	2.7%	13.6%	5.9%	20.3%

Figure 9-4 Screenshot of percentages of extraction or production from different countries

9.4 Summary

This chapter firstly gives an overview of popular MCDA methods sustainability-related studies and provides reasons for selecting ELECTRE III method. A detailed description of fuzzy ELECTRE III method is given, which mainly includes the generation of fuzzy outranking relations and characterization of fuzzy dominance

relations. Finally, an integrated LCSA model for sustainability-oriented decision-making was summarized, which was established based on a combination of AHP and ELECTRE methods. In this model, weighting among the criteria is generated using CFPR-based AHP, evaluation processes are conducted by LCCA, E-LCA and S-LCA, alternatives' rankings are calculated using fuzzy ELECTRE III method. To facilitate the application of this model in practice, some background data were prepared for E-LCA and S-LCA, which are endpoint environmental impacts, normalized country-level social performance scores, and extraction or exporting proportion of different countries.

Chapter 10 Application and Validation of LCSA Model

The aim of this chapter is to demonstrate the applicability and validity of the proposed model in dealing with sustainability-oriented decision-making problems. Case study is seen as a better approach to validating the model compared with surveys or experimental strategies considering the complex nature of the research (Gillham 2000). Case study can also be used to illustrate how this model works to rank different alternatives. This chapter first introduces the background information of the selected case study and presents the data collection results. Procedure to conduct S-LCA is presented in detail, followed by the ranking process using fuzzy ELECTRE III method.

10.1 Background Information and Data Collection

This case study aims to investigate the sustainability performance of adopting prefabricated prefinished volumetric construction (PPVC) method in building construction, and to compare its sustainability performance with two other commonly adopted construction techniques. PPVC is promoted by Singapore government recently as a way of driving up productivity in the construction industry that is traditionally manpower-intensive. It refers to a modular construction method whereby free-standing volumetric modules (complete with finishes for walls, floors and ceilings) are manufactured and assembled in an accredited fabrication facility and then installed on site.

In this case study, PPVC method is applied to a student residential hall project located in Singapore with a total gross floor area of 48,550 m². PPVC module in this project is principally a steel-type module and is adopted for the typical units of the building with its modular design and standardized dimensions, accounting for around 42% of the total gross floor area. There are 676 modules installed to provide 1233 single occupancy rooms and 294 double occupancy rooms. Typical modular designs are presented in Figure 10-1. Two rooms are usually combined in one PPVC module, as in Types 1, 2 and 5.

Figure 10-1 Typical PPVC modular designs

In addition to the typical PPVC levels, the rest parts shown in Figure 10-2 adopted conventional cast-in-situ construction method, which include podium levels (to handle sloping terrain at site), transfer slab between conventional construction and PPVC modules, as well as core areas for lateral stability of the steel structure building.

Figure 10-2 Elevation view of PPVC project

Material quantity data were collected separately for PPVC parts and conventional construction parts. For conventional construction parts, bill of quantity documents was used to calculate the material quantity. Material usage for PPVC modules were calculated based on drawings of different PPVC module types. A typical module is comprised of structural parts and architectural parts. Structural skeleton is made up of beams (for roof, floor and walls), columns, bracings and plates (roof, floor and walls); beams and columns adopt hot-finished structural hollow sections and other steel members adopt hot-dipped galvanized steel. Architectural parts include roof, floor and wall boards with Rockwool infill and floor tiles. Roof, floor and wall boards adopt Promat boards, which are lightweight, non-combustible, fire resisting calcium silicate boards installed in PPVC modules mainly for fireproofing purpose of steel structure. Figure 10-3 shows the weight decomposition of a typical PPVC module, indicating that boards, beams, plates and columns contribute the most to the total weight. Based on the calculation results, the self-weight of PPVC modules ranges from 6 ton to 17 ton and the average weight is around 12 ton. Steel is the mostly

consumed material, which weighs around 3470 ton in total for 676 modules, followed by 2,420 ton of Promat boards.

Figure 10-3 Weight decomposition of a typical PPVC module

During construction process, this project only consumes diesel, and electricity is generated on-site using generators. Equipment that use diesel include generators, excavators, crawler cranes, forklifts, air compressors, cutting and bending machines. Electricity from generators was used mainly for the operation of tower cranes and other on-site electricity needs. Records on monthly diesel usage were provided by the contractors, as summarized in Figure 10-4. As for the energy use in the modular factories, it is estimated based on utility bills provided by the company. Electricity consumption for manufacturing PPVC modules were estimated based on average monthly energy expenditure, electricity tariffs and monthly yield, which was around 11 kWh per m². Accordingly, the off-site electricity consumption in this project was estimated to be 226,600 kWh.

Figure 10-4 Monthly diesel consumption during construction phase of PPVC project

PPVC project was compared with a semi-prefabricated reinforced concrete structure building project (hereafter referred to as Semi-Prefab project) and a conventional reinforced concrete structure building project in which concrete are all cast-in-situ (hereafter referred to as Conventional project). Information on Semi-Prefab and Conventional projects was derived from a previous study (Mao, Shen et al. 2013), in which these two residential buildings employing semi-prefabrication and conventional construction methods were compared regarding their environmental performance. As for Semi-Prefab project, 11% of the total concrete volumes were prefabricated components, including precast facades, precast staircases and precast corridor slab. To facilitate the further comparison, a consistent calculation basis was established. Sizes of Semi-Prefab and Conventional projects were adjusted to 48,550 m² from 216,000 m² as in the original study (Mao, Shen et al. 2013), and material and energy usages were adjusted accordingly. In this case study, only structure-related and main-difference parts (i.e., Promat boards for fireproofing) were considered while common parts such as windows and paintings were excluded from further analysis.

As for operational energy consumption, monthly electricity consumption records for 6 months were collected from housing services department of NTU. Since operational energy consumption information for Semi-Prefab and Conventional projects was not provided in (Mao, Shen et al. 2013), the author used the records of a student hall at

NTU that adopts semi-prefabricated reinforced concrete structure to represent the electricity consumption of Semi-Prefab project. Considering both Semi-Prefab and Conventional projects adopt reinforced concrete structure, it was assumed that these two projects have similar performance on operational energy consumption. Figure10-5 shows the monthly electricity consumption per tenant. For PPVC and Semi-Prefab projects, their average electricity consumptions were calculated as 166.87 kWh/month · tenant and 163.38 kWh/month · tenant respectively. It was assumed that the three projects accommodate same amount of people and are fully rented with 1821 tenants living in. Accordingly, the annual operational energy consumption and annual operational costs can be calculated. Data collection results are listed in Table 10-1.

Figure 10-5 Six-month record on monthly electricity consumption per tenant for PPVC and Semi-prefabrication projects

Table 10-1 Data collection results for PPVC, Semi-Prefabrication and Conventional projects

	PPVC Project		Semi-Prefab Project		Conventional Project
Basic Information					
Structural Frame	Steel Structure		Concrete Structure		Concrete Structure
Construction Method	42% of total gross floor area being PPVC modules + Conventional cast-in-situ concrete		10% of the total concrete volume being prefabricated concrete components + Conventional cast-in-situ concrete		100% case-in-site
Building Materials (ton)					
	Off-Site	On-Site	Off-Site	On-Site	On-Site
Concrete	-	37,135	6,289	53,749	57,677
Brick	-	2,089	-	11,844	13,941
Mortar	-	362	-	2,937	3,309
Steel reinforcing bars	-	1,986	409	2,558	2,867
Steel structural members	3,470	-	-	-	-
Promat boards (fireproofing)	2,420	-	-	-	-
Energy Usage during Construction					
	Off-Site	On-Site	Off-Site	On-Site	On-Site
Diesel (L)	-	350,185	2,620	49,367	52,704
Electricity (kWh)	226,600	-	24,043	480,851	555,383
Annual Electricity Consumption (MWh)					
Electricity	3,646		3,570		3,570
Cost (Million Singapore Dollar)					
Initial Cost	138		116		119
Annual Cost	0.8634		0.8443		0.8443

10.2 Comparison of Social Sustainability Performance of PPVC and Semi-Prefabrication Projects

This section presents a comparative study on social sustainability performance of PPVC and Semi-Prefab Projects using the S-LCIA method proposed in Chapter 7. In the following subsection, results on generic analysis and site-specific analysis will be presented, followed by the integrated social sustainability performance results.

10.2.1 Generic Analysis

Generic analysis was conducted on raw material extraction as well as manufacturing and fabrication phase. Activity contributions of countries involved in these two phases are shown in Figure 10-6 and Table 10-2; they were obtained based on material quantity information and material extraction or import statistical data. It is found that most of the activities were carried out in China, Malaysia and Indonesia for both designs in raw material extraction, which was mainly due to their provisions of crude steel, crushed stone and sand. For manufacturing and fabrication phase, since PPVC modules were produced in China, while prefabricated concrete components were fabricated in Singapore, main activity contributors of two designs are different.

Figure 10-6 Activity contribution of countries involved in raw material extraction, manufacturing and fabrication processes

Table 10-2 Activity contribution of countries involved in raw material extraction, manufacturing and fabrication processes

Country	Raw Material Extraction		Manufacturing and Fabrication	
	PPVC	Semi-Prefab.	PPVC	Semi-Prefab.
Australia	4.01%	1.63%		
Brazil	2.41%	1.19%		
Cambodia	3.49%	3.83%		
Canada	0.37%	0.20%		
China	33.49%	29.84%	39.54%	12.38%
France	0.34%	0.23%		
Germany	0.74%	0.47%		
India	4.95%	7.79%		
Indonesia	11.68%	13.25%		
Iran	0.37%	0.24%		
Italy	0.28%	0.22%		
Japan	0.58%	0.45%	19.87%	19.43%
Korea, Republic of	0.40%	0.31%		
Malaysia	24.15%	27.17%	3.50%	3.42%
Poland	0.28%	0.17%		
Russia	1.68%	0.99%		
Singapore	-	-	37.09%	64.77%
South Africa	0.58%	0.23%		
Turkey	2.16%	4.56%		
Ukraine	0.50%	0.28%		
USA	2.55%	1.49%		
Vietnam	4.99%	5.46%		

Social performance scores were then obtained using information on activity contribution of countries and country-level social performance score for different impact subcategories. As illustrated in Figure 10-7 and Table 10-3, for raw material extraction phase, PPVC project performs better in most indicators, but the differences are not significant for most indicators. For manufacturing and fabrication phase, Semi-Prefab project performed much better due to the higher activity contribution of

Singapore, which performed much better in most of the indicators except for *local employment*.

(a) Raw Material Extraction Phase

(b) Manufacturing & Fabrication Phase

Figure 10-7 Comparison of social performance score of PPVC and Semi-Prefabrication buildings in raw material extraction, and manufacturing and fabrication phases

Table 10-3 Social performance score of PPVC and semi-prefabrication building in raw material extraction, and manufacturing and fabrication phase

	Raw Material Extraction		Manufacturing & Fabrication	
	PPVC	Semi-Pref.	PPVC	Semi-Pref.
Health and safety of workers	0.793	0.715	1.298	1.313
Fair Salary	0.064	0.010	0.157	0.284
Working Hours	0.233	0.154	0.306	0.459
Discrimination	0.622	0.503	1.503	1.646
Forced Labor	1.654	1.601	1.815	1.836
Child Labor	1.256	1.110	2.000	2.000
Living Condition	0.528	0.514	1.012	1.494
Local Employment	0.957	0.969	1.234	1.200
Integration & Interaction	0.180	0.182	1.049	1.519
Accessibility	1.004	0.979	1.569	1.847

10.2.2 Site-Specific Analysis

Site-specific analysis was conducted to investigate social performance in construction and use phase. As discussed in Section 7.2.2, site-specific analysis involves the analysis on direct social performance regarding each impact subcategories, as well as the analysis on organizational efforts in design consideration or management practices to address certain social issues. In this case study, interview with designers and project managers was conducted to investigate their design consideration. As for managerial practices, information was collected through people from project management team, including assistant project director, project managers (from both developer and contractor), safety supervisors, site engineer, lifting supervisors, construction manager, and WSH officers. Sources for information on direct social performance includes project records or design parameters for quantitative indicators, as well as on-site observation and interviewed with relevant stakeholders, such as neighbourhood, pedestrians/bicyclists passing by and students living in, for semi-quantitative indicators. Collected data were calculated and normalized, and further integrated via averaging of two aspects (managerial practices/design consideration and direct social performance). The results are presented in Table 10-4.

Table 10-4 social performance score of PPVC and semi-prefabricated building in construction and use phases

Impact Category		Managerial practices/ design consideration		Direct social performance		Integrated score	
		PPVC	Semi-Prefab	PPVC	Semi-Prefab	PPVC	Semi-Prefab
Worker (Construction)	Worker's Health and Safety	0.988	0.819	2.000	-0.125	1.409	0.354
	Fair Salary	0.438	0.438	0.600	0.600	0.519	0.519
	Working Hours	0.438	0.438	0.920	0.920	0.679	0.679
	Discrimination	0.188	0.188	2.000	2.000	1.094	1.094
	Forced Labour *	-	0.000	2.000	2.000	1.000	1.000
	Child Labour *	-	0.000	2.000	2.000	1.000	1.000
Local Community (construction)	Living Condition	0.617	0.617	1.550	1.480	1.084	1.049
	Local Employment	0.063	0.063	0.200	0.260	0.132	0.162
	Integration and Interaction	0.376	0.156	0.970	0.970	0.673	0.563
	Accessibility	0.563	0.563	1.188	1.200	0.876	0.882

Table 10-4 (Continued)

Local Community (Use)	Living Condition		0.136		0.136	0.321	0.321	0.229	0.229
	Local Employment		0.189		0.189	1.640	1.640	0.915	0.915
	Integration and Interaction		0.166		0.166	0.127	0.127	0.147	0.147
	Accessibility		0.731		0.731	1.570	1.570	1.151	1.151
Occupant (Use)	Functionality and Usability		1.196		1.196	1.730	1.730	1.463	1.463
	Health and Comfort		1.196		1.196	0.760	1.032	0.978	1.114
	Accessibility		0.942		0.942	1.680	1.680	1.311	1.311
	Feedback Mechanism		1.233		1.233	1.780	1.780	1.507	1.507
Society	Technology development		0.700		0.375	1.500	0.500	1.100	0.438
	Public commitments to sustainability issues		0.031		0.031	0.500	0.500	0.266	0.266

* For *forced labour* and *child labour*, no information regarding managerial practices were available and actual performance is assumed to be identical to country-level performance, i.e., Singapore average performance

In Table 10-4, for managerial practices/design consideration, four aspects of PDCA cycle are shown in a column chart, and the average of the four aspects was calculated. Specifically, PPVC project performs better in *worker's health and safety* since it involves less people working at height for construction; it also performs better in *integration and interaction*, and *technology development*, since project teams organized regular meeting open to the public and shared their experience regarding modular construction, which created chances to communicate with and get feedback from local community, and thus performed proactively regarding technology development. Otherwise, two projects gain the same score for most other impact categories due to involvement of the same contractor and developer.

For direct social performance, PPVC project performed better in *worker's health and safety* since there was no injury recorded and in *local community's living conditions* as the construction period was quiet and with less construction noise. Performance of PPVC in *Integration and integration* and *technology development* are also better due to regular sharing sessions as previously mentioned. Semi-Prefab project performed better in local employment because of larger share of purchasing from local supplier; yet, it is worth mentioning that local workforce percentage of PPVC project is higher than that of semi-prefabrication project, which are 20% and 17% respectively. *Accessibility of local community* during construction period of PPVC project also gained less score due to some complaints that there were always trucks that carried a PPVC module waiting outside the construction site, and thus negatively influenced the mobility of pedestrians and drivers. Furthermore, PPVC projects, being a steel-structure building, performed worse regarding thermal and acoustic comfort. Almost all the occupants interviewed complained about sound-proof issue.

10.2.3 Integrated Social Sustainability Performance

Based on the performance scores and weighting sets as provided in Section 7.4, single social performance scores were calculated as 0.926 and 0.821 for PPVC and Semi-Prefab project, respectively. This indicates an overall better social performance of PPVC project from life-cycle perspective. Detailed comparison results were summarized in Figs.10-12 and 10-13.

As indicated in Figure 10-8, PPVC performs significantly better in *worker's health and safety* and *technology development* due to the shortened working time at height and active actions in adopting new construction technology and technology sharing. Significant advantage in these two aspects also explained the better performance regarding stakeholder *worker* and *society* of PPVC project, as illustrated in Figure 10-9. PPVC, when adopting a steel-structure skeleton, does not perform as well as semi-prefabricated concrete-structure building in *occupant's health and comfort* due to relatively poor thermal and sound comfort. As for *local employment*, PPVC does not show much advantage from life-cycle perspective although resident workforce percentage of PPVC project is slightly increased, as PPVC modules are manufactured in China and thus lower the share of purchasing from local suppliers.

Figure 10-8 Scores of social impact subcategories for PPVC and semi-prefabrication projects

Figure 10-9 Scores of stakeholder categories for PPVC and semi-prefabrication projects

10.2.4 Sensitivity Analysis

Sensitivity analysis can help with interpretation of results in the case study. One of the main uncertainty sources in this study is the weighting sets, especially weights among different phases, as provided in Table 4. This analysis adopted another set of phase weights in a previous building-related study (Hosseinijou, Mansour et al. 2014), in which weights were obtained from experts' opinions through AHP process. The new phase weight set was extracted as 0.26, 0.26, 0.24, 0.24 for the four phases. Compared with original weights set, it weighs life-cycle phases almost equally and puts slightly more emphasis on the raw material extraction and manufacturing phases.

Change on phase weights influenced the comparison results of stakeholder *worker* and *local community*. As illustrated in Table 10-5, advantage of the PPVC project become much less when compared with the semi-prefabrication project in worker category, and the performance of the PPVC project in local community category become much worse. This is because that the semi-prefabrication project performed

better in manufacturing phase (as shown in Table 10-3), *while* the PPVC project showed more advantage in the construction phase (as shown in Table 10-4). However, as for overall performance, the PPVC project still gained a higher score of 0.944 than that of the semi-prefabrication project, 0.868.

Table 10-5 Relative change of the score of PPVC project to semi-prefabrication project

Stakeholder Category	Impact Subcategory	Relative Change in impact subcategories*		Relative Change in Stakeholder categories*	
		Original weights	New weights	Original weights	New weights
Worker	Health and safety	83.7%	44.7%		
	Fair Salary	-2.9%	-9.4%		
	Working Hours	-1.5%	-5.9%	19.9%	11.1%
	Discrimination	0.7%	-0.7%		
	Forced Labour	0.9%	0.7%		
	Child Labour	3.5%	3.6%		
Local Community	Living Condition	-4.4%	-13.7%		
	Local Employment	-1.6%	-0.2%	-2.7%	-7.9%
	Integration and Interaction	-0.7%	-15.7%		
	Accessibility	-2.4%	-5.5%		

*The value was calculated by (the score of PPVC project– the score of semi-prefabrication project)/the score of semi-prefabrication project

10.3 Ranking Three Building Projects in Terms of Life Cycle Sustainability Performance

This section aims to rank three building projects (as summarized in Table 10-1) in terms of life cycle sustainability performance using the LCSA Model proposed in Chapter 9. Evaluation matrix is firstly constructed, and ranking results can be obtained through fuzzy ELECTRE III process.

10.3.1 Evaluation Matrix and Ranking Results

Evaluation results of economic and environmental aspects were calculated based on data in Table 10-1. Economic optimization was reflected by life cycle costs. Operational costs were reduced to their present value using a discount rate of 5.37%, which was estimated based on an average statistic data of prime lending rates for the past ten years (Trading Economics 2016). As for E-LCA, inventory datasets were extracted from Ecoinvent database, and the calculation followed the general E-LCA process using characterization factors of ReCiPe method. Calculation of social impact evaluation results have been explained in the last section. Scores for stakeholder categories were used, instead of the integrated single scores; that is because it has been questioned by some experts during the survey process that whether it is fair to weigh among different stakeholders, and the author would like to investigate this concern during the sensitivity analysis part. Bolded values in Table 10-6 form the evaluation matrix and were used for further calculation.

Table 10-6 LCCA, E-LCA, and S-LCA results of three alternatives

Impact Categories		PPVC	Semi-Prefab	Conventional
Worker's wellbeing (C1)		0.85	0.71	0.64
Occupants' wellbeing (C2)		1.29	1.33	1.33
Local community's wellbeing (C3)		0.71	0.73	0.74
Development of industry/society (C4)		0.78	0.37	0.24
Economic	Initial cost	138	116	119
Optimization	Operational cost (NPV)	14.90	14.57	14.57
(C5)	Sum (million SGD)	152.90	130.57	133.57
Human Health (C6)	Production	38.91	35.83	35.72
	Construction	3.33	1.4	1.58
	Operation	190.25	186.29	186.29
	Sum (DALY)	232.49	223.52	223.59
Ecosystem	Production	0.14	0.15	0.15
Diversity (C7)	Construction	0.01	0.01	0.01
	Operation	1.17	1.15	1.15
	Sum (species year)	1.32	1.31	1.31
Resource Availability (C8)	Production	68.59	60.12	59.95
	Construction	6.22	2.51	2.82
	Operation	814.18	797.22	797.22
	Sum (million \$)	888.99	859.85	859.99

Based on the evaluation matrix, ranking process was conducted using fuzzy ELECTRE III procedure, from which the degree of dominance (φ) of each alternative can be obtained, being 0.348 for PPVC project, 0.313 for Semi-Prefab project, and 0.443 for Conventional project. As explained previously, φ value refers to the maximum degree of being dominated by other alternatives, and alternative with lowest φ value is preferred since the evaluation goal is expressed as a benefit index, that is, sustainability level. Therefore, Semi-Prefab project is the best option regarding sustainability level achieved, PPVC project is ranked in the second place, while conventional project is the worst.

10.3.2 Sensitivity Analysis

One-at-a-time sensitivity analysis was conducted to investigate how weights variation affects the robustness of final rankings. Eight sets of weights examined are described as follows.

- S1-S4: Original weight set $(w_1, w_2, \dots, w_n)$ was replaced by $(w_1, w_2, \dots, w_n)^\alpha$, where $\alpha \geq 0$. This operator does not reverse the order of criteria preference, yet it changes the differences among weights. Specifically, $\alpha \rightarrow 0$ leads to the increasing equalization of weights, whereas $\alpha \rightarrow \infty$ increases the differences among weights. In this part, four α values, 0, 0.5, 1.5, 2, were applied to S1 to S4 respectively, and results were normalized between zero and one.
- S5-S7: three sustainability dimensions were assumed to be equally important, which could be questionable sometimes. S5 to S7 address this issue by investigating scenarios when one aspect is dominant while remaining two are equally weighted. Specifically, 0.6, 0.2, 0.2 were assigned to level I criteria depending on which aspect is the dominant, while weights for level II criteria kept the same. Social acceptability, economic optimization, and environmental protection were the dominants for S5 to S7 respectively.
- S8: stakeholder categories were pairwise compared during questionnaire survey, yet some experts thought it might have ethical issue to compare among different stakeholders. To address this concern, equal weights were assigned to four

stakeholders and weights for level I criteria and level II criteria of environmental aspects remained the same.

Alternative rankings for each weight sets are presented in Table 10-7. Semi-Prefab project is the best alternative except for S5, when social aspect is dominated. It is also observed that ranking orders of PPVC and Conventional projects were changed when the weight for economic optimization increased compared to the base case, as revealed in Cases S3, S4 and S6.

Table 10-7 Sensitivity analysis results due to weight change

	Criteria Weights								Alternative Rankings		
	C1	C2	C3	C4	C5	C6	C7	C8	PPVC	Semi-Prefab	Conventional
Base Case	0.129	0.113	0.065	0.026	0.333	0.133	0.133	0.067	2	1	3
S1	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	2	1	3
S2	0.134	0.126	0.095	0.060	0.216	0.136	0.136	0.097	2	1	3
S3	0.113	0.092	0.040	0.010	0.467	0.118	0.118	0.042	3	1	2
S4	0.090	0.069	0.023	0.004	0.599	0.096	0.096	0.024	3	1	2
S5	0.233	0.203	0.116	0.047	0.200	0.080	0.080	0.040	1	2	3
S6	0.078	0.068	0.039	0.016	0.600	0.080	0.080	0.040	3	1	2
S7	0.078	0.068	0.039	0.016	0.200	0.240	0.240	0.120	2	1	3
S8	0.083	0.083	0.083	0.083	0.333	0.133	0.133	0.067	2	1	3

10.3.3 Discussion

This case study shows how the proposed LCSA model can be used to facilitate sometimes difficult decision-making regarding sustainability when multiple criteria and alternatives are presented. Results show that semi-prefabricated design is the best option regarding sustainability level achieved, PPVC-based design is ranked in the second place, while conventional design is the worst.

It is worth mentioning that although the technique has been strongly promoted locally in Singapore, PPVC did not gain the highest rank as expected in this study. The main reason is that costs for producing PPVC modules are relatively high since its market is still immature. This aspect is also indicated through ranking results of Cases S3,

S4, and S6 in sensitive analysis where economic consideration is significantly more important than other criteria. Another reason is related to the environmental performance. Steel-based PPVC module is much heavier compared to prefabricated concrete components. As a result, tower crane with higher power is needed, which increases the costs and energy consumption during construction process.

Nevertheless, the most significant advantage of PPVC-base design lies in the social performance as indicated by Case S5. As much of the works are finished in the manufacturing plants, on-site work and manpower is reduced, and thus building quality can be better controlled, construction safety is improved and disturbance to surrounding residents is minimized. These make this technique very promising and authors believe that cost issues will be addressed by scale-up of the market and advancement of the techniques through, for example, manufacturing modules in parallel and engaging in bulk material ordering in manufacturing factories (Quale, Eckelman et al. 2012). Furthermore, better quality control in modularized manufacturing may lead to long-term savings in O&M phase due to higher quality and durability of the building as well as longer service life. These aspects were not considered in this study due to lack of data at this stage.

10.4 Summary

This chapter demonstrates the applicability and validity of the proposed model in dealing with sustainability-oriented decision-making problems. A case study is presented, which investigates the sustainability performance of a PPVC project, and compares its sustainability performance with semi-prefabrication and conventional projects. Social sustainability assessment is presented in detail to demonstrate the use of the proposed S-LCIA method. Results indicate an overall better social performance of PPVC project from life-cycle perspective. Specifically, PPVC performs significantly better in *worker's health and safety* and *technology development*. PPVC does not perform as well as semi-prefabricated concrete-structure building in *occupant's health and comfort* due to relatively poor thermal and sound comfort. As for *local employment*, PPVC does not show much advantage from life-cycle perspective, as PPVC modules are manufactured in China and thus lower the share of purchasing from local suppliers. The proposed LCSA model is demonstrated

through ranking three projects in terms of overall sustainability performance. Results show that semi-prefabrication project is the best option regarding sustainability level achieved, while PPVC project is ranked the second place.

Chapter 11 Conclusions and Recommendations

This chapter presents the summary, conclusions and recommendations of this study. Limitations of this research and suggestions for future research are also presented in this chapter.

11.1 Achievements and Contributions

The construction industry is of great economic significance and influences human being's well-being and the environment in both positive and negative manners. To achieve sustainable development in the construction industry, decision-making should be based on the awareness of key issues and understanding of impacts of individual actions, which highlights the necessity of evaluation and monitoring of the sustainability performance on various aspects. Accordingly, development of building-specific sustainability assessment methods is crucial to attain the goals of sustainable construction.

Recognizing the necessity of providing quantitative information on both short- and long-term performance of building systems to facilitate sustainability-oriented decision-making, a comprehensive model for building sustainability assessment that encompasses three dimensions of sustainability was developed, which is considered as the major contribution of this study. This model can facilitate sustainability-oriented decision-making, which will place a positive influence on the movement towards sustainable construction. Through completing several research objectives and tasks, the entire study contributes to both the knowledge base and the practical application. The major findings associated with individual objectives are summarized as follows.

- Objective 1: To obtain an in-depth understanding of existing building-specific assessment methods or tools

This research objective was achieved through a comprehensive literature review in Chapters 2 and 3, and a preliminary study as presented in Chapter 4. In Chapter 2, a definition of sustainable construction was proposed based on the review on the interpretations of sustainability and sustainable construction. Two types of existing building-specific assessment methods or tools were reviewed: green building rating systems (GBRSs) and quantitative assessment methods. A detailed comparison among three GBRSs, namely, Singapore Green Mark, LEED and BREEAM, was conducted, which gives an insight to the current sustainable construction practices in Singapore. A detailed review on life-cycle based methods was presented in Chapter 3, which highlights the methodological issues in S-LCA and E-LCA. A case study

with E-LCA and LCCA assessments on CC and VAV systems in Chapter 5 leads to a more in-depth understanding of these two methods.

- Objective 2: To establish a set of assessment criteria and corresponding indicators for measuring building performances in terms of three dimensions of sustainability

This research objective was achieved through extracting impact categories from LCCA, E-LCA and S-LCA methods, as presented in Chapter 6. Economic aspect is evaluated through LCCA, whose results are reported by NPV. Environmental impacts are calculated through E-LCIA process in E-LCA studies, and thus impact categories were extracted from a selected E-LCIA method, which is ReCiPe endpoint approach in this study. Accordingly, three environmental (endpoint) impact categories were included in the conceptual framework, which are protection of human health, protection of ecosystem diversity and protection of resource availability. As for social impact assessment, impact categories were selected using stakeholder-based approach according to *the Guidelines*. Four groups of stakeholders were firstly identified, which are worker, occupant, local community and society. This was followed by identification of impact subcategories through content analysis of *the Guidelines* and fifteen previous studies that proposed social criteria. This part of works is a very first attempt to construct and classify building-specific social sustainability assessment criteria from the stakeholder perspective, which leads to a more comprehensive coverage of social concerns.

- Objective 3: To propose a social impact assessment approach for quantitative evaluation of life-cycle social impacts of buildings

This part of work is presented in Chapter 7. The proposed S-LCIA method applies multi-stakeholder approach and includes several life-cycle phases in the analysis which enables the investigation on potential transfer of impacts between life-cycle phases. Specifically, three groups of indicators are involved, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis. Each type of indicators adopts different scoring methods.

For generic analysis, SPS was obtained by integrating country activity contribution and normalized country-level performance scores, which were calculated from different sources of statistics. For site-specific analysis, SPS was the average of scores for organizational managerial practices and direct social performance. Organizational managerial practices adopted semi-quantitative indicators and their scores were obtained based on performance reference scales (PRS). The PRS scales were constructed based on PDCA Cycle theory, aided by fuzzy theory for the conversion of qualitative evaluation results. As for direct social performance, scores for semi-quantitative indicators were also obtained using PRSs and fuzzy numbers. Scores for quantitative indicators were calculated using actual performance data and performance reference values (PRVs), which can be country and/or sector average performance values. In addition, weights among life-cycle phases were determined considering the degree of possibility to place control as well as level of concern of construction practitioners. The proposed method was applied to an illustrative case study comparing social performance of CC and VAV systems, and a comprehensive case study in Chapter 10 on a large-scale building project adopting different construction methods.

- Objective 4: To provide suggestions on method selection for characterizing parameter uncertainties in E-LCA

This research objective was achieved based on a comparative assessment on global sensitivity analysis methods in terms of uncertainty propagation efficiency and output variance accountability, as reported in Chapter 8. Focusing on sampling-based GSA methods, the comparison started from comparison among three sampling methods (i.e., MCS, LHS and LDS) regarding convergence rate and computation effort. This was followed by the comparison of four GSA methods (i.e., SRC, SRRC, FAST and Sobol's methods), which evaluated the capability of each method in explaining total output variance as well as the ranking of variance contribution of each parameter.

It was found that distribution type did not influence the performance of compared methods, while uncertainty levels did have significant impact. Accordingly, suggestions on method selection were given. In case of input parameters with small uncertainty, LHS is recommended for uncertainty propagation and SRCs for the

calculation of contribution to output variance. In case of input parameters with large uncertainty, LDS is suggested for uncertainty propagation, and SRRC or Sobol's Method for GSA. Accordingly, methods for characterizing parameter uncertainties can be selected in a more reasonable manner in future E-LCA studies, which will help decision makers understand the quality of E-LCA models more accurately and efficiently.

- Objective 5: To develop an integrated LCSA model for sustainability-oriented decision-making

This part of work is reported in Chapter 9, in which a detailed description of fuzzy ELECTRE III method is given and an integrated LCSA model is summarized. A procedure to conducting LCSA for building projects is also presented with background data prepared. This LCSA model can be applied to dealing with sustainability-oriented decision-making problems, and its applicability and validity were tested through a case study in Chapter 10. This case study investigated sustainability performance of a PPVC project and compared with semi-prefabrication and conventional cast-in-place projects. Results showed that semi-prefabrication project is the best option regarding sustainability level achieved and PPVC project is ranked the second place.

11.2 Recommendations on Future Work

The outcomes of this study are significant in several aspects, yet there are still limitations associated with this study. Firstly, this study proposed an extensive methodology for social sustainability assessment of building projects. However, indicator selected to characterize impact categories need continuous improvement through investigation of cause-effect relationships. Furthermore, data availability for social assessment also restricts the selection of indicators, which highlights the need to establish relevant database. Accordingly, the scope of analysis could be broadened to include maintenance and end-of-life phases, which were excluded in this study due to data unavailability.

Secondly, this study conducted a comparative assessment on GSA methods in terms of uncertainty propagation efficiency and output variance accountability. However,

this study only focused on the most popular GSA methods i.e. sampling-based ones, yet there are many other methods that also show promising results in the literature outside LCA-related studies, such as extend-FAST method and Metal-based methods. These methods should be further explored and investigated, which is beyond the scope of this study.

At last, a building-specific LCSA model was developed and validated through case studies. However, this model does not differentiate between various building types. Buildings can be classified in various types based on different occupancies, such as commercial, industrial, residential, government and educational buildings. Different building types may have different stakeholder interests, which leads to different perspectives to define, evaluate and optimize sustainability. For example, sustainability optimization of private and business buildings should be conducted from owner's perspective, while sustainability optimization of public buildings (such as schools and hospitals) should be conducted from the public's perspective considering their construction and maintenance relies on taxpayers' money. Therefore, further studies are necessary to capture different characteristics of various building types through in-depth investigation on the typology, sustainability criteria and performance reference values or scales. In addition, more case studies are needed. With more evaluation results from different building projects, a benchmark of sustainability assessment results can be established to guide further development or improvement of standards for various types of buildings.

REFERENCE

- Adalberth, K. (1997). "Energy use during the life cycle of single-unit dwellings: examples." Building and environment **32**(4): 321-329.
- Adalberth, K., et al. (2001). "Life-cycle assessment of four multi-family buildings." International Journal of Low Energy and Sustainable Buildings.
- Adams, W. M. (2006). The future of sustainability: Re-thinking environment and development in the twenty-first century. Report of the IUCN renowned thinkers meeting.
- Akadiri, O. P. (2011). "Development of a multi-criteria approach for the selection of sustainable materials for building projects."
- Aktacir, M. A., et al. (2006). "Life-cycle cost analysis for constant-air-volume and variable-air-volume air-conditioning systems." Applied Energy **83**(6): 606-627.
- Ali, H. H. and S. F. Al Nsairat (2009). "Developing a green building assessment tool for developing countries—Case of Jordan." Building and Environment **44**(5): 1053-1064.
- Almahmoud, E. and H. K. Doloi (2015). "Assessment of social sustainability in construction projects using social network analysis." Facilities **33**(3/4): 152-176.
- Alshamrani, O. S., et al. (2014). "Integrated LCA–LEED sustainability assessment model for structure and envelope systems of school buildings." Building and Environment **80**: 61-70.
- Alwaer, H. and D. Clements-Croome (2010). "Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings." Building and Environment **45**(4): 799-807.
- Alyami, S. H. and Y. Rezgui (2012). "Sustainable building assessment tool development approach." Sustainable Cities and Society **5**: 52-62.
- Andersson, P. and A. Johansson (2012). "Disturbances of the surroundings in an urban infrastructure project."
- Andrade, J. B. and L. Bragança (2011). Analysis of the impacts of economic and social indicators to sustainability assessment. International Conference Sustainability of Constructions Towards a Better Built Environment, University of Malta. Faculty for the Built Environment.
- Aparcana, S. and S. Salhofer (2013). "Application of a methodology for the social life cycle assessment of recycling systems in low income countries: three Peruvian case studies." The international journal of life cycle assessment **18**(5): 1116-1128.

Aranda-Usón, A., et al. (2013). "Phase change material applications in buildings: an environmental assessment for some Spanish climate severities." Science of the total environment **444**: 16-25.

Ardente, F., et al. (2005). "Life cycle assessment of a solar thermal collector." Renewable energy **30**(7): 1031-1054.

Arikan, E., et al. (2017). "Solid waste disposal methodology selection using multi-criteria decision making methods and an application in Turkey." Journal of Cleaner Production **142**: 403-412.

Asdrubali, F., et al. (2013). "Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings." Energy and buildings **64**: 73-89.

ASHRAE (2010). "Standard 55-2010." Thermal environmental conditions for human occupancy.

Asiedu, Y. and P. Gu (1998). "Product life cycle cost analysis: state of the art review." International journal of production research **36**(4): 883-908.

Asif, M., et al. (2007). "Life cycle assessment: a case study of a dwelling home in Scotland." Building and environment **42**(3): 1391-1394.

Athawale, V. M. and S. Chakraborty (2010). Facility location selection using PROMETHEE II method. Proceedings of the 2010 international conference on industrial engineering and operations management.

Awadh, O. (2017). "Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis." Journal of Building Engineering **11**: 25-29.

Bare, J. C. (2002). "Traci." Journal of industrial ecology **6**(3-4): 49-78.

Basbagill, J., et al. (2013). "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts." Building and environment **60**: 81-92.

Basset-Mens, C., et al. (2009). "Uncertainty of global warming potential for milk production on a New Zealand farm and implications for decision making." The International Journal of Life Cycle Assessment **14**(7): 630-638.

Basson, L. and J. G. Petrie (2007). "An integrated approach for the consideration of uncertainty in decision making supported by Life Cycle Assessment." Environmental Modelling & Software **22**(2): 167-176.

BCA (2014). 3rd Green Building Masterplan.

BCA (2015). " BCA Green Mark for New Non-Residential Buildings 2015." from https://www.bca.gov.sg/GreenMark/others/Green_Mark_NRB_2015_Criteria.pdf (Accessed Jun 2018).

BCA (2017). "About BCA Green Mark Scheme." from https://www.bca.gov.sg/greenmark/green_mark_buildings.html (Accessed June, 2018).

BCA (2017). "Energy Modeling for Green Mark Incentive Scheme (GMIS)." Retrieved March, 2018, from <https://www.bca.gov.sg/GreenMark/energymod.html>.

BCA (2017). "Legislation on Environmental Sustainability for Buildings." Retrieved March, 2018, from https://www.bca.gov.sg/EnvSusLegislation/Environmental_Sustainability_Legislation.html.

Beccali, M., et al. (2012). "LCA of a solar heating and cooling system equipped with a small water-ammonia absorption chiller." *Solar Energy* **86**(5): 1491-1503.

Benoît-Norris, C., et al. (2011). "Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA." *The international journal of life cycle assessment* **16**(7): 682-690.

Berardi, U. (2012). "Sustainability assessment in the construction sector: rating systems and rated buildings." *Sustainable Development* **20**(6): 411-424.

Berardi, U. (2013). "Clarifying the new interpretations of the concept of sustainable building." *Sustainable Cities and Society* **8**: 72-78.

Bisinella, V., et al. (2016). "A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems." *The International Journal of Life Cycle Assessment* **21**(3): 378-394.

Björklund, A. E. (2002). "Survey of approaches to improve reliability in LCA." *The International Journal of Life Cycle Assessment* **7**(2): 64.

Blair, J., et al. (2013). *Designing surveys: A guide to decisions and procedures*, Sage Publications.

Blengini, G. A. (2009). "Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy." *Building and Environment* **44**(2): 319-330.

Blengini, G. A. and T. Di Carlo (2010). "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings." *Energy and buildings* **42**(6): 869-880.

Blom, I., et al. (2010). "LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings." Building and environment **45**(11): 2362-2372.

Bossel, H. (1999). Indicators for sustainable development: theory, method, applications, International Institute for Sustainable Development Winnipeg.

Bozhilova-Kisheva, K. P., et al. (2015). "An integrated life cycle inventory for demolition processes in the context of life cycle sustainability assessment." Newsletter.

Bragança, L., et al. (2010). "Building sustainability assessment." Sustainability **2**(7).

BRE (2016). "International New Construction 2016." from <https://www.breeam.com/discover/technical-standards/newconstruction/> (Accessed June, 2018).

BRE (2017). BRE Annual Review Accounts 2017.

Brent, A. and C. Labuschagne (2006). "Social indicators for sustainable project and technology life cycle management in the process industry (13 pp+ 4)." The international journal of life cycle assessment **11**(1): 3-15.

Bribián, I. Z., et al. (2011). "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential." Building and environment **46**(5): 1133-1140.

Bribián, I. Z., et al. (2009). "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification." Building and environment **44**(12): 2510-2520.

British Standards Institution (2008). Standardized method of life cycle costing for construction procurement. A supplement to BS ISO 15686-5. Buildings and constructed assets.

Brown, T. J., et al. (2014). World mineral production 2010-2014, British Geological Survey.

Brundtland Commission (1987). Our common future, Oxford: Oxford University Press.

Bullen, P. A. (2007). "Adaptive reuse and sustainability of commercial buildings." Facilities **25**(1/2): 20-31.

Burgan, B. A. and M. R. Sansom (2006). "Sustainable steel construction." Journal of Constructional Steel Research **62**(11): 1178-1183.

Buyle, M., et al. (2013). "Life cycle assessment in the construction sector: A review." Renewable and Sustainable Energy Reviews **26**: 379-388.

Cabeza, L. F., et al. (2014). "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review." Renewable and Sustainable Energy Reviews **29**: 394-416.

Cao, X., et al. (2015). "A comparative study of environmental performance between prefabricated and traditional residential buildings in China." Journal of Cleaner Production **109**: 131-143.

Castell, A., et al. (2013). "Life Cycle Assessment of alveolar brick construction system incorporating phase change materials (PCMs)." Applied Energy **101**: 600-608.

Chan, E. and G. K. Lee (2008). "Critical factors for improving social sustainability of urban renewal projects." Social Indicators Research **85**(2): 243-256.

Chan, E. H., et al. (2009). "The market for green building in developed Asian cities—the perspectives of building designers." Energy Policy **37**(8): 3061-3070.

Chau, C., et al. (2015). "A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings." Applied Energy **143**: 395-413.

Chauhan, A. and A. Singh (2016). "A hybrid multi-criteria decision making method approach for selecting a sustainable location of healthcare waste disposal facility." Journal of Cleaner Production **139**: 1001-1010.

Chen, T., et al. (2001). "Analysis of embodied energy use in the residential building of Hong Kong." Energy **26**(4): 323-340.

Chen, W. and N. M. Holden (2017). "Social life cycle assessment of average Irish dairy farm." The International Journal of Life Cycle Assessment **22**(9): 1459-1472.

Chen, X. and M. S. Corson (2014). "Influence of emission-factor uncertainty and farm-characteristic variability in LCA estimates of environmental impacts of French dairy farms." Journal of Cleaner Production **81**: 150-157.

Chen, Y.-H. and R.-J. Chao (2012). "Supplier selection using consistent fuzzy preference relations." Expert Systems with Applications **39**(3): 3233-3240.

Chen, Y., et al. (2010). "Sustainable performance criteria for construction method selection in concrete buildings." Automation in construction **19**(2): 235-244.

Chhipi-Shrestha, G. K., et al. (2015). "'Socializing' sustainability: a critical review on current development status of social life cycle impact assessment method." Clean technologies and environmental policy **17**(3): 579-596.

Cho, S.-H. and C.-U. Chae (2016). "A study on life cycle CO₂ emissions of low-carbon building in South Korea." Sustainability **8**(6): 579.

CIB (2010). Towards Sustainable and Smart-ECO Buildings.

Cinelli, M., et al. (2014). "Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment." Ecological indicators **46**: 138-148.

Ciroth, A. and F. Eisele (2017). "PSILCA—A Product Social Impact Life Cycle Assessment database." from https://www.openlca.org/wp-content/uploads/2017/12/PSILCA_documentation_update_PSILCA_v2_final.pdf (accessed 25 October 2018).

Ciroth, A., et al. (2004). "Uncertainty calculation in life cycle assessments." The International Journal of Life Cycle Assessment **9**(4): 216.

Ciroth, A. and J. Franze (2011). "LCA of an ecolabeled notebook: consideration of social and environmental impacts along the entire life cycle." from https://www.greendelta.com/wp-content/uploads/2017/03/LCA_laptop_final.pdf (accessed 10 October 2018).

Citherlet, S., et al. (2000). "Window and advanced glazing systems life cycle assessment." Energy and buildings **32**(3): 225-234.

Clavreul, J., et al. (2012). "Quantifying uncertainty in LCA-modelling of waste management systems." Waste management **32**(12): 2482-2495.

Cobut, A., et al. (2015). "The environmental footprint of interior wood doors in non-residential buildings—part 1: life cycle assessment." Journal of Cleaner Production **109**: 232-246.

Cole, R. J. (2005). "Building environmental assessment methods: redefining intentions and roles." Building Research & Information **33**(5): 455-467.

Communities, S. (2009). "Non-poverty wages for countries around the world." from <https://digitalcommons.ilr.cornell.edu/cgi/viewcontent.cgi?referer=https://scholar.google.com.sg/&httpsredir=1&article=2332&context=globaldocs> (accessed 10 October 2018).

COMTRADE (2017). "Singapore Imports By Category." from <https://tradingeconomics.com/singapore/imports-by-category> (accessed 15 October 2018).

Crawley, D. B., et al. (2008). "Contrasting the capabilities of building energy performance simulation programs." Building and Environment **43**(4): 661-673.

Cucurachi, S., et al. (2016). "A protocol for the global sensitivity analysis of impact assessment models in life cycle assessment." Risk Analysis **36**(2): 357-377.

Dai, H. and W. Wang (2009). "Application of low-discrepancy sampling method in structural reliability analysis." Structural Safety **31**(1): 55-64.

Dave, S. (2011). "Neighbourhood density and social sustainability in cities of developing countries." Sustainable Development **19**(3): 189-205.

De Giuli, V., et al. (2012). "Indoor environmental quality and pupil perception in Italian primary schools." Building and Environment **56**: 335-345.

Devuyst, D. (2000). "Linking impact assessment and sustainable development at the local level: the introduction of sustainability assessment systems." Sustainable Development **8**(2): 67-78.

Ding, G. K. (2008). "Sustainable construction—The role of environmental assessment tools." Journal of environmental management **86**(3): 451-464.

Doan, D. T., et al. (2017). "A critical comparison of green building rating systems." Building and Environment **123**: 243-260.

Dong, Y. H. and S. T. Ng (2014). "Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong." The International Journal of Life Cycle Assessment **19**(7): 1409-1423.

Dong, Y. H. and S. T. Ng (2015). "A social life cycle assessment model for building construction in Hong Kong." The International Journal of Life Cycle Assessment **20**(8): 1166-1180.

DOS (2018). Share of GDP by Industry.

Dreyer, L., et al. (2006). "A framework for social life cycle impact assessment (10 pp)." The International Journal of Life Cycle Assessment **11**(2): 88-97.

Dreyer, L. C., et al. (2010). "Characterisation of social impacts in LCA." The International Journal of Life Cycle Assessment **15**(3): 247-259.

Du Plessis, C. (2007). "A strategic framework for sustainable construction in developing countries." Construction Management and Economics **25**(1): 67-76.

Ekener-Petersen, E. and G. Finnveden (2013). "Potential hotspots identified by social LCA—part 1: a case study of a laptop computer." The International Journal of Life Cycle Assessment **18**(1): 127-143.

Energy Market Authority of Singapore (2014). Singapore Energy Statistics, Energy Market Authority of Singapore.

EPD (2015). "Environmental Product Declaration of CenTraVac™ Chiller."

ERI@N (2013). Chilled Ceiling Test-Bed at CleanTech One, Energy Research Institute@NTU and SGL Carbon.

Finnveden, G., et al. (2009). "Recent developments in life cycle assessment." Journal of environmental management **91**(1): 1-21.

Flower, D. J. and J. G. Sanjayan (2007). "Green house gas emissions due to concrete manufacture." The International Journal of Life Cycle Assessment **12**(5): 282.

Foolmaun, R. K. and T. Ramjeeawon (2013). "Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius." Environment, development and sustainability **15**(3): 783-806.

Foolmaun, R. K. and T. Ramjeeawon (2012). "Comparative life cycle assessment and life cycle costing of four disposal scenarios for used polyethylene terephthalate bottles in Mauritius." Environmental technology **33**(17): 2007-2018.

Foolmaun, R. K. and T. Ramjeeawon (2013). "Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius." The International Journal of Life Cycle Assessment **18**(1): 155-171.

Forsberg, A. and F. Von Malmborg (2004). "Tools for environmental assessment of the built environment." Building and Environment **39**(2): 223-228.

Fowler, K. M. and E. M. Rauch (2006). Sustainable building rating systems summary, Pacific Northwest National Laboratory (PNNL), Richland, WA (US).

Franze, J. and A. Ciroth (2011). "A comparison of cut roses from Ecuador and the Netherlands." The International Journal of Life Cycle Assessment **16**(4): 366-379.

Fuller, S. (2010). "Life-Cycle Cost Analysis (LCCA)". from <https://www.wbdg.org/resources/lcca.php>

Geisler, G., et al. (2005). "Uncertainty analysis in life cycle assessment (LCA): case study on plant-protection products and implications for decision making (9 pp+ 3 pp)." The International Journal of Life Cycle Assessment **10**(3): 184-192.

Gillham, B. (2000). Case study research methods, Bloomsbury Publishing.

Glasserman, P. (2013). Monte Carlo methods in financial engineering, Springer Science & Business Media.

Gluch, P. and H. Baumann (2004). "The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making." Building and environment **39**(5): 571-580.

Goedkoop, M., et al. (2009). "ReCiPe 2008." A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level **1**.

Goedkoop, M. and R. Spriensma (2000). "The Eco-indicator 99: a damage oriented method for life cycle assessment, methodology report." PreConsultans BV, The Netherlands **12**.

Gou, Z., et al. (2012). "Subjective and objective evaluation of the thermal environment in a three-star green office building in China." Indoor and Built Environment **21**(3): 412-422.

Gould, R., et al. (2017). "Using social sustainability principles to analyse activities of the extraction lifecycle phase: Learnings from designing support for concept selection." Journal of Cleaner Production **140**: 267-276.

Groen, E., et al. (2014). "Methods for uncertainty propagation in life cycle assessment." Environmental Modelling & Software **62**: 316-325.

Groen, E. A., et al. (2017). "Methods for global sensitivity analysis in life cycle assessment." The International Journal of Life Cycle Assessment **22**(7): 1125-1137.

Groen, E. A., et al. (2014). Sensitivity analysis in life cycle assessment. Proceedings of the 9th international conference on life cycle assessment in the agri-food sector.

Guggemos, A. A. and A. Horvath (2006). "Decision-support tool for assessing the environmental effects of constructing commercial buildings." Journal of Architectural Engineering **12**(4): 187-195.

Guinée, J. B. (2002). "Handbook on life cycle assessment operational guide to the ISO standards." The International Journal of Life Cycle Assessment **7**(5): 311-313.

Gunerhan, H. and A. Hepbasli (2007). "Exergetic modeling and performance evaluation of solar water heating systems for building applications." Energy and Buildings **39**(5): 509-516.

Guo, M. and R. Murphy (2012). "LCA data quality: sensitivity and uncertainty analysis." Science of the total environment **435**: 230-243.

Gustavsson, L. and R. Sathre (2006). "Variability in energy and carbon dioxide balances of wood and concrete building materials." Building and environment **41**(7): 940-951.

Haapio, A. and P. Viitaniemi (2008). "A critical review of building environmental assessment tools." Environmental impact assessment review **28**(7): 469-482.

Häkkinen, T. and K. Belloni (2011). "Barriers and drivers for sustainable building." Building Research & Information **39**(3): 239-255.

Hämäläinen, P., et al. (2006). "Global estimates of occupational accidents." Safety science **44**(2): 137-156.

Hao, X., et al. (2007). "A combined system of chilled ceiling, displacement ventilation and desiccant dehumidification." Building and Environment **42**(9): 3298-3308.

Hatami-Marbini, A. and M. Tavana (2011). "An extension of the Electre I method for group decision-making under a fuzzy environment." Omega **39**(4): 373-386.

Hauschild, M., et al. (2011). "Recommendations for Life Cycle Impact Assessment in the European context-based on existing environmental impact assessment models and factors. European Commission-DG Joint Research Centre, JRC." Institute for Environment and Sustainability (IES), retrieved from: <http://lct.jrc.ec.europa.eu/assessment/projects>.

Hazra, A. and N. Gogtay (2016). "Biostatistics series module 5: Determining sample size." Indian journal of dermatology **61**(5): 496.

Heijungs, R. (1996). "Identification of key issues for further investigation in improving the reliability of life-cycle assessments." Journal of Cleaner Production **4**(3-4): 159-166.

Heijungs, R. and M. A. Huijbregts (2004). "A review of approaches to treat uncertainty in LCA."

Heijungs, R., et al. (2005). "Numerical approaches to life cycle interpretation-the case of the Ecoinvent'96 database (10 pp)." The International Journal of Life Cycle Assessment **10**(2): 103-112.

Heikkilä, K. (2008). "Environmental evaluation of an air-conditioning system supplied by cooling energy from a bore-hole based heat pump system." Building and Environment **43**(1): 51-61.

Hellweg, S. and L. M. i Canals (2014). "Emerging approaches, challenges and opportunities in life cycle assessment." Science **344**(6188): 1109-1113.

Helton, J. C. and F. Davis (2002). "Illustration of sampling-based methods for uncertainty and sensitivity analysis." Risk Analysis **22**(3): 591-622.

Helton, J. C. and F. J. Davis (2003). "Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems." Reliability Engineering & System Safety **81**(1): 23-69.

Henry, A. and N. Frascaria-Lacoste (2012). "Comparing green structures using life cycle assessment: a potential risk for urban biodiversity homogenization?" The International Journal of Life Cycle Assessment: 1-2.

Herrera-Viedma, E., et al. (2004). "Some issues on consistency of fuzzy preference relations." European Journal of Operational Research **154**(1): 98-109.

Hill, R. C. and P. A. Bowen (1997). "Sustainable construction: principles and a framework for attainment." Construction Management & Economics **15**(3): 223-239.

Homma, T. and A. Saltelli (1996). "Importance measures in global sensitivity analysis of nonlinear models." Reliability Engineering & System Safety **52**(1): 1-17.

Hoogmartens, R., et al. (2014). "Bridging the gap between LCA, LCC and CBA as sustainability assessment tools." Environmental impact assessment review **48**: 27-33.

Hossaini, N., et al. (2015). "AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver." Journal of Environmental Planning and Management **58**(7): 1217-1241.

Hosseinijou, S. A., et al. (2014). "Social life cycle assessment for material selection: a case study of building materials." The International Journal of Life Cycle Assessment **19**(3): 620-645.

Hoxha, E., et al. (2014). "Method to analyse the contribution of material's sensitivity in buildings' environmental impact." Journal of Cleaner Production **66**: 54-64.

Hsieh, T.-Y., et al. (2004). "Fuzzy MCDM approach for planning and design tenders selection in public office buildings." International journal of project management **22**(7): 573-584.

Hu, M., et al. (2013). "An approach to LCSA: the case of concrete recycling." The international journal of life cycle assessment **18**(9): 1793-1803.

Huberman, N. and D. Pearlmutter (2008). "A life-cycle energy analysis of building materials in the Negev desert." Energy and buildings **40**(5): 837-848.

Huijbregts, M. A. (1998). "Application of uncertainty and variability in LCA." The international journal of life cycle assessment **3**(5): 273-280.

Huijbregts, M. A., et al. (2003). "Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling." Environmental science & technology **37**(11): 2600-2608.

Huijbregts, M. A., et al. (2001). "Framework for modelling data uncertainty in life cycle inventories." The International Journal of Life Cycle Assessment **6**(3): 127.

Humbert, S., et al. (2005). "IMPACT 2002+: user guide." Draft for version 2.

Hunkeler, D. (2006). "Societal LCA methodology and case study (12 pp)." The international journal of life cycle assessment **11**(6): 371-382.

Hussin, J. M., et al. (2013). "The way forward in sustainable construction: issues and challenges." International Journal of Advances in Applied Sciences **2**(1): 15-24.

Hwang, B. G. and J. S. Tan (2012). "Green building project management: obstacles and solutions for sustainable development." Sustainable Development **20**(5): 335-349.

ILO (2017). "Key Indicators of the Labour Market ". from <https://www.ilo.org/ilostat> (accessed 10 October 2018).

Imbeault-Tétreault, H., et al. (2013). "Analytical propagation of uncertainty in life cycle assessment using matrix formulation." Journal of industrial ecology **17**(4): 485-492.

Infante, C. E. D. d. C., et al. (2013). "Triple bottom line analysis of oil and gas industry with multicriteria decision making." Journal of Cleaner Production **52**: 289-300.

Ionescu, C., et al. (2015). "The historical evolution of the energy efficient buildings." Renewable and Sustainable Energy Reviews **49**: 243-253.

Iooss, B. and P. Lemaître (2015). A review on global sensitivity analysis methods. Uncertainty management in simulation-optimization of complex systems, Springer: 101-122.

ISO (2006). "14040: Environmental management–life cycle assessment–principles and framework." London: British Standards Institution.

ISO (2006). ISO14040:2006 Environmental Management-Life Cycle Assessment: Principles and Framework.

ISO, B. (2008). "15392 (2008) Sustainability in Building Construction–General principles." available through NTU library.

Jaillon, L., et al. (2009). "Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong." Waste management **29**(1): 309-320.

Jolliet, O., et al. (2003). "IMPACT 2002+: a new life cycle impact assessment methodology." The international journal of life cycle assessment **8**(6): 324-330.

Jørgensen, A., et al. (2008). "Methodologies for social life cycle assessment." The International Journal of Life Cycle Assessment **13**(2): 96.

Jørgensen, A., et al. (2008). "Methodologies for social life cycle assessment." The international journal of life cycle assessment **13**(2): 96-103.

Joshi, D. and S. Kumar (2016). "Interval-valued intuitionistic hesitant fuzzy Choquet integral based TOPSIS method for multi-criteria group decision making." European journal of operational research **248**(1): 183-191.

Junnila, S. and A. Horvath (2003). "Life-cycle environmental effects of an office building." Journal of Infrastructure Systems **9**(4): 157-166.

Junnila, S., et al. (2006). "Life-cycle assessment of office buildings in Europe and the United States." Journal of Infrastructure Systems **12**(1): 10-17.

Kahuthu, A. (2006). "Economic growth and environmental degradation in a global context." Environment, development and sustainability **8**(1): 55-68.

Kamali, M. and K. Hewage (2017). "Development of performance criteria for sustainability evaluation of modular versus conventional construction methods." Journal of Cleaner Production **142**: 3592-3606.

Kamali, M. and K. N. Hewage (2015). "Performance indicators for sustainability assessment of buildings."

Kannan, R., et al. (2006). "Life cycle assessment study of solar PV systems: an example of a 2.7 kW p distributed solar PV system in Singapore." Solar Energy **80**(5): 555-563.

Kannan, R., et al. (2006). "Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore." Solar energy **80**(5): 555-563.

Kaya, T. and C. Kahraman (2010). "Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul." Energy **35**(6): 2517-2527.

Kaya, T. and C. Kahraman (2011). "An integrated fuzzy AHP–ELECTRE methodology for environmental impact assessment." Expert Systems with Applications **38**(7): 8553-8562.

Kaya, T. and C. Kahraman (2011). "Multicriteria decision making in energy planning using a modified fuzzy TOPSIS methodology." Expert Systems with Applications **38**(6): 6577-6585.

Khalili, N. R. and S. Duecker (2013). "Application of multi-criteria decision analysis in design of sustainable environmental management system framework." Journal of Cleaner Production **47**: 188-198.

Khang, D. S., et al. (2017). "Design of experiments for global sensitivity analysis in life cycle assessment: the case of biodiesel in Vietnam." Resources, Conservation and Recycling **119**: 12-23.

Khoshnava, S. M., et al. (2016). "Rank of green building material criteria based on the three pillars of sustainability using the hybrid multi criteria decision making method." Journal of Cleaner Production.

Kibert, C. J. (1994). Establishing principles and a model for sustainable construction. Proceedings of the first international conference on sustainable construction, Tampa Florida, November.

Kibert, C. J. (2008). Sustainable construction: green building design and delivery, John Wiley & Sons.

Kibert, C. J. (2012). Sustainable construction: green building design and delivery, John Wiley & Sons.

Kibert, C. J. (2016). Sustainable construction: green building design and delivery, John Wiley & Sons.

Kiesse, T. S., et al. (2017). "Introducing economic actors and their possibilities for action in LCA using sensitivity analysis: Application to hemp-based insulation products for building applications." Journal of Cleaner Production **142**: 3905-3916.

Kishore, K. (2006). "Concrete Mix Design with Fly Ash and Superplasticizer." 2018, from <https://www.engineeringcivil.com/concrete-mix-design-with-fly-ash-and-superplasticizer.html>.

Klaus Schwab, et al. (2018). The Global Competitiveness Report 2017-2018.

Klöpffer, W. (2003). "Life-cycle based methods for sustainable product development." The international journal of life cycle assessment **8**(3): 157-159.

Klöpffer, W. (2008). "Life cycle sustainability assessment of products." The international journal of life cycle assessment **13**(2): 89-95.

Kluczek, A. and B. Gladysz (2015). "Analytical Hierarchy Process/Technique for Order Preference by Similarity to Ideal Solution-based approach to the generation of environmental improvement options for painting process e Results from an industrial case study." Journal of Cleaner Production **101**: 360-367.

Kobetičová, K. and R. Černý (2017). "Ecotoxicology of building materials: a critical review of recent studies." Journal of Cleaner Production **165**: 500-508.

Kofoworola, O. F. and S. H. Gheewala (2008). "Environmental life cycle assessment of a commercial office building in Thailand." The international journal of life cycle assessment **13**(6): 498-511.

Korjenic, A., et al. (2011). "Development and performance evaluation of natural thermal-insulation materials composed of renewable resources." Energy and Buildings **43**(9): 2518-2523.

Korkmaz, S., et al. (2010). "Piloting evaluation metrics for sustainable high-performance building project delivery." Journal of construction engineering and management **136**(8): 877-885.

Koroneos, C. and A. Dompros (2007). "Environmental assessment of brick production in Greece." Building and environment **42**(5): 2114-2123.

Korpi, E. and T. Ala-Risku (2008). "Life cycle costing: a review of published case studies." Managerial Auditing Journal **23**(3): 240-261.

Kosareo, L. and R. Ries (2007). "Comparative environmental life cycle assessment of green roofs." Building and environment **42**(7): 2606-2613.

Krajnc, D. and P. Glavič (2005). "A model for integrated assessment of sustainable development." Resources, Conservation and Recycling **43**(2): 189-208.

Kruse, S. A., et al. (2009). "Socioeconomic indicators as a complement to life cycle assessment—an application to salmon production systems." The International Journal of Life Cycle Assessment **14**(1): 8.

Kua, H. W. and C. L. Wong (2012). "Analysing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective." Energy and buildings **51**: 6-14.

Kucherenko, S., et al. (2015). "Exploring multi-dimensional spaces: A comparison of Latin hypercube and quasi Monte Carlo sampling techniques." arXiv preprint arXiv:1505.02350.

Lai, E., et al. (2008). "Review of multi-criteria decision aid for integrated sustainability assessment of urban water systems." Urban water journal **5**(4): 315-327.

Langdon, D. (2006). Literature Review of Life Cycle Costing (LCC) and Life Cycle Assessment (LCA), Davis Langdon Management Consulting London.

Lee, W. (2012). "Benchmarking energy use of building environmental assessment schemes." Energy and Buildings **45**: 326-334.

Lee, W. (2013). "A comprehensive review of metrics of building environmental assessment schemes." Energy and Buildings **62**: 403-413.

Legarth, J. B., et al. (2000). "A screening level life cycle assessment of the ABB EU 2000 air handling unit." The International Journal of Life Cycle Assessment **5**(1): 47-58.

Leigh, S.-B. and J.-S. Won (2004). "A case study for design decisions on building service system using LCC analysis." Journal of Asian Architecture and Building Engineering **3**(1): 77-84.

Li, X. (2008). "Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete." Resources, Conservation and Recycling **53**(1-2): 36-44.

Li, Y. Y., et al. (2011). "Critical project management factors of AEC firms for delivering green building projects in Singapore." Journal of construction engineering and management **137**(12): 1153-1163.

Linkov, I. and T. P. Seager (2011). Coupling multi-criteria decision analysis, life-cycle assessment, and risk assessment for emerging threats, ACS Publications.

Liping, W. and W. N. Hien (2007). "The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore." Building and environment **42**(12): 4006-4015.

Liu, S., et al. (2016). "Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore." Building and Environment **102**: 207-216.

Liu, S., et al. (2016). "Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): a case study in Singapore." Building and environment.

Lloyd, S. M. and R. Ries (2007). "Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches." Journal of industrial ecology **11**(1): 161-179.

Lo, S.-C., et al. (2005). "Quantifying and reducing uncertainty in life cycle assessment using the Bayesian Monte Carlo method." Science of the total environment **340**(1-3): 23-33.

Love, P. E. and Z. Irani (2004). "An exploratory study of information technology evaluation and benefits management practices of SMEs in the construction industry." Information & Management **42**(1): 227-242.

Macombe, C., et al. (2011). "2nd International Seminar in Social Life Cycle Assessment—recent developments in assessing the social impacts of product life cycles." The International Journal of Life Cycle Assessment **16**(9): 940.

Mahase, M., et al. (2016). "A survey of applications of multi-criteria decision analysis methods in mine planning and related case studies." Journal of the Southern African Institute of Mining and Metallurgy **116**(11): 1051-1056.

Majdi, I. (2013). Comparative evaluation of PROMETHEE and ELECTRE with application to sustainability assessment, Concordia University.

Malça, J. and F. Freire (2010). "Uncertainty analysis in biofuel systems." Journal of industrial ecology **14**(2): 322-334.

Malmqvist, T., et al. (2011). "Life cycle assessment in buildings: The ENSLIC simplified method and guidelines." Energy **36**(4): 1900-1907.

Manik, Y., et al. (2013). "Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia." The International Journal of Life Cycle Assessment **18**(7): 1386-1392.

Mao, C., et al. (2013). "Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects." Energy and Buildings **66**: 165-176.

Marino, S., et al. (2008). "A methodology for performing global uncertainty and sensitivity analysis in systems biology." Journal of theoretical biology **254**(1): 178-196.

Marszal, A. J., et al. (2011). "Zero Energy Building—A review of definitions and calculation methodologies." Energy and Buildings **43**(4): 971-979.

Martín-Gamboa, M., et al. (2017). "A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems." Journal of Cleaner Production **150**: 164-174.

Martínez-Blanco, J., et al. (2014). "Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment." Journal of Cleaner Production **69**: 34-48.

Mateus, R. and L. Bragança (2011). "Sustainability assessment and rating of buildings: Developing the methodology SBToolPT-H." Building and Environment **46**(10): 1962-1971.

MEA (2017). Singapore Energy Statistics.

Menoufi, K., et al. (2013). "Life cycle assessment of experimental cubicles including PCM manufactured from natural resources (esters): a theoretical study." Renewable energy **51**: 398-403.

Min, H. and I. Kim (2012). "Green supply chain research: past, present, and future." Logistics Research **4**(1-2): 39-47.

Ministry of the Environment and Water Resources (2014). Key Environmental Statistics, Ministry of the Environment and Water Resources.

Mishra, S., et al. (2009). "Global sensitivity analysis techniques for probabilistic ground water modeling." Groundwater **47**(5): 727-744.

MIT (2018). "The Observatory of Economic Complexity: OEC." from <https://atlas.media.mit.edu/en/> (accessed July, 2018).

Moffatt, S., et al. (2006). "Using quantitative and qualitative data in health services research—what happens when mixed method findings conflict?[ISRCTN61522618]." BMC Health Services Research **6**(1): 28.

MOM (2016). "Occupational Safety and Health Division Annual Report." from <https://www.mom.gov.sg/~media/mom/documents/safety-health/reports-stats/oshd-annual-report-2017.pdf?la=en> (accessed 15 October 2018).

MOM (2017). Singapore Yearbook Of Manpower Statistics 2017.

Mutel, C. L., et al. (2013). "Two-step sensitivity testing of parametrized and regionalized life cycle assessments: methodology and case study." Environmental science & technology **47**(11): 5660-5667.

Nebel, B., et al. (2006). "Life cycle assessment of wood floor coverings-a representative study for the german flooring industry (11 pp)." The international journal of life cycle assessment **11**(3): 172-182.

Ness, B., et al. (2007). "Categorising tools for sustainability assessment." Ecological economics **60**(3): 498-508.

New South Wales Treasury (2004). Life Cycle Costing Guideline

Nguyen, B. K. and H. Altan (2011). "Tpsi-tall-building projects sustainability indicator." Procedia Engineering **21**: 387-394.

Nicoletti, G. M., et al. (2002). "Comparative Life Cycle Assessment of flooring materials: ceramic versus marble tiles." Journal of Cleaner Production **10**(3): 283-296.

Norris, G. A. (2001). "Integrating life cycle cost analysis and LCA." The international journal of life cycle assessment **6**(2): 118-120.

Norris, G. A. (2006). "Social impacts in product life cycles-Towards life cycle attribute assessment." The international journal of life cycle assessment **11**(1): 97-104.

Nyman, M. and C. J. Simonson (2004). "Life-Cycle Assessment (LCA) of Air-Handling Units with and without Air-to-Air Energy Exchangers." ASHRAE Transactions **110**(1).

Nyman, M. and C. J. Simonson (2005). "Life cycle assessment of residential ventilation units in a cold climate." Building and environment **40**(1): 15-27.

Ochoa, C. E. and I. G. Capeluto (2008). "Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate." Building and Environment **43**(11): 1829-1839.

Ortiz-Rodríguez, O., et al. (2010). "Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development." Science of the total environment **408**(12): 2435-2443.

Ortiz, O., et al. (2009). "Sustainability in the construction industry: A review of recent developments based on LCA." Construction and Building Materials **23**(1): 28-39.

Pacheco, R., et al. (2012). "Energy efficient design of building: A review." Renewable and Sustainable Energy Reviews **16**(6): 3559-3573.

Padey, P., et al. (2013). "From LCAs to simplified models: a generic methodology applied to wind power electricity." Environmental science & technology **47**(3): 1231-1238.

Pan, W., et al. (2012). "Establishing and weighting decision criteria for building system selection in housing construction." Journal of construction engineering and management **138**(11): 1239-1250.

Pan, Y., et al. (2008). "Energy modeling of two office buildings with data center for green building design." Energy and Buildings **40**(7): 1145-1152.

Parent, J., et al. (2010). "Impact assessment in SLCA: sorting the sLCIA methods according to their outcomes." The International Journal of Life Cycle Assessment **15**(2): 164-171.

Peuportier, B. (2001). "Life cycle assessment applied to the comparative evaluation of single family houses in the French context." Energy and buildings **33**(5): 443-450.

Pitt, M., et al. (2009). "Towards sustainable construction: promotion and best practices." Construction innovation **9**(2): 201-224.

Pohekar, S. and M. Ramachandran (2004). "Application of multi-criteria decision making to sustainable energy planning—a review." Renewable and Sustainable Energy Reviews **8**(4): 365-381.

Poon, C.-S., et al. (2004). "Reducing building waste at construction sites in Hong Kong." Construction Management and Economics **22**(5): 461-470.

Prek, M. (2004). "Environmental impact and life cycle assessment of heating and air conditioning systems, a simplified case study." Energy and buildings **36**(10): 1021-1027.

Prescott-Allen, R. (2001). Wellbeing of nations: A country-by-country index of quality of life and the environment, IDRC, Ottawa, ON, CA.

Quale, J., et al. (2012). "Construction matters: Comparing environmental impacts of building modular and conventional homes in the United States." Journal of industrial ecology **16**(2): 243-253.

Radhi, H. and S. Sharples (2013). "Global warming implications of façade parameters: A life cycle assessment of residential buildings in Bahrain." Environmental impact assessment review **38**: 99-108.

Ramesh, T., et al. (2010). "Life cycle energy analysis of buildings: An overview." Energy and Buildings **42**(10): 1592-1600.

Raut, S., et al. (2011). "Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks." Construction and Building Materials **25**(10): 4037-4042.

- Rebitzer, G. and D. Hunkeler (2003). "Life cycle costing in LCM: ambitions, opportunities, and limitations." The international journal of life cycle assessment **8**(5): 253-256.
- Reich, M. C. (2005). "Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC)." Journal of Cleaner Production **13**(3): 253-263.
- Reijnders, L. and A. Van Roekel (1999). "Comprehensiveness and adequacy of tools for the environmental improvement of buildings." Journal of Cleaner Production **7**(3): 221-225.
- Reitinger, C., et al. (2011). "A conceptual framework for impact assessment within SLCA." The International Journal of Life Cycle Assessment **16**(4): 380-388.
- Ren, J., et al. (2015). "Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making." The International Journal of Life Cycle Assessment **20**(6): 842-853.
- Ren, J., et al. (2016). "Sustainability decision support framework for industrial system prioritization." AIChE Journal **62**(1): 108-130.
- Revéret, J.-P., et al. (2015). Socioeconomic LCA of milk production in Canada. Social Life Cycle Assessment, Springer: 25-69.
- Reza, B., et al. (2011). "Sustainability assessment of flooring systems in the city of Tehran: An AHP-based life cycle analysis." Construction and Building Materials **25**(4): 2053-2066.
- Richman, R., et al. (2009). "Life-cycle analysis of roofing insulation levels for cold storage buildings." Journal of Architectural Engineering **15**(2): 55-61.
- Ries, R., et al. (2006). "The economic benefits of green buildings: a comprehensive case study." The Engineering Economist **51**(3): 259-295.
- Robichaud, L. B. and V. S. Anantatmula (2010). "Greening project management practices for sustainable construction." Journal of Management in Engineering **27**(1): 48-57.
- Rogers, M. and M. Bruen (1998). "Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within ELECTRE." European Journal of Operational Research **107**(3): 542-551.
- Röös, E., et al. (2010). "Uncertainties in the carbon footprint of food products: a case study on table potatoes." The International Journal of Life Cycle Assessment **15**(5): 478-488.

Ross, S. A. and L. Cheah (2017). "Uncertainty Quantification in Life Cycle Assessments: Interindividual Variability and Sensitivity Analysis in LCA of Air-Conditioning Systems." Journal of industrial ecology **21**(5): 1103-1114.

Roy, B. (1977). "Partial preference analysis and decision-aid: the fuzzy outranking relation concept." Conflicting objectives in Decisions **1**: 40.

Roy, B. (1990). The outranking approach and the foundations of ELECTRE methods. Readings in multiple criteria decision aid, Springer: 155-183.

RSMeans (2012). RSMeans construction cost data, Construction Publishers & Consultants. Norwell, Massachusetts.

Rwelamila, P., et al. (2000). "Project procurement systems in the attainment of sustainable construction." Sustainable Development **8**(1): 39.

Sadineni, S. B., et al. (2011). "Passive building energy savings: A review of building envelope components." Renewable and Sustainable Energy Reviews **15**(8): 3617-3631.

Saiz, S., et al. (2006). "Comparative life cycle assessment of standard and green roofs." Environmental science & technology **40**(13): 4312-4316.

Saltelli, A. and P. Annoni (2010). "How to avoid a perfunctory sensitivity analysis." Environmental Modelling & Software **25**(12): 1508-1517.

Saltelli, A. and B. D'Hombres (2010). "Sensitivity analysis didn't help. A practitioner's critique of the Stern review." Global Environmental Change **20**(2): 298-302.

Saltelli, A., et al. (2008). Global sensitivity analysis: the primer, John Wiley & Sons.

Saltelli, A., et al. (2004). Sensitivity analysis in practice: a guide to assessing scientific models, John Wiley & Sons.

Sambasivan, M. and N. Y. Fei (2008). "Evaluation of critical success factors of implementation of ISO 14001 using analytic hierarchy process (AHP): a case study from Malaysia." Journal of Cleaner Production **16**(13): 1424-1433.

Sánchez-Lozano, J., et al. (2016). "Comparative TOPSIS-ELECTRE TRI methods for optimal sites for photovoltaic solar farms. Case study in Spain." Journal of Cleaner Production **127**: 387-398.

Sartori, I. and A. G. Hestnes (2007). "Energy use in the life cycle of conventional and low-energy buildings: A review article." Energy and buildings **39**(3): 249-257.

Scheuer, C., et al. (2003). "Life cycle energy and environmental performance of a new university building: modeling challenges and design implications." Energy and buildings **35**(10): 1049-1064.

Selim Jahan, et al. (2016). "Human Development Report 2016." from http://hdr.undp.org/sites/default/files/2016_human_development_report.pdf (accessed 15 October 2018).

SETAC (1993). Conceptual Framework for Life-Cycle Impact Assessment.

SETAC/UNEP (2012). Towards a Life Cycle Sustainability Assessment

Sev, A. (2009). "How can the construction industry contribute to sustainable development? A conceptual framework." Sustainable Development **17**(3): 161-173.

Shah, V. P., et al. (2008). "Life cycle assessment of residential heating and cooling systems in four regions in the United States." Energy and Buildings **40**(4): 503-513.

Shanian, A., et al. (2008). "A new application of ELECTRE III and revised Simos' procedure for group material selection under weighting uncertainty." Knowledge-Based Systems **21**(7): 709-720.

Sharma, A., et al. (2011). "Life cycle assessment of buildings: a review." Renewable and Sustainable Energy Reviews **15**(1): 871-875.

Shen, L.-y., et al. (2010). "Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice." Journal of Cleaner Production **18**(3): 254-259.

Shen, L. Y., et al. (2007). "A checklist for assessing sustainability performance of construction projects." Journal of civil engineering and management **13**(4): 273-281.

Siebert, A., et al. (2016). "Social life cycle assessment: in pursuit of a framework for assessing wood-based products from bioeconomy regions in Germany." The International Journal of Life Cycle Assessment: 1-12.

Sierra-Pérez, J., et al. (2016). "Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions." Journal of Cleaner Production **113**: 102-113.

Silva, R., et al. (2014). "Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production." Construction and Building Materials **65**: 201-217.

Simoes, A. (2017). "The Observatory of Economic Complexity." from <https://atlas.media.mit.edu/en/profile/country/sgp/> (accessed 15 October 2018).

Singapore Power (2016). "Electricity Tariff in Singapore from 2010 to 2016." from <http://www.singaporepower.com.sg/irj/go/km/docs/wpccontent/Sites/SP%20Services/Site%20Content/Tariffs/documents/Historical%20Electricity%20Tariff.pdf>.

Singh, M. K., et al. (2011). "Adaptive thermal comfort model for different climatic zones of North-East India." *Applied Energy* **88**(7): 2420-2428.

Sobol, I. M. (1993). "Sensitivity estimates for nonlinear mathematical models." *Mathematical modelling and computational experiments* **1**(4): 407-414.

Song, X., et al. (2015). "Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications." *Journal of hydrology* **523**: 739-757.

SPRING Singapore (2009). "Code of Practice for Air-Conditioning and Mechanical Ventilation in Buildings." *SPRING Singapore*.

Stanford University (2005). Guidelines for life cycle cost analysis.

Stevanović, S. (2013). "Optimization of passive solar design strategies: A review." *Renewable and Sustainable Energy Reviews* **25**: 177-196.

Strand, R. and K. Baumgartner (2005). "Modeling radiant heating and cooling systems: integration with a whole-building simulation program." *Energy and Buildings* **37**(4): 389-397.

Tan, R. B. H., et al. (2010). "LCI (Life cycle inventory) analysis of fuels and electricity generation in Singapore." *Energy* **35**(12): 4910-4916.

Tan, R. R., et al. (2007). "Fuzzy data reconciliation in reacting and non-reacting process data for life cycle inventory analysis." *Journal of Cleaner Production* **15**(10): 944-949.

Tan, Y., et al. (2011). "Sustainable construction practice and contractors' competitiveness: A preliminary study." *Habitat international* **35**(2): 225-230.

Tarantola, S., et al. (2012). "A comparison of two sampling methods for global sensitivity analysis." *Computer Physics Communications* **183**(5): 1061-1072.

Thanki, S., et al. (2016). "An investigation on lean-green implementation practices in Indian SMEs using analytical hierarchy process (AHP) approach." *Journal of Cleaner Production* **135**: 284-298.

Thormark, C. (2006). "The effect of material choice on the total energy need and recycling potential of a building." Building and Environment **41**(8): 1019-1026.

Tian, W. (2013). "A review of sensitivity analysis methods in building energy analysis." Renewable and Sustainable Energy Reviews **20**: 411-419.

Trading Economics (2016). "Singapore Prime Lending Rate." from <http://www.tradingeconomics.com/singapore/bank-lending-rate>.

Traverso, M., et al. (2012). "Towards life cycle sustainability assessment: an implementation to photovoltaic modules." The International Journal of Life Cycle Assessment **17**(8): 1068-1079.

Trusty, W. B. (2000). "Introducing an assessment tool classification system." Advanced Building Newsletter **25**(7).

Tseng, M.-L., et al. (2009). "Fuzzy AHP-based study of cleaner production implementation in Taiwan PWB manufacturer." Journal of Cleaner Production **17**(14): 1249-1256.

UNDP (2016). 2016 Human Development Report.

UNEP (2013). "Why Buildings." from <http://www.unep.org/sbci/AboutSBCI/Background.asp>.

UNEP/SETAC (2009). Guidelines for Social Life Cycle Assessment of Products.

UNICEF (2017). "Child Labour." from <https://data.unicef.org/topic/child-protection/child-labour/> (accessed 15 October 2018).

Urban Redevelopment Authority (2012). "Designing our city : Planning for a sustainable Singapore." from https://www.ura.gov.sg/skyline/skyline12/skyline12-03/special/URA_Designing%20our%20City%20Supplement_July12.pdf.

USEPA (2016). "Green Building." Retrieved March, 2018, from <https://archive.epa.gov/greenbuilding/web/html/>.

USGBC (2013). "LEED v4 for BUILDING DESIGN AND CONSTRUCTION." from https://www.usgbc.org/sites/default/files/LEED%20v4%20BDC_04.6.18_current.pdf (Accessed Jun 2018).

USGBC (2018). "LEED is green building." Retrieved March, 2018, from <https://new.usgbc.org/leed>.

USGS (2017). "Commodity Statistics and Information." from <https://minerals.usgs.gov/minerals/pubs/commodity/> (accessed 15 October 2018).

Vakili-Ardebili, A. and A. H. Boussabaine (2010). "Ecological building design determinants." Architectural Engineering and Design Management **6**(2): 111-131.

Valdes-Vasquez, R. and L. E. Klotz (2012). "Social sustainability considerations during planning and design: framework of processes for construction projects." Journal of construction engineering and management **139**(1): 80-89.

Van der Lugt, P., et al. (2006). "An environmental, economic and practical assessment of bamboo as a building material for supporting structures." Construction and Building Materials **20**(9): 648-656.

Venkatesh, A., et al. (2010). Uncertainty analysis of life cycle greenhouse gas emissions from petroleum-based fuels and impacts on low carbon fuel policies, ACS Publications.

WalkFree (2016). "The Global Slavery Index 2016." from <https://www.globalslaveryindex.org/> (accessed 10 October 2018).

Wallhagen, M. and M. Glaumann (2011). "Design consequences of differences in building assessment tools: a case study." Building Research & Information **39**(1): 16-33.

Wang, E. and Z. Shen (2013). "A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of complex system—application to the whole-building embodied energy analysis." Journal of Cleaner Production **43**: 166-173.

Wang, G., et al. (2009). "Landfill site selection using spatial information technologies and AHP: a case study in Beijing, China." Journal of environmental management **90**(8): 2414-2421.

Wang, S.-W., et al. (2016). "An analytic framework for social life cycle impact assessment—part 1: methodology." The International Journal of Life Cycle Assessment **21**(10): 1514-1528.

Wang, X. and I. H. Sloan (2008). "Low discrepancy sequences in high dimensions: How well are their projections distributed?" Journal of Computational and Applied Mathematics **213**(2): 366-386.

Wang, X., et al. (2009). "Review on thermal performance of phase change energy storage building envelope." Chinese science bulletin **54**(6): 920-928.

Wedding, G. C. and D. Crawford-Brown (2007). "An analysis of variation in the energy-related environmental impacts of LEED certified buildings." Journal of Green Building **2**(4): 151-170.

Weidema, B. P. (2006). "The integration of economic and social aspects in life cycle impact assessment." The international journal of life cycle assessment **11**(1): 89-96.

Weidema, B. P., et al. (2013). "Overview and methodology: Data quality guideline for the ecoinvent database version 3."

Weidema, B. P., et al. (2013). Overview and methodology: Data quality guideline for the ecoinvent database version 3, Swiss Centre for Life Cycle Inventories.

Wen, Z., et al. (2016). "Best available techniques assessment for coal gasification to promote cleaner production based on the ELECTRE-II method." Journal of Cleaner Production **129**: 12-22.

WHO (2015). "Global Health Estimates 2015: Disease burden by Cause, Age, Sex, by Country and by Region, 2000-2015." from http://www.who.int/healthinfo/global_burden_disease/estimates/en/index2.html (accessed 15 October 2018).

Williams, E. D., et al. (2009). "Hybrid framework for managing uncertainty in life cycle inventories." Journal of industrial ecology **13**(6): 928-944.

Wong, K.-d. and Q. Fan (2013). "Building information modelling (BIM) for sustainable building design." Facilities **31**(3/4): 138-157.

Wong, N. H., et al. (2003). "Life cycle cost analysis of rooftop gardens in Singapore." Building and Environment **38**(3): 499-509.

WorldBank (2016). "World Bank Open Data." from <https://data.worldbank.org/indicator?tab=all> (accessed 15 October 2018).

WorldBank (2017). "Doing Business: Measuring Business Regulations." from <http://www.doingbusiness.org/data/exploretopics/dealing-with-construction-permits> (accessed 15 October 2018).

Worldsteel (2018). "Steel and raw materials." from https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact_raw+materials_2018.pdf (accessed 15 October 2018).

WSH (2016). "Workplace Safety and Health Report ". from [https://www.wsh-institute.sg/files/wshi/upload/cms/file/Workplace%20Safety%20and%20Health%20Report%202016%20\(January%20-%20June\)2309.pdf](https://www.wsh-institute.sg/files/wshi/upload/cms/file/Workplace%20Safety%20and%20Health%20Report%202016%20(January%20-%20June)2309.pdf). Assessed Aug. 2017.

Wu, P. and S. P. Low (2010). "Project management and green buildings: lessons from the rating systems." Journal of Professional Issues in Engineering Education and Practice **136**(2): 64-70.

Wu, S.-H. (2017). Use BIM and Prefabrication to Reduce Construction Waste.

Ximenes, F. A. and T. Grant (2013). "Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia." The international journal of life cycle assessment **18**(4): 891-908.

Yi, S., et al. (2011). "Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches." The International Journal of Life Cycle Assessment **16**(7): 652-668.

Yu, B., et al. (2018). "Data quality and uncertainty assessment methodology for pavement LCA." International Journal of Pavement Engineering **19**(6): 519-525.

Yudelson, J. (2010). The green building revolution, Island Press.

YUN, Z. (2013). Decision support system for the selection of structural frame material to achieve sustainability and constructability.

Yunus, R. and J. Yang (2011). "Sustainability criteria for industrialised building systems (IBS) in Malaysia." Procedia Engineering **14**: 1590-1598.

Zadeh, L. A. (1965). "Fuzzy sets." Information and control **8**(3): 338-353.

Zhang, X., et al. (2015). "Embedding "green" in project-based organizations: the way ahead in the construction industry?" Journal of Cleaner Production **107**: 420-427.

Zuo, J., et al. (2017). "Green building evaluation from a life-cycle perspective in Australia: A critical review." Renewable and Sustainable Energy Reviews **70**: 358-368.

Zuo, J. and Z.-Y. Zhao (2014). "Green building research—current status and future agenda: A review." Renewable and Sustainable Energy Reviews **30**: 271-281.

APPENDIX

Appendix A Sample of Questionnaire

Questionnaire Survey on Social Impact Assessment of Building Project in the Singapore Construction Industry

Background of the Survey

This questionnaire survey forms part of my PhD study which aims to develop a model to evaluate the social performance of a building project throughout the building's life span which includes preparation of the building materials (including extraction of raw materials as well as production and manufacturing of building products), transportation, construction process, and operation and maintenance (O&M) in my study.

The objective to carry out this questionnaire survey is to collect your opinion on the importance of different factors to achieve social sustainability of building projects. These factors are firstly divided into four main stakeholder categories, including workers' well-being, occupants' well-being, local community' well-being, and society's development. Under each main category, there are several sub-categories. You are supposed to pair-wisely compare these (sub)categories based on your industrial experience in Singapore. Detailed explanation of these (sub)categories can be found in the appendix of this questionnaire.

It will require approximately 30 minutes completing the questionnaire. All the answers will be treated in absolute confidence and used for academic purposes only.

Please note:

- The comparison is based on the context of Singapore, and it is neither for a single life-cycle process, nor for a single type of building project; it is supposed to be based on the comprehensive and general consideration.
- Factors are repeated in the questionnaire due to the pair-wise comparison. It uses a special seven points scale and please read the examples given in the questionnaire.

If you require additional information or have any questions, please contact me by the contact details stated below.

We appreciate your valuable time to complete the questionnaire. Without your kind and expert input, the research objectives aimed at improving sustainability implementation cannot be realized. To this end, we would like to thank you very much for your valued and kind consideration. Please return the completed questionnaire to:

Siyu LIU, PhD Candidate

E-mail: sliu018@e.ntu.edu.sg

School of Civil and Environmental Engineering, Nanyang Technological University
N1-B04b-05, 50 Nanyang Avenue, Singapore 639798

Section A Respondent Details

1. Industry stakeholder in which you are representing:

☐ Government agency	☐ Supplier/Manufacturer
☐ Private developer	☐ Academic
☐ Designer	☐ Sustainability Consultant
☐ Contractor	☐ Others (Please specify: _____)

2. Years of working experience in the construction industry or relevant field (please specify: Click here to enter text.)

☐ <5 years	☐ 16-20 years
☐ 5-10 years	☐ >20 years
☐ 11-15 years	

3. If you are willing to participate in our following survey, please leave your email or other contact information here: Click here to enter text.

Section B Pair-wise comparison of criteria regarding achieving social sustainability of building projects

Introduction of pair-wise comparison and Example

Please compare in pairs the relative importance between two given statements (A and B) regarding social evaluation of building projects.

Here are some examples. Example 1 shows A is strongly more important than B and Example 2 shows B is slightly more important than A. If the given level cannot precisely describe your opinion, you can also mark at the position between two levels, as shown in Example 3.

		Abso.		Strong		Slight		Equally		Slight		Strong		Abso.	
Example 1	A	☐	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	B
Example 2	A	☐	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐	B
Example 3	A	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	B

The notations of relative importance are following:

- Abso. – Absolutely more important
 Strong – Strongly more important
 Slight – Slightly more important
 Equally – Equally important

Please Note: Detailed explanation of these (sub)categories can be found in the appendix of this questionnaire.

	(Sub)Categories	Abso.		Strong		Slight		Equally		Slight		Strong		Abso.	(Sub)Categories
[1] Stakeholder Categories	Workers' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Occupants' Well-being
	Occupants' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local Community's Well-being
	Local Community's Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Development of Industry/ Society
[2.1] Sub-category Workers' Well-being	Health and safety of workers	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fair Salary
	Fair Salary	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working Hours
	Working Hours	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Discrimination
	Discrimination	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Forced Labour
	Forced Labour	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child Labour
[2.2] Sub-category occupants' Well-being	Functionality and Usability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Health and Comfort
	Health and Comfort	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Accessibility
	Accessibility	☐	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐	Feedback Mechanism
[2.3] Sub-category Local Community's Well-being	Safety and Health	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Accessibility
	Accessibility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Integration and Interaction
	Integration and Interaction	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local Employment
[2.4] Sub-category Development of Industry/ Society	Technology development	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Public commitments to sustainability issues

Section C Importance of living condition-related aspects for health and comfort of occupants

There are many aspects for achieving healthy and comfortable living condition of occupants. Please score the importance of the following statements. If you think there are any other aspects that should be considered, please indicate them and give scores.

- 1 -- Unimportant
- 2 -- Of Little Importance
- 3 -- Moderately Important
- 4 -- Important
- 5 -- Very Important

Statements	Scores				
	1	2	3	4	5
Indoor air quality	☐	☐	☐	☐	☐
Usage of construction material, furniture and equipment (should be properly tested and certified and should be not harmful to the residents)	☐	☐	☐	☐	☐
Thermal comfort	☐	☐	☐	☐	☐
Acoustic comfort	☐	☐	☐	☐	☐
Visual comfort	☐	☐	☐	☐	☐
Provide necessary facilities surrounding the building, such as outdoor transitory structure and lighting.	☐	☐	☐	☐	☐
Others (Please specific)					
1.					
2.					
3.					
4.					
5.					

– This is the end of the survey –

Please kindly send the file back to sliu018@e.ntu.edu.sg

Thank you very much for your time!

Appendix B Raw Data from Questionnaire Survey

	Response	Worker--> Occupant	Occupant --> Local Community	Local --> Society or Industry	Health & Safety --> Fair Salary	Fair Salary--> Working Hours
1	Private Developer	3.00	4.00	5.00	1.00	5.00
2	Government Agency	0.20	5.00	0.33	1.00	1.00
3	contractor	3.00	5.00	5.00	3.00	2.00
4	contractor	0.33	0.50	0.50	3.00	4.00
5	Government Agency	0.25	1.00	4.00	0.50	5.00
6	Government Agency	1.00	1.00	1.00	3.00	0.33
7	Government Agency	1.00	1.00	1.00	3.00	5.00
8	contractor	0.33	3.00	0.50	1.00	1.00
9	contractor	3.00	7.00	5.00	0.50	5.00
10	Supervisor	1.00	0.33	3.00	0.33	1.00
11	Government Agency	3.00	0.50	0.50	1.00	5.00
12	contractor	5.00	3.00	5.00	3.00	3.00
13	contractor	5.00	5.00	5.00	1.00	4.00
14	Designer/Engineer	1.00	0.33	0.33	1.00	0.50
15	Designer/Engineer	1.00	0.33	1.00	0.50	5.00
16	Supplier/Manufacturer	1.00	0.33	0.50	5.00	5.00
17	Designer/Engineer	1.00	1.00	0.33	2.00	0.25
18	contractor	2.00	0.50	0.33	1.00	5.00
19	Supervisor	1.00	5.00	3.00	2.00	5.00
20	Government Agency	1.00	0.33	3.00	1.00	0.20
21	contractor	0.20	0.50	5.00	1.00	1.00
22	Sustainability Consultan	3.00	0.33	0.33	3.00	3.00
23	Government Agency	0.20	3.00	3.00	1.00	5.00
24	other (Consultant)	1.00	0.33	3.00	0.33	3.00
25	Private Developer	1.00	2.00	0.33	1.00	1.00
26	Government Agency	1.00	1.00	3.00	3.00	5.00
27	contractor	5.00	1.00	0.20	1.00	5.00
28	contractor	1.00	1.00	1.00	1.00	1.00
29	Government Agency	0.20	3.00	3.00	0.50	2.00
30	Government Agency	0.17	1.00	4.00	1.00	2.00
31	contractor	4.00	0.50	0.50	3.00	0.33
32	Supplier/Manufacturer	0.33	2.00	0.33	1.00	3.00
33	contractor	3.00	0.50	1.00	1.00	2.00
34	Supplier/Manufacturer	1.00	3.00	5.00	1.00	3.00
35	Government Agency	0.50	3.00	1.00	1.00	1.00
36	contractor	0.17	2.00	1.00	1.00	3.00
37	Supervisor	1.00	1.00	0.50	0.50	2.00
38	Private Developer	1.00	0.50	1.00	0.50	0.20
39	Private Developer	3.00	3.00	1.00	4.00	0.50
40	Supervisor	0.33	5.00	1.00	1.00	0.33
41	Sustainability Consultan	4.00	0.25	1.00	1.00	4.00
42	Designer/Engineer	0.20	3.00	2.00	0.33	3.00
43	Government Agency	3.00	3.00	3.00	3.00	1.00
44	contractor	1.00	1.00	1.00	1.00	1.00
45	Government Agency	1.00	1.00	1.00	3.00	1.00
46	Sustainability Consultan	2.00	4.00	0.50	1.00	0.33
47	Sustainability Consultan	1.00	1.00	3.00	1.00	1.00
48	Academic	0.50	1.00	3.00	0.50	1.00
49	Supervisor	0.17	2.00	3.00	1.00	1.00

	Response	Working Hours--> Discrimination	Discrimination --> Forced Labor	Forced Labor-- > Child Labor	Functionality -- > Health	Health --> Accessibility
1	Private Developer	3.00	3.00	1.00	1.00	5.00
2	Government Agency	1.00	2.00	1.00	1.00	1.00
3	contractor	5.00	3.00	1.00	1.00	2.00
4	contractor	0.33	4.00	2.00	1.00	4.00
5	Government Agency	5.00	5.00	2.00	1.00	5.00
6	Government Agency	0.33	1.00	3.00	2.00	1.00
7	Government Agency	0.33	3.00	0.50	1.00	5.00
8	contractor	3.00	1.00	0.20	1.00	1.00
9	contractor	1.00	5.00	1.00	1.00	5.00
10	Supervisor	0.20	1.00	2.00	1.00	1.00
11	Government Agency	1.00	5.00	3.00	1.00	5.00
12	contractor	1.00	5.00	1.00	1.00	3.00
13	contractor	0.25	4.00	0.33	1.00	4.00
14	Designer/Engineer	0.33	1.00	0.50	1.00	1.00
15	Designer/Engineer	0.25	5.00	0.25	1.00	5.00
16	Supplier/Manufacturer	0.14	5.00	1.00	1.00	5.00
17	Designer/Engineer	3.00	1.00	1.00	1.00	1.00
18	contractor	0.20	5.00	2.00	1.00	5.00
19	Supervisor	3.00	5.00	1.00	1.00	5.00
20	Government Agency	3.00	1.00	0.20	1.00	1.00
21	contractor	3.00	1.00	1.00	1.00	1.00
22	Sustainability Consultant	2.00	3.00	0.50	1.00	3.00
23	Government Agency	1.00	5.00	1.00	1.00	5.00
24	other (Consultant)	4.00	2.00	1.00	1.00	3.00
25	Private Developer	3.00	5.00	1.00	1.00	1.00
26	Government Agency	0.33	5.00	2.00	1.00	5.00
27	contractor	3.00	5.00	1.00	1.00	5.00
28	contractor	2.00	2.00	1.00	1.00	1.00
29	Government Agency	1.00	1.00	0.33	1.00	2.00
30	Government Agency	0.50	4.00	1.00	1.00	2.00
31	contractor	1.00	1.00	3.00	1.00	2.00
32	Supplier/Manufacturer	5.00	5.00	3.00	1.00	3.00
33	contractor	0.33	1.00	2.00	1.00	2.00
34	Supplier/Manufacturer	2.00	3.00	1.00	1.00	3.00
35	Government Agency	3.00	4.00	0.33	1.00	1.00
36	contractor	1.00	1.00	2.00	1.00	3.00
37	Supervisor	1.00	1.00	2.00	1.00	2.00
38	Private Developer	1.00	1.00	1.00	1.00	1.00
39	Private Developer	1.00	3.00	5.00	1.00	3.00
40	Supervisor	1.00	3.00	2.00	1.00	5.00
41	Sustainability Consultant	1.00	5.00	1.00	1.00	4.00
42	Designer/Engineer	3.00	2.00	2.00	1.00	3.00
43	Government Agency	3.00	5.00	1.00	1.00	1.00
44	contractor	0.33	3.00	3.00	1.00	1.00
45	Government Agency	1.00	4.00	1.00	1.00	1.00
46	Sustainability Consultant	0.50	2.00	3.00	1.00	3.00
47	Sustainability Consultant	0.33	5.00	1.00	1.00	1.00
48	Academic	1.00	2.00	1.00	2.00	1.00
49	Supervisor	2.00	2.00	3.00	1.00	1.00

	Response	Accessibility--> feedback	Health --> Accessibility	Accessibility--> Interaction	Interaction--> Local Employment	Tech-->Public Commitment
1	Private Developer	3.00	2.00	0.25	0.33	2.00
2	Government Agency	1.00	3.00	1.00	0.33	3.00
3	contractor	3.00	3.00	2.00	0.50	3.00
4	contractor	1.00	5.00	0.50	0.33	1.00
5	Government Agency	1.00	2.00	0.33	0.50	2.00
6	Government Agency	1.00	2.00	1.00	0.50	2.00
7	Government Agency	1.00	3.00	0.33	0.50	3.00
8	contractor	3.00	3.00	1.00	0.50	3.00
9	contractor	1.00	2.00	0.33	0.50	2.00
10	Supervisor	0.50	5.00	1.00	0.20	1.00
11	Government Agency	1.00	3.00	0.33	0.33	3.00
12	contractor	1.00	5.00	3.00	0.50	5.00
13	contractor	2.00	3.00	0.20	0.50	3.00
14	Designer/Engineer	3.00	3.00	1.00	0.20	3.00
15	Designer/Engineer	1.00	3.00	2.00	0.33	3.00
16	Supplier/Manufacturer	1.00	3.00	0.50	0.20	3.00
17	Designer/Engineer	1.00	2.00	1.00	0.50	2.00
18	contractor	1.00	3.00	1.00	0.50	3.00
19	Supervisor	3.00	3.00	0.50	0.33	3.00
20	Government Agency	3.00	5.00	1.00	0.33	5.00
21	contractor	3.00	3.00	1.00	0.50	3.00
22	Sustainability Consultant	2.00	3.00	3.00	0.33	3.00
23	Government Agency	1.00	3.00	0.20	0.50	3.00
24	other (Consultant)	2.00	5.00	3.00	0.50	5.00
25	Private Developer	3.00	3.00	1.00	0.50	3.00
26	Government Agency	1.00	2.00	1.00	0.33	3.00
27	contractor	3.00	3.00	1.00	0.33	3.00
28	contractor	2.00	3.00	1.00	0.33	3.00
29	Government Agency	1.00	3.00	2.00	0.50	3.00
30	Government Agency	0.50	3.00	2.00	0.20	3.00
31	contractor	1.00	3.00	2.00	0.33	3.00
32	Supplier/Manufacturer	5.00	3.00	3.00	0.50	3.00
33	contractor	0.33	2.00	2.00	0.50	2.00
34	Supplier/Manufacturer	2.00	2.00	3.00	0.50	2.00
35	Government Agency	3.00	2.00	1.00	0.33	2.00
36	contractor	1.00	3.00	3.00	0.50	3.00
37	Supervisor	1.00	3.00	2.00	0.50	3.00
38	Private Developer	1.00	3.00	1.00	0.20	3.00
39	Private Developer	1.00	5.00	0.33	0.50	5.00
40	Supervisor	1.00	2.00	4.00	0.33	2.00
41	Sustainability Consultant	1.00	5.00	3.00	0.50	5.00
42	Designer/Engineer	2.00	3.00	1.00	0.50	3.00
43	Government Agency	3.00	3.00	1.00	0.50	3.00
44	contractor	1.00	3.00	1.00	1.00	3.00
45	Government Agency	1.00	3.00	3.00	0.50	3.00
46	Sustainability Consultant	2.00	2.00	3.00	0.50	2.00
47	Sustainability Consultant	1.00	2.00	1.00	0.50	2.00
48	Academic	1.00	2.00	2.00	0.50	2.00
49	Supervisor	2.00	1.00	1.00	0.50	1.00

	Response	Worker--> Occupant	Occupant --> Local Community	Local --> Society or Industry	Health & Safety --> Fair Salary	Fair Salary--> Working Hours
50	contractor	3.00	2.00	5.00	3.00	1.00
51	Supervisor	1.00	1.00	2.00	3.00	1.00
52	Private Developer	1.00	3.00	3.00	3.00	1.00
53	Private Developer	2.00	1.00	2.00	1.00	1.00
54	Supplier/Manufacturer	2.00	2.00	3.00	1.00	1.00
55	Government Agency	0.25	1.00	1.00	1.00	0.33
56	Designer/Engineer	2.00	1.00	1.00	0.33	4.00
57	Government Agency	2.00	3.00	1.00	2.00	0.33
58	contractor	0.20	3.00	1.00	1.00	0.50
59	Academic	3.00	3.00	0.50	0.50	3.00
60	Academic	3.00	1.00	1.00	1.00	1.00
61	contractor	0.33	2.00	2.00	2.00	3.00
62	Academic	1.00	1.00	1.00	1.00	2.00
63	Designer/Engineer	0.50	3.00	2.00	1.00	0.33
64	Supervisor	0.33	1.00	3.00	2.00	3.00
65	Government Agency	1.00	4.00	3.00	1.00	2.00
66	Supplier/Manufacturer	2.00	0.25	1.00	2.00	3.00
67	Supervisor	0.50	0.50	1.00	3.00	3.00
68	Academic	0.50	0.50	2.00	1.00	1.00
69	Supplier/Manufacturer	4.00	0.33	3.00	2.00	1.00
70	Academic	2.00	3.00	5.00	1.00	4.00
71	Designer/Engineer	3.00	3.00	1.00	0.33	3.00
72	contractor	0.33	1.00	1.00	1.00	1.00
73	contractor	3.00	1.00	1.00	1.00	0.33
74	others	0.33	3.00	0.50	3.00	3.00
75	Private Developer	4.00	1.00	6.00	1.00	3.00
76	others	0.25	0.50	3.00	1.00	3.00
77	Designer/Engineer	0.20	1.00	2.00	1.00	1.00
78	Academic	2.00	0.50	3.00	1.00	1.00
79	Supervisor	2.00	5.00	2.00	3.00	1.00
80	Sustainability Consultan	1.00	3.00	0.33	1.00	1.00
81	Designer/Engineer	2.00	1.00	1.00	2.00	3.00
82	Academic	2.00	3.00	1.00	2.00	1.00
83	Sustainability Consultan	1.00	3.00	4.00	1.00	3.00
84	Private Developer	0.20	1.00	1.00	0.33	3.00
85	Supervisor	0.33	1.00	1.00	3.00	3.00
86	Supplier/Manufacturer	4.00	3.00	3.00	2.00	0.33
87	contractor	0.25	1.00	1.00	2.00	3.00
88	Academic	3.00	1.00	1.00	1.00	2.00
89	Academic	3.00	1.00	1.00	3.00	1.00
90	Supervisor	0.50	3.00	3.00	2.00	5.00
91	Academic	0.50	2.00	0.50	3.00	3.00
92	Sustainability Consultan	1.00	2.00	1.00	4.00	2.00
93	Sustainability Consultan	0.50	0.50	3.00	3.00	1.00
94	Designer/Engineer	1.00	2.00	1.00	1.00	1.00
95	Designer/Engineer	1.00	3.00	1.00	1.00	3.00
96	Academic	1.00	3.00	1.00	1.00	1.00
97	Private Developer	1.00	2.00	2.00	0.50	0.50
98	Government Agency	0.50	1.00	2.00	3.00	3.00
99	Supervisor	0.25	1.00	0.50	0.50	1.00
100	Designer/Engineer	0.50	4.00	1.00	1.00	2.00
101	Supplier/Manufacturer	0.20	1.00	1.00	1.00	4.00
102	Private Developer	0.50	1.00	3.00	0.50	5.00
103	Supervisor	1.00	1.00	1.00	1.00	2.00

	Response	Working Hours--> Discrimination	Discrimination --> Forced Labor	Forced Labor--> Child Labor	Functionality --> Health	Health --> Accessibility
50	contractor	0.33	4.00	1.00	1.00	1.00
51	Supervisor	0.33	3.00	1.00	1.00	3.00
52	Private Developer	2.00	1.00	1.00	1.00	1.00
53	Private Developer	1.00	3.00	1.00	1.00	1.00
54	Supplier/Manufacturer	0.33	1.00	0.50	1.00	1.00
55	Government Agency	1.00	4.00	1.00	1.00	1.00
56	Designer/Engineer	2.00	1.00	1.00	1.00	4.00
57	Government Agency	1.00	1.00	3.00	1.00	2.00
58	contractor	1.00	5.00	3.00	1.00	3.00
59	Academic	2.00	3.00	1.00	3.00	3.00
60	Academic	1.00	2.00	1.00	2.00	1.00
61	contractor	0.33	3.00	2.00	1.00	3.00
62	Academic	1.00	3.00	1.00	1.00	2.00
63	Designer/Engineer	1.00	3.00	2.00	1.00	2.00
64	Supervisor	5.00	1.00	1.00	1.00	3.00
65	Government Agency	0.50	3.00	3.00	1.00	2.00
66	Supplier/Manufacturer	3.00	2.00	1.00	1.00	3.00
67	Supervisor	3.00	1.00	0.33	1.00	3.00
68	Academic	3.00	1.00	0.50	1.00	1.00
69	Supplier/Manufacturer	3.00	1.00	3.00	1.00	1.00
70	Academic	2.00	5.00	1.00	1.00	4.00
71	Designer/Engineer	3.00	3.00	1.00	1.00	3.00
72	contractor	0.33	1.00	1.00	1.00	1.00
73	contractor	0.33	1.00	1.00	1.00	1.00
74	others	3.00	2.00	1.00	1.00	3.00
75	Private Developer	1.00	3.00	0.33	1.00	3.00
76	others	1.00	1.00	1.00	1.00	3.00
77	Designer/Engineer	1.00	3.00	3.00	1.00	1.00
78	Academic	1.00	2.00	1.00	1.00	3.00
79	Supervisor	0.50	2.00	1.00	1.00	1.00
80	Sustainability Consultan	3.00	3.00	2.00	1.00	1.00
81	Designer/Engineer	1.00	3.00	1.00	1.00	3.00
82	Academic	1.00	3.00	3.00	1.00	1.00
83	Sustainability Consultan	1.00	3.00	1.00	1.00	3.00
84	Private Developer	2.00	3.00	3.00	1.00	3.00
85	Supervisor	1.00	2.00	3.00	1.00	3.00
86	Supplier/Manufacturer	2.00	3.00	3.00	1.00	1.00
87	contractor	1.00	1.00	1.00	1.00	3.00
88	Academic	2.00	2.00	1.00	1.00	2.00
89	Academic	0.50	3.00	1.00	1.00	1.00
90	Supervisor	1.00	1.00	2.00	1.00	5.00
91	Academic	1.00	2.00	3.00	1.00	3.00
92	Sustainability Consultan	1.00	5.00	1.00	1.00	2.00
93	Sustainability Consultan	1.00	3.00	1.00	1.00	1.00
94	Designer/Engineer	1.00	3.00	1.00	1.00	1.00
95	Designer/Engineer	1.00	3.00	2.00	1.00	3.00
96	Academic	1.00	5.00	1.00	1.00	2.00
97	Private Developer	1.00	3.00	1.00	1.00	1.00
98	Government Agency	1.00	3.00	1.00	1.00	3.00
99	Supervisor	1.00	5.00	1.00	1.00	1.00
100	Designer/Engineer	3.00	3.00	2.00	2.00	2.00
101	Supplier/Manufacturer	2.00	5.00	1.00	1.00	4.00
102	Private Developer	3.00	4.00	2.00	1.00	3.00
103	Supervisor	1.00	3.00	1.00	1.00	2.00

	Response	Accessibility--> feedback	Health --> Accessibility	Accessibility--> Interaction	Interaction--> Loca Employment	Tech-->Public Commitment
50	contractor	1.00	3.00	1.00	0.50	3.00
51	Supervisor	1.00	5.00	2.00	0.33	1.00
52	Private Developer	2.00	3.00	1.00	0.33	3.00
53	Private Developer	1.00	5.00	2.00	0.20	1.00
54	Supplier/Manufacturer	1.00	3.00	3.00	0.50	3.00
55	Government Agency	1.00	2.00	1.00	0.33	2.00
56	Designer/Engineer	2.00	3.00	2.00	0.20	3.00
57	Government Agency	3.00	6.00	1.00	0.25	1.00
58	contractor	1.00	4.00	1.00	0.50	4.00
59	Academic	3.00	3.00	2.00	0.14	3.00
60	Academic	3.00	7.00	1.00	0.50	2.00
61	contractor	1.00	5.00	1.00	0.33	5.00
62	Academic	3.00	5.00	1.00	0.50	0.50
63	Designer/Engineer	1.00	2.00	1.00	0.50	2.00
64	Supervisor	1.00	2.00	3.00	0.50	2.00
65	Government Agency	1.00	3.00	1.00	0.33	3.00
66	Supplier/Manufacturer	1.00	3.00	1.00	0.33	3.00
67	Supervisor	3.00	4.00	3.00	0.33	4.00
68	Academic	1.00	3.00	1.00	0.50	0.33
69	Supplier/Manufacturer	3.00	3.00	1.00	0.33	3.00
70	Academic	2.00	3.00	1.00	0.50	3.00
71	Designer/Engineer	3.00	3.00	1.00	0.50	3.00
72	contractor	1.00	3.00	1.00	0.50	3.00
73	contractor	3.00	3.00	1.00	0.50	3.00
74	others	1.00	3.00	1.00	0.50	3.00
75	Private Developer	1.00	3.00	0.33	0.20	3.00
76	others	1.00	3.00	1.00	0.50	3.00
77	Designer/Engineer	1.00	2.00	1.00	0.33	1.00
78	Academic	1.00	3.00	1.00	0.50	3.00
79	Supervisor	1.00	5.00	3.00	0.33	2.00
80	Sustainability Consultan	1.00	3.00	1.00	0.33	3.00
81	Designer/Engineer	1.00	5.00	1.00	0.33	5.00
82	Academic	1.00	4.00	1.00	0.33	4.00
83	Sustainability Consultan	1.00	1.00	0.33	0.33	1.00
84	Private Developer	1.00	4.00	1.00	0.50	0.50
85	Supervisor	1.00	2.00	1.00	0.50	2.00
86	Supplier/Manufacturer	1.00	3.00	1.00	0.50	3.00
87	contractor	1.00	4.00	3.00	0.50	4.00
88	Academic	1.00	3.00	1.00	0.50	3.00
89	Academic	1.00	3.00	1.00	0.50	3.00
90	Supervisor	1.00	4.00	0.50	0.50	4.00
91	Academic	1.00	5.00	3.00	0.50	1.00
92	Sustainability Consultan	3.00	3.00	2.00	0.50	3.00
93	Sustainability Consultan	1.00	3.00	1.00	0.17	3.00
94	Designer/Engineer	1.00	3.00	1.00	0.50	3.00
95	Designer/Engineer	1.00	4.00	3.00	0.50	1.00
96	Academic	1.00	3.00	2.00	0.50	3.00
97	Private Developer	1.00	2.00	1.00	0.50	2.00
98	Government Agency	1.00	5.00	3.00	0.25	2.00
99	Supervisor	1.00	1.00	1.00	0.50	1.00
100	Designer/Engineer	1.00	2.00	2.00	0.33	2.00
101	Supplier/Manufacturer	0.50	3.00	0.33	0.50	3.00
102	Private Developer	1.00	2.00	3.00	0.50	2.00
103	Supervisor	1.00	3.00	2.00	0.50	3.00

Appendix C Data Collection for Case Study on PPVC project

Overview of PPVC Project

C1 Summary of PPVC Layout

Room Type	Structural Type	Length (mm)	Width (mm)	Quantity
Apartment bedroom (Senior Hall Fellow)	8A	4170	3350	4
Apartment bedroom with ledge (Hall Fellow)	8	4170	3350	12
Single Bedroom with Corridor	6	4875 - 4900	2900	116
Single Bedroom and corridor	13	5784	2900	10
Single Bedroom and Corridor with planter	10B	8305	3350	6
Two Single Bedroom separated by corridor	1	8150	2900	44
Single Bedroom and part of Double bedroom separated by corridor	7	8150	2900	35
Part of Double Bedroom and corridor with planter	7B	8150	2900	5
Single Bedroom and Corridor with planter	9A	8585	2900	11
Single Bedroom and Corridor with AC ledge	9B	8585	2900	4
Single Bedroom and Corridor with AC ledge	11A-1/11B	9200	3350	6
Two Single Bedroom separated by middle corridor	2/3B	9160	2900	69
Single Bedroom and Super Single Bedroom separated by corridor	4A-1/4C-4-2/4C-3	9200	3350	10
Super Single bedroom and Breakout space	4C-3-1	9200	3350	1
Single Bedroom and Breakout Space	4C-4/4C-4-1	9200	3350	6
Breakout Space and Corridor with riser	4D-3	9200	3350	1
Single Bedroom and Corridor with riser	4D-2	9200	3350	5
Breakout space and corridor	10B-1	8305	3350	1
Single Bedroom and part of Apartment unit separated by corridor	4C-2/4C-5/4C-6	9200	3350	16
Double Bedroom and corridor	10A	9205	3350	4
Double Bedroom and corridor	11A	10030	3350	5
Double Bedroom and Single Bedroom separated by middle corridor	4A/4C-1	10100	3350	190
Double Bedroom and Breakout space separated by corridor	4A-2 / 4A-3/4C-1-1 /4C-1-2	10100	3350	12
Double Bedroom and Corridor	4D-1	10100	3350	5
Lounge area and Corridor	6D	6430	2900	4
Dining and Corridor	9B-1	10117	2900	4
Breakout Space and lounge separated by corridor	4B-1/4B-3/4B-4	10700	3350	4
Single Bedroom and Lounge /dining separated by corridor	4B-2 / 4B-5	10700	3350	12
Single Bedroom with toilet	5	10700	3350	66
Single Bedroom and Lounge/ Dining separated by Corridor	3A	10760	2900	8
Corridor (Triangular Linkway)	12	-	-	41
Total Modules				717

C1-1 Type 1

C1-2 Type 2

C1-3 Type 3

230

231

C1-6 Type 6

C1-7 Type 7

C1-8 Type 8

C1-9 Type 9

236

237

238

239

C1-14 Example on Calculation of Material Composite of PPVC Module

(1) Steel Structure

NTU 2 HOSTEL - 1 Blk of 11 Storey & 3 Blks of 13 Storey Weight of Module PPVC - 4A (3-1301,1314)							
	Member Size	Unit Weight, kg/m	Length, m	Width, m	Qty, nr	Sub-Total Weight, km	Total Weight, kg
	Structural Steel						5934.92
FB1	160 X 80 X 6.3 RHS	22.3	3.200		5	356.8	
FB2	160 X 80 X 8 RHS	27.9	10.670		2	595.39	
						0	
FPL2	150 X 65 X 4 Plain Channel	8.38	3.250		4	108.94	
						0	
						0	
						0	
FPL1	125 X 50 X 20 X 2.3 LIP Channel	4.51	3.250		4	58.63	
		4.51	3.250		15	219.86	
		4.51	1.750		11	86.82	
		4.51	3.250		9	131.92	
FPL5	100 X 50 X 4 Plain Channel	5.87	3.032		4	71.19	
RB1	300 X 100 X 8 RHS (ROOF)	48	3.200		6	921.6	
		48	10.160		2	975.36	
		48			5	0	
RB6	120 X 80 X 5 RHS (ROOF)	14.8	3.250		1	48.1	
		14.8	0.765		2	22.64	
RPL1	125 X 50 X 20 X 4 thk LC @ 305 c/c	7.5	0.750		11	61.88	
		7.5	0.860		11	70.95	
		7.5	3.250		15	365.63	
		7.5	1.750		11	144.38	
		7.5	3.250		9	219.38	
RPL3	75 X 45 X 15 X 2.3 thk LC @ 305 c/c	3.24	3.250		3	31.59	
		3.24	3.250		4	42.12	
WB1	80 X 80 X 3 SHS	7.18	3.250		2	46.67	
WB2	81 X 80 X 3 SHS					0	
	452mm width Grating	25.10				0	
	Columns						
MC4*	200 X 100 X 8 RHS	35.4	3.314		6	703.89	
ST1	80 X 80 X 3 SHS	7.18	3.032		2	43.54	
ST2	80 X 80 X 5 SHS	11.7	3.032		4	141.9	
		11.7	3.142		2	73.52	
	Plates	kg/m3					
TR2	200 X 3mm thk plate	7850	5.370		4	101.17	
TR2	200 X 3mm thk plate	7850	4.000		4	75.36	
TR2	200 X 3mm thk plate	7850	3.000		4	56.52	
TR1	200 X 3mm thk plate	7850	5.560		2	52.38	
TR1	200 X 3mm thk plate	7850	4.257		2	40.1	
TR1	200 X 3mm thk plate	7850	3.389		2	31.92	
TR1	200 X 3mm thk plate	7850	3.691		2	34.77	
2	Roof, Floor and Wall Plate	kg/m3					2381.38
Roof	3mm thk Flat Steel Roofing Plate	7850	10.750	3.250	1	822.78	
Roof	1mm thk galv Flat Sheet (Roof)	9500	0.820	3.250	1	25.32	
Wall	1mm thk Profile Wall Plate (Horizontal)	11147	5.460	3.032	2	269.07	
		11147	2.750	3.032	2	185.89	
Wall	1mm thk Profile Wall Plate (Vertical)	11147	3.250	1.082	4	156.79	
Floor	1mm thk galv Steel Floor Sheet	7850	11.525	3.250	1	294.03	
	1.6mm thk Aluminium Perforated Grating Sheet	7850	0.700	3.250	2	57.15	
		kg/m2					
	4mm thk Aluminium Cladding	10.80	12.220	3.032	1	400.15	
	4mm thk Aluminium Cladding	10.80	3.250	1.000	2	70.20	
	Total Weight (kg)						8316.3

(2) Promat Board, Rockwool & Tiles

NTU 2 HOSTEL - 1 Blk of 11 Storey & 3 Blks of 13 Storey Weight of Module PPVC - 4A (3-1301,1314)									
	Member Size	Unit Weight, kg/m3	Thick, mm	Length, m	Height/Width, m	Layer Board, nr	Qty, nr	Sub-Total Weight, km	Total Weight, kg
1	Promated Board								4121.2
	Promat System Ceiling	1200	18	12.455	3.250	1	1	874.34	
	Promat System Floor	1200	18	10.755	3.250	1	1	756.41	
	Promat Underlayment	1200	12	10.755	3.250	1	1	504.27	
	Promat Wall (Internal)	1200	15	2.750	3.032	1	1	150.08	
	Promat Wall (External)	1200	15	5.460	3.032	1	1	297.98	
	Promat Wall (External)	1200	15	6.200	3.032	2	1	676.74	
	Promat Wall (External)	1200	15	2.750	3.032	2	1	300.17	
	Promat Wall (Internal)	1200	15	3.250	3.032	2	2	709.49	
	Promat Wall (Internal)	1200	15	1.000	2.200	2	-2	(158.40)	
	Promat Wall (Internal)	1200	15	1.500	0.630	2	-2	(68.04)	
	Promat Wall (Internal)	1200	15	1.500	1.030	2	-1	(55.62)	
	Promat Wall (External)	1200	15	3.250	2.730	2	1	319.41	
	Promat Wall (External)	1200	15	3.125	1.650	2	-1	(185.63)	
2	Rockwool								669.5
	Rockwool Ceiling	80	50	10.775	3.250		1	140.08	
	Rockwool Floor	80	100	9.960	3.250		1	258.96	
	Rockwool (Internal)	80	50	2.750	3.032		1	33.35	
	Rockwool (Internal)	80	50	5.460	3.032		1	66.22	
	Rockwool (External)	80	50	6.200	3.032		1	75.19	
	Rockwool (External)	80	50	2.750	3.032		1	3.35	
	Rockwool (Internal)	80	50	3.250	3.032		2	78.83	
	Rockwool (Internal)	80	50	1.000	2.200		-2	(17.60)	
	Rockwool (Internal)	80	50	1.500	0.630		-2	(7.56)	
	Rockwool (Internal)	80	50	1.500	1.030		-1	(6.18)	
	Rockwool (External)	80	50	3.250	2.730		1	35.49	
	Rockwool (External)	80	50	3.125	1.650		-1	(20.63)	
	Floor Tiles	kg/m2							873.85
	Area 1	36		5.250	3.120		1	589.68	
	Area 2	36		2.530	3.120		1	284.17	
									5664.55
									8316.30
									500.00
									14480.85

C2 Manpower Record

S/No.	Trade/Category	2015 Ma	2015 Jun	2015 July	2015 Aug	2015 Sep	2015 Oct	2015 Nov	2015 Dec	2016 Jan
1	Asst Project Director	3	25	21	19	18	20	19	20	23
2	Managers	9	69	70	67	58	76	58	66	64
3	Site Agent	3	23	13	5	8	6	6	3	5
4	Project Engineer	3	24	48	43	44	49	66	73	68
5	M&E Manager	3	25	22	17	20	24	17	24	23
6	Draftman	3	23	24	20	17	45	38	14	18
7	Supervisors/Co-ordinator	6	97	177	149	150	208	210	221	231
8	Safety Officer/Supervisor	9	81	160	133	140	159	138	144	130
9	Safety Workers	20	118	232	250	341	379	392	349	375
10	General Workers	20	134	336	369	351	378	360	353	380
11	Guard	0	66	73	89	79	83	73	78	75
12	Barbender	0	106	507	654	819	1054	943	988	777
13	Carpentry	36	712	1110	1163	1147	1417	1250	1300	1245
14	System Formwork installation	0	0	0	0	0	0	0	0	0
15	Steel Reinforcement Fixing	0	0	0	0	0	0	0	0	0
16	Concrete Placement	0	0	0	0	0	0	0	0	0
17	Moderna	0	0	0	0	0	0	9	109	68
18	Precast Concrete Installation/Post Tension	0	0	0	0	0	0	48	52	0
19	Structural Steel Work/Civil Work	0	0	4	6	0	0	46	124	37
20	Anti-termite treatment	0	0	3	13	19	19	6	0	16
21	Piling Work W-foundation	0	78	37	0	0	0	0	0	0
22	Piling - Keat Seng	0	21	158	118	9	40	0	6	0
23	Welding	0	46	34	12	26	2	0	36	46
24	Soil Instrumentation	0	0	12	0	4	0	0	2	4
25	Brick/Blockwall	0	0	0	0	0	0	0	0	0
26	Precst Concrete Installation	0	0	0	0	0	0	0	0	0
27	Plaster	0	0	0	0	9	9	46	101	333
28	Skim-coat	0	0	0	0	0	0	0	0	0
29	Dry Partition Wall	0	0	0	0	0	0	0	0	0
30	Glass Partition	0	0	0	0	0	0	0	0	0
31	Cladding/Curtain Wall	0	0	0	0	0	0	0	0	0
32	Waterproofing	0	0	8	8	12	6	4	2	0
33	Floor Screeds & Hardeners	0	0	0	0	0	0	0	0	0
34	Tiling	0	0	0	0	0	0	0	0	0
35	Wood Flooring	0	0	0	0	0	0	0	0	0
36	Resilient Flooring (Vinyl)	0	0	0	0	0	0	0	0	0
37	False Ceiling	0	0	0	0	0	0	0	0	0
38	Door	0	0	0	0	0	0	0	0	0
39	Window	0	0	0	0	0	2	0	0	0
40	Cabinets & Wardrobe	0	0	0	0	0	0	0	0	0
41	Painting	0	0	0	0	0	0	0	0	17
42	Roofing System	0	0	0	0	0	0	0	0	0
43	Mirror	0	0	0	0	0	0	0	0	0
44	Signage	0	0	0	0	0	0	0	0	0
45	Toilet Cubicle	0	0	0	0	0	0	0	0	0
46	Weather Stations	0	0	0	0	0	0	0	0	0
47	Synthetic Field	0	0	0	0	0	0	0	0	0
48	Fencing	0	0	0	0	0	0	0	0	0
49	Landscape	0	0	0	0	0	0	0	0	0
50	Plumbing/Sanitary/Gas system	0	172	211	486	316	245	197	214	194
51	Fire Prevention and Protection System	0	0	0	0	14	8	4	7	42
52	Electrical System	0	110	177	281	276	366	358	503	590
53	ACMV System	0	45	8	5	30	35	43	48	82
54	Lift	0	0	0	0	0	0	0	0	0
55	Crane Operator	0	22	58	128	125	135	120	118	100
56	Excavator Operator	0	68	166	118	65	36	19	51	21
57	Forklift Operator	0	20	30	29	26	27	24	26	25
58	Scaffold	0	0	0	0	0	10	6	33	109
59	Lifting Supervisor	0	17	56	130	118	133	118	113	100
60	Tower Crane - Manta	0	0	68	0	0	0	0	0	0
61	United	0	0	0	0	0	0	0	0	44
	Total	115	2102	3823	4312	4241	4971	4618	5178	5242

S/No.	Trade/Category	2016 Feb	2016 Ma	2016 Apr	2016 Ma	2016 Jun	2016 July	2016 Aug	2016 Sep
1	Asst Project Director	16	16	21	19	23	24	26	23
2	Managers	53	70	64	65	68	56	49	49
3	Site Agent	7	4	2	0	3	0	1	5
4	Project Engineer	50	58	53	59	66	55	35	45
5	M&E Manager	17	19	23	22	22	22	24	17
6	Draftman	16	25	23	23	68	3	7	9
7	Supervisors/Co-ordinator	181	254	300	262	214	209	187	206
8	Safety Officer/Supervisor	112	129	115	95	142	121	107	109
9	Safety Workers	319	368	362	320	292	270	261	274
10	General Workers	284	330	336	307	290	289	286	267
11	Guard	66	78	78	72	78	75	78	75
12	Barbender	388	874	838	711	596	275	178	148
13	Carpentry	1100	1300	1300	1200	1250	870	499	387
14	System Formwork installation	0	0	0	0	0	0	0	0
15	Steel Reinforcement Fixing	0	0	0	0	0	0	0	0
16	Concrete Placement	0	0	0	0	0	0	0	0
17	Moderna	37	103	154	507	724	800	839	900
18	Precast Concrete Installation/Post Tension	0	0	0	0	0	0	0	0
19	Structural Steel Work/Civil Work	73	67	20	65	187	198	100	55
20	Anti-termite treatment	0	7	22	4	0	0	6	0
21	Piling Work W-foundation	0	0	0	0	0	0	0	0
22	Piling - Keat Seng	0	0	0	0	0	0	0	0
23	Welding	44	49	60	72	48	82	123	157
24	Soil Instrumentation	2	6	4	6	5	3	2	2
25	Brick/Blockwall	0	0	0	0	0	0	0	0
26	Precst Concrete Installation	0	0	0	0	0	0	0	0
27	Plaster	375	595	989	849	471	1026	1298	1247
28	Skim-coat	0	0	0	0	0	0	0	0
29	Dry Partition Wall	0	0	0	0	22	166	146	128
30	Glass Partition	0	0	0	0	0	0	0	0
31	Cladding/Curtain Wall	0	0	0	0	0	0	0	0
32	Waterproofing	0	1	14	17	28	59	145	199
33	Floor Screeds & Hardeners	0	0	0	0	0	0	0	0
34	Tiling	0	0	33	144	111	97	153	220
35	Wood Flooring	0	0	0	0	0	0	0	0
36	Resilient Flooring (Vinyl)	0	0	0	0	0	0	0	0
37	False Ceiling	0	0	0	0	0	0	0	0
38	Door	6	3	20	29	36	32	59	72
39	Window	1	3	112	123	113	196	243	334
40	Cabinets & Wardrobe	0	0	0	0	0	3	1	0
41	Painting	0	4	22	95	78	110	106	113
42	Roofing System	0	0	0	0	0	0	5	0
43	Mirror	0	0	0	0	0	0	0	0
44	Signage	0	0	0	0	0	0	0	0
45	Toilet Cubicle	0	0	0	0	0	0	0	0
46	Weather Stations	0	0	0	0	0	0	0	0
47	Synthetic Field	0	0	0	0	0	0	0	0
48	Fencing	0	0	0	0	0	0	0	0
49	Landscape	0	0	0	0	0	0	0	0
50	Plumbing/Sanitary/Gas system	172	190	536	613	994	977	1088	1126
51	Fire Prevention and Protection System	90	173	108	120	344	295	328	248
52	Electrical System	603	757	892	805	887	874	998	1199
53	ACMV System	117	225	286	361	422	495	623	594
54	Lift	0	0	8	12	8	4	68	198
55	Crane Operator	88	104	104	96	104	100	104	100
56	Excavator Operator	16	36	26	13	17	48	76	75
57	Forklift Operator	22	26	26	24	26	25	26	25
58	Scaffold	102	104	115	94	40	162	68	48
59	Lifting Supervisor	88	103	102	95	98	100	97	100
60	Tower Crane - Manta	0	26	0	0	0	0	0	0
61	United	104	0	0	0	0	0	0	0
Total		4549	6107	7168	7299	7875	8121	8440	8754

C3 Machinery Record

S/No.	Machinery	2015 May	2015 June	2015 July	2015 August	2015 September	2015 October	2015 November	2015 December
1	50T Crawler Crane	0	29	33	31	22	31	30	31
2	50T Mobile Crane	0	0	2	0	0	0	0	0
3	Air Breaker	12	0	60	57	2	0	0	0
4	Air Compressor	4	90	93	93	90	72	90	93
5	Bar Bending Machine	4	33	47	62	67	93	69	93
6	Bar Cutting Machine	4	30	47	62	67	93	69	93
7	Boomlift	0	30	1	0	0	21	0	0
8	Concrete Pump	0	0	1	3	5	2	4	7
9	Electrical Breaker	4	29	60	62	67	62	50	58
10	Excavator	4	129	163	119	75	36	30	31
11	Forklift	4	29	28	31	30	31	30	31
12	Generator	8	120	225	232	180	186	180	186
13	Gondola	0	0	0	0	0	0	0	0
14	Hydraulic Breaker	0	20	31	31	2	0	4	0
15	Mini Hydraulic Breaker	0	0	20	62	15	0	0	0
16	Mini Excavator	0	0	0	0	42	38	47	77
17	Piling Rig (RC Piles)	0	13	2	0	0	0	0	0
18	Roller Compactor	0	13	46	57	30	31	30	23
19	Scissor Lift	4	0	0	0	3	0	0	35
20	Tower Crane	0	0	59	124	120	124	120	124
21	Vibrator Machine	0	0	0	0	21	0	0	0
22	Water Pump	0	52	94	93	111	93	90	93

C4 Summary for the Usage of Diesel

S/No.: Trade/Category	2015 June	2015 July	2015 August	2015 September	2015 October	2015 November	2015 December	2016 January	2016 February	2016 March	2016 April	2016 May	2016 June	2016 July	2016 August	2016 September	2016 October	2016 November
1 IN	11957	26763	23722	17578	19231	17798	20399	18167	15155	19738	19909	18379	20145	19474	20064	20173	27660	21873
2 Generator Washing Bay	1338	1544	420	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3 Generator ECM1-150KVA	377	1933	2533	2366	2723	2590	3053	3134	2683	3341	3403	3204	3664	3703	3671	3623	3448	3304
4 Generator ECM2-100KVA	450	1167	1821	2023	2042	2079	2360	2567	2503	3345	3579	3205	3696	3636	3204	3217	3532	3539
5 Generator 4 - Office-100KVA	1189	1746	260	0	0	0	0	0	0	0	0	0	0	0	361	1201	1439	2063
6 Generator 5 - Office-50KVA	1714	2320	482	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7 Excavator 11 - 235M	127	2295	1714	383	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8 Excavator 10 - 235M	355	2340	234	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9 Excavator 14 - 135M	468	2320	1253	0	83	0	0	0	0	0	0	0	0	0	0	0	0	0
10 Excavator U50 - 4M	846	1630	131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 Excavator ACLM - 115M	1136	945	205	266	507	749	505	232	146	145	156	110	286	486	684	988	480	457
12 Excavator 14 - ZK P85	340	926	466	556	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 Mini Excavator - 2 nos	0	366	1402	577	369	404	1940	580	0	50	85	0	0	495	1146	1436	732	669
14 Forklift	275	1054	513	289	279	323	424	369	311	486	323	407	496	463	463	445	393	361
15 Crawler Crane	547	1169	995	906	966	607	245	0	0	0	0	0	0	0	0	0	0	0
16 Dumper	0	1504	45	29	25	10	0	0	0	0	0	0	0	0	0	40	0	0
17 Lorry XD 3296	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18 Lorry GZ 1564	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0
19 Oiling	195	170	70	170	250	235	180	250	210	260	250	240	190	120	250	200	240	260
20 Wash Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 Roller	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	40	80	0
22 Roller	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 Genset TC1 - 220KVA	0	0	2374	2070	2455	2298	2641	2738	2356	2900	2982	2715	3079	2615	2434	2363	2524	2450
24 Genset TC2 - 220KVA	0	818	1971	1743	2096	1896	2045	2110	2985	2364	2338	2325	2476	2368	2197	2319	2410	2512
25 Genset TC3 - 220KVA	0	120	1793	2065	2195	2128	2376	2267	1928	2456	2602	2101	2255	2036	1902	2172	2521	2665
26 Genset TC4 - 220KVA	0	1248	2533	2339	2590	2513	3303	2833	2568	3347	3130	3112	3380	2910	2724	2698	2819	2735
27 Air Compressor 1	178	583	131	188	199	157	169	180	210	139	158	120	0	198	0	120	150	240
28 Air Compressor 2	178	736	319	328	165	40	262	50	120	180	90	60	0	82	80	0	0	0
29 Air Compressor 3	0	326	246	337	105	110	0	0	50	190	95	0	0	0	0	0	0	0
30 Air Compressor	0	0	168	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0
31 Machine Cutting - 2nos	0	195	275	245	270	240	325	250	220	260	130	120	115	110	130	75	125	130
32 BarBending Machine - 2nos	0	175	275	245	270	240	325	250	220	260	130	120	115	110	130	75	125	130
33 Mini Genset - 5 nos	365	495	495	400	540	485	620	170	0	0	10	0	0	0	0	0	0	0
34 Tower Light- 1 nos	30	497	360	70	105	120	0	0	0	355	30	0	0	0	192	0	0	0
35 Boomlift	100	0	0	0	0	0	0	0	0	0	53	21	151	387	0	0	0	62
Total	10199	28622	23484	17595	18299	17224	20773	17980	15510	20078	19544	17860	19903	19719	19668	21012	21018	21577

Appendix D Background Data for S-LCA Case Study

normalized country-level social performance scores

	Health and safety of workers	Fair Salary			Working Hours			Discrimination	Forced Labor	Child Labor	Living Condition	Local Employment	Integration and Interaction	Accessibility
		Mining	Prod.	General	Mining	Prod.	General							
Australia	1.80	1.80			0.62		1.75	1.55	2.00	2.00	1.72	0.49	0.66	1.53
Brazil	0.66	0.56			0.77		1.13	-0.15	1.94	-0.33	-0.26	0.12	-1.59	0.68
Cambodia	-0.34	-0.42		-0.42	0.38		0.38	-1.03	0.50	-0.79	-0.78	0.48	-0.78	-0.55
Canada	1.53	1.31			1.50		1.50	1.65	2.00	2.00	1.40	0.65	0.88	1.71
China	1.17	-0.29	-0.37		0.31	-0.14	0.13	1.28	1.79	2.00	0.06	1.09	0.29	0.98
France	1.81	0.89			1.08		1.50	1.65	2.00	2.00	1.35	0.61	0.17	1.89
Germany	1.76	1.13			1.08		1.63	1.81	2.00	2.00	1.09	1.54	0.92	1.74
India	1.09	0.19		0.19	0.00		0.00	-0.85	0.73	-0.48	-0.44	0.97	0.20	0.27
Indonesia	0.29	-0.19		-0.19	0.46		0.88	-0.38	1.75	-0.28	0.34	0.71	-0.09	0.35
Iran	0.64	0.05		0.05	0.00		0.00	-0.62	1.44	-0.47	0.94	0.06	-0.56	1.02
Italy	1.48	0.74			1.23		1.50	1.70	1.82	2.00	0.57	0.54	-1.35	1.43
Japan	1.80	1.52	1.31		1.08	1.00	1.13	1.57	1.81	2.00	1.33	2.00	0.86	1.94
Korea, Republic of	0.73	1.49			0.77		0.50	1.82	1.65	2.00	1.26	1.17	-0.92	1.78
Malaysia	0.51	0.05	0.05	0.05	-0.31	0.14	0.38	0.60	1.63	2.00	1.40	1.27	0.58	1.58
Poland	1.22	0.48			1.08		1.00	1.43	1.58	2.00	0.58	0.80	-0.91	1.22
Russia	1.13	-0.13			1.38		1.25	0.64	1.34	2.00	-0.11	0.42	-0.36	0.42
Singapore	1.24		0.11			0.43	0.50	1.79	1.86	2.00	1.82	0.98	2.00	2.00
South Africa	0.44	2.00		2.00	0.31		0.63	-0.01	1.60	2.00	-0.31	-1.10	-0.55	0.70
Turkey	0.44	0.34		0.34	-0.31		0.13	0.29	1.44	-0.24	0.53	0.29	-0.27	1.52
Ukraine	0.60	0.21		0.21	1.23		1.13	0.55	1.59	-0.10	0.17	0.28	-0.70	0.62
USA	1.63	0.91			1.13		1.13	1.00	2.00	2.00	1.25	1.34	0.56	1.79
Vietnam	-0.23	0.34		0.34	0.15		0.50	0.40	1.88	-0.67	0.85	0.73	-0.33	0.69