

Durham E-Theses

An Agent-Based Modelling and Simulation Framework to Investigate Manufacturing and Retail Small and Medium-Sized Enterprises' Immediate Response to and Short-Term Recovery from Flood Events

MESHAL GHALIB M ALHARBI

How to cite:

ALHARBI, MESHAL GHALIB M (2020) An Agent-Based Modelling and Simulation Framework to Investigate Manufacturing and Retail Small and Medium-Sized Enterprises' Immediate Response to and Short-Term Recovery from Flood Events. Doctoral thesis, Durham University.

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a <https://etheses.durham.ac.uk/id/eprint/13539/> is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full Durham E-Theses policy](#) for further details.

**An Agent-Based Modelling and Simulation Framework to
Investigate Manufacturing and Retail Small and Medium-
Sized Enterprises' Immediate Response to and Short-Term
Recovery from Flood Events**

by

Meshal Ghalib M Alharbi

A thesis presented for the degree of
Doctor of Philosophy



Innovative Computing Group,
Department of Computer Science

Durham University

United Kingdom

January, 2020

This thesis is dedicated to

Allah almighty,

my mother and father,

my wife, and

my children (Ghalib, Maya, and Hisham).

A Thesis Presented for the Degree of Doctor of Philosophy

Meshal Alharbi

Abstract

The predominance and economic significance of small and medium-sized enterprises (SMEs) means widespread disruption to their operations can have severe financial consequences for a nation's economy. For instance, the 2007 summer floods in the UK caused damage estimated at £2.3 billion and a significant proportion of this damage was sustained by SMEs, which, in 2018, represented 99.9% (5.7 million) of all UK businesses. Thus, due to the importance of this size of business to developed nations' economies, this research seeks to develop an agent-based modelling and simulation (ABMS) framework to investigate manufacturing and retail SMEs' immediate response to and short-term recovery from flooding. This ABMS framework consists of three main components: (i) flood-event simulation; (ii) a modelled geographical environment (MGE); and (iii) agent-based modelling and simulation. First, flood-event simulation represents the input (inundation) data that feeds into the MGE component, which provides a common platform for the flood-event simulation and the agent-based modelling and simulation. Specifically, the MGE combines Ordnance Survey (OS) MasterMap® data (i.e. *Topography*, Integrated Transport Network (*ITN*), and *AddressBase Plus* layers) with the input from the flood-event simulation to enable the identification of the flooded and non-flooded organisations. Consequently, a proportion of these identified organisations, and particularly SMEs from manufacturing and retail sectors, are modelled as autonomous agents and simulated over three stages, namely pre-flood, flood (no operation), and post-flood. In addition, SME-related organisations (e.g. suppliers, customers, electrical service providers, plumbing service providers, IT service providers, cleaning service providers, the Environment Agency (EA), mutual aid partners, refurbishment companies, and insurance companies) are also modelled as autonomous agents and simulated to support SMEs' operation and/or recovery. In terms of SMEs, manufacturing and retail SMEs are modelled as autonomous agents with different sets of attributes (e.g. static and dynamic), behaviours (e.g. pre- and post-flood), and pre-defined precautionary measures (e.g. flood resistance, flood resilience, and business

continuity/risk management). Production level and service capability are computed at each simulation tick for every manufacturing and retail SME modelled, respectively, to determine their performance throughout the simulation. In terms of simulation, two real-life case studies of UK flood events in 2007 have been considered: (a) the Lower Don Valley of Sheffield, south Yorkshire, and (b) Tewkesbury, Gloucestershire. For the analysis, manufacturing and retail SMEs are categorised according to the level the floodwater reached in their respective premises (i.e. lightly, moderately, and severely) and then each category is investigated individually against each of the simulation experiments defined, which corresponds to different combinations of precautionary measures. As a result, this research has found that the flood resistance precautionary measures, which include a bund-wall being erected around SMEs' premises, are effective for lightly and moderately flooded manufacturing and retail SMEs. However, the severely flooded manufacturing and retail SMEs simulated with a combination of flood resistance precautionary measures as well as business continuity/risk management tend to achieve higher production levels and service capability profiles, respectively.

Declaration

The work in thesis is based on research carried out in the Innovative Computing Group, School of Computer Science Durham University, United Kingdom. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless reference to the contrary in the text.

Copyright © 2020 by Meshal Alharbi.

“The copyright of this thesis rests with the author. No quotations from it should be published without the author’s prior written consent and information derived from it should be acknowledged”.

Acknowledgements

Alhamdulillah, first and foremost; I am truly grateful to Allah almighty for the countless blessings he has bestowed upon me, both generally and in accomplishing this thesis in particular.

I would like to express my warmest gratitude and sincere appreciation to my academic supervisor, Professor Graham Coates, for his dedicated support, patience, kindness, enthusiasm, calm advice, valuable feedback, suggestions backed by immense knowledge, and guidance throughout my work and during the writing of this thesis. He gave a lot of his time while supervising my research and the writing process. I cannot forget the moment he told me he was moving to Newcastle University, although he kindly promised to continue supervising me until I had completed it and I appreciate this immensely. He is a very supportive and nice person and I have learned a lot from him that will have a significant impact on my future life. Also, I would like to thank my supervisor at Durham University Dr. Tobias Weinzierl, who has supported all my needs at Durham University. I have great respect and appreciation for him. In addition, I would like to thank colleagues from the School of Civil Engineering at the University of Leeds for providing inundation data from flood event simulation.

I am truly grateful to my father and my mother who have been a great source of motivation, support, love, and prayers, and have always stood by me and been proud of me. Special thanks and warm appreciation also for my beloved wife, Najah Alharbi, for her patience, love, prayers, standing by me, her kindness, and taking care of our children, Ghalib, Maya, and Hisham while I was busy with my research. Also, many thanks go to my children for being the source of my happiness.

I gratefully acknowledge the financial support from Prince Sattam bin Abdulaziz University, Saudi Arabia, and the Saudi Arabian Cultural Bureau (SACB) in London to allow me to pursue my PhD studies at Durham University

Many thanks also to Durham University for providing me with an enjoyable academic atmosphere and offering me great opportunities to participate and present my work at international conferences and for the facilities that have enabled me to study in comfort.

Finally, many thanks go to my colleagues, friends, and to everyone who has assisted me, stood by me or contributed to my educational progress in any way.

Publications

Parts of work in this thesis have been published, accepted, presented:

Alharbi, M., & Coates, G. (2017). An agent-based modelling and simulation framework to assess small businesses' recovery from flooding. In 29th European Modelling and Simulation Symposium, EMSS 2017.

Alharbi, M., & Coates, G. (2018). An Investigation of Small and Medium-Sized Enterprises' flood Preparation and Insurance Coverage using Agent-Based Modelling. *Wit Transactions on the Built Environment*, 184, 143-152.

Alharbi, M., & Coates, G. (2019). Assessing Flood Recovery of Small Businesses using Agent-Based Modelling and Simulation. *Proceedings of the 16th International Conference on Information Systems for Crisis Response And Management*

Alharbi, M., & Coates, G. (2019). Investigating manufacturing small and medium-sized enterprises' immediate response and short-term recovery from flooding using an agent-based approach. *International Journal of Simulation and Process Modelling*, 14(2), 87-104.

Coates, G., Li, C., Ahilan, S., Wright, N., & Alharbi, M. (2019). Agent-based modeling and simulation to assess flood preparedness and recovery of manufacturing small and medium-sized enterprises. *Engineering Applications of Artificial Intelligence*, 78, 195-217.

Coates, G., Alharbi, M., Li, C., Ahilan, S., & Wright, N. (2019). Evaluating the resilience of SMEs to flooding using a computational modelling and simulation approach: a case study of the 2007 flood in Tewkesbury. *Philosophical Transactions A, Royal Society*.

Table of Contents

Chapter 1	Introduction.....	1
1.1	Contribution of this Thesis	3
1.2	Motivation for the Research	5
1.3	Research Methodology	6
1.4	Organisation of the Thesis.....	7
1.4.1	Problem Identification and Motivation (Chapters 2 and 3)	7
1.4.2	Objectives of a Solution (Chapter 4)	8
1.4.3	Design and Development (Chapters 5 - 7)	8
1.4.4	Demonstration (Chapters 8 and 9).....	9
1.4.5	Evaluation (Chapter 10).....	10
1.4.6	Conclusion (Chapter 11)	10
Chapter 2	Business and Disruptive Events	11
2.1	Small and Medium-Sized Enterprises (SMEs).....	11
2.1.1	Definition of Small and Medium-Sized Enterprises (SMEs).....	12
2.1.2	Characteristics of Small and Medium-Sized Enterprises (SMEs).....	12
2.1.3	Business Sectors	13
2.2	Disruptive Events.....	14
2.2.1	Extreme Weather Events (EWEs)	15
2.2.2	Flooding.....	16
2.3	Small and Medium-Sized Enterprises (SMEs) and Flooding.....	16
2.3.1	Impacts of Flooding on Small and Medium-Sized Enterprises (SMEs) and National Economies.....	17
2.3.2	Investigating Small and Medium-Sized Enterprises (SMEs) in the context of Flooding	21
2.4	Emergency/Disaster Risk Management Cycle.....	26
2.5	Immediate Response and Short-Term Recovery.....	27
2.6	Summary	29
Chapter 3	Computational Models of SMEs and Flooding	30
3.1	Agent-Based Modelling and related Flood Events	30
3.2	Agent-Based Modellings and Small and Medium-Sized Enterprises (SMEs)	38
3.3	Summary	43
Chapter 4	Requirements of Agent-Based Modelling and Simulation Framework.....	45

4.1	Overview	45
4.2	Modelling the Geographical Environment.....	46
4.3	Modelling Small and Medium Enterprises.....	46
4.3.1	Behaviours.....	47
4.3.2	Attributes	47
4.3.3	Precautionary Measures	47
4.4	Modelling SME-related Organisations	48
4.4.1	Environment Agency	50
4.4.2	Suppliers and Customers	50
4.4.3	Insurance Companies.....	50
4.4.4	Cleaning Service Providers	50
4.4.5	Service Provider Organisations	51
4.4.6	Mutual Aid Partners.....	51
4.5	Modelling Interactions between SMEs and SME-related organisations	51
4.6	Modelling Performance Metrics	51
4.7	Summary	52
Chapter 5	Overview of Agent-Based Modelling and Simulation (ABMS) Framework.....	54
5.1	Agent-Based Modelling and Simulation Framework	54
5.1.1	Flood Event Simulation	55
5.1.2	Modelled Geographical Environment.....	56
5.1.3	Agent-Based Modelling and Simulation.....	57
5.2	Summary	59
Chapter 6	Modelled Geographical Environment (MGE).....	60
6.1	Modelled Geographical Environment (MGE) Layers	60
6.2	Constructing the Modelled Geographical Environment (MGE).....	64
6.3	Identifying Flooded and Non-Flooded SMEs	65
6.4	Visual Representation of the Modelled Geographical Environment (MGE).....	65
6.5	Summary	67
Chapter 7	Agent-Based Modelling and Simulation.....	68
7.1	Model design and development	69
7.1.1	Pre-Flood Behaviours	69
7.1.2	Post-Flood Behaviours	75
7.1.3	Precautionary Measures	83
7.1.3.1	Property-Level Precautionary Measures	87

7.1.3.1.1	Flood Resistance Precautionary Measures	87
7.1.3.1.2	Flood Resilience Precautionary Measures	88
7.1.3.2	Business Continuity/Risk Management Precautionary Measures	90
7.1.4	Attributes of Small and Medium Enterprises	91
7.1.5	Manufacturing SMEs Performance Measurement.....	93
7.1.6	Retail SMEs Performance Measurement	96
7.2	Modelling SME-related organizations	99
7.2.1	Environment Agency	100
7.2.2	Suppliers and Customers.....	101
7.2.3	Insurance Companies	102
7.2.4	Cleaning Service Providers	105
7.2.5	Service Provider Organizations	106
7.2.6	Mutual Aid Partners	108
7.2.7	SME-Related Organisations Attributes.....	109
7.3	Model validation	110
7.4	Summary	114
Chapter 8	Case Studies and Simulation Experiments	115
8.1	Case Studies.....	115
8.1.1	Lower Don Valley, Sheffield.....	117
8.1.2	Tewkesbury	121
8.2	Method of SMEs' Analysis	124
8.2.1	Operational Disruption Analysis	124
8.2.2	Statistical Analysis	131
8.3	Simulation experiments	132
8.3.1	SME Simulation Experiments	135
8.3.2	SME-Related Organisation Simulation Experiments	140
8.4	Summary	141
Chapter 9	Results and Discussion	143
9.1	Overview.....	143
9.2	SMEs Located in the Lower Don Valley, Sheffield	146
9.2.1	Lightly Flooded Manufacturing SMEs.....	149
9.2.1.1	Simulation Experiment E1 for the Lightly Flooded Manufacturing SMEs	151
9.2.1.2	Simulation Experiments E2 (A) to E3 for the Lightly Flooded Manufacturing SMEs	152

9.2.1.3	Simulation Experiments E4 to E6 (B) for the Lightly Flooded Manufacturing SMEs	155
9.2.1.4	Simulation Experiments E7 to E11 for the Lightly Flooded Manufacturing SMEs	159
9.2.1.5	Statistical Analysis for the Lightly Flooded Manufacturing SMEs	163
9.2.2	Moderately Flooded Manufacturing SMEs	166
9.2.3	Severely Flooded Manufacturing SMEs	171
9.3	SMEs Located in Tewkesbury	176
9.4	Recommendations for Manufacturing SMEs	183
9.4.1	Recommendations for the Lightly Flooded Manufacturing SMEs	183
9.4.2	Recommendations for the Moderately Flooded Manufacturing SMEs	185
9.4.3	Recommendations for the Severely Flooded Manufacturing SMEs	185
9.5	Summary	186
Chapter 10	Evaluation	189
10.1	Accomplishments and Weaknesses	189
10.1.1	Modelled Geographical Environment (MGE)	189
10.1.2	Modelling and Simulating SMEs	190
10.1.2.1	Behaviours	190
10.1.2.2	Attributes	192
10.1.2.3	Precautionary Measures	193
10.1.3	Modelling SME-Related Organisations	194
10.1.3.1	The Environment Agency (EA)	194
10.1.3.2	Suppliers and Customers	194
10.1.3.3	Insurance Companies	196
10.1.3.4	Cleaning Service Providers	197
10.1.3.5	Service Provider Organisations	198
10.1.3.6	Mutual Aid Partners	198
10.1.4	Modelling Interactions between SMEs and SME-Related Organisations	199
10.1.5	Modelling Performance Metrics	200
10.2	Summary	201
Chapter 11	Conclusion	202
11.1	Motivation for the Research	202
11.2	Key Elements of ABMS Framework	202
11.3	Requirements of ABMS Framework	204
11.4	ABMS Framework	207

11.5	Case studies and results	207
11.6	Evaluation	208
11.7	Future Work	209
	References.....	211
	References of Content of Tables	226
	List of Figures in Appendices	230
	List of Tables in Appendices	233
Appendix A	Computational Models and Software Toolkits.....	234
Appendix B	Visual Enhancement	249
Appendix C	ODD Protocol	256
Appendix D	Results and Discussion for Retail SMEs and SME-Related Organisations.....	296
Appendix E	Graphical Representations	317

List of Figures

Figure 1.1: Overview of the research methodology (Peffer et al., 2007).....	6
Figure 2.1: Phases of disaster risk management (Jha et al., 2013).....	27
Figure 5.1: ABMS framework overview	55
Figure 5.2: Series of inundation data files for a specific geographical area	56
Figure 5.3: Overview of the agents' design (Tran et al., 2015).....	58
Figure 6.1: MGE elements.....	61
Figure 6.2: <i>Address</i> layer filtering process.....	63
Figure 6.3: Overview of how inundation data was stored into a structured list	65
Figure 6.4: Coupling the inundation data with the OS MasterMap® layers	66
Figure 7.1: Pre-flood behaviours' relationships with sequencing order of behaviour execution indicated in the brackets in each action box	73
Figure 7.2: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (1)	78
Figure 7.3: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (2)	80
Figure 7.4: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (3)	82
Figure 7.5: Manufacturing SMEs dynamic attributes relationships.....	94
Figure 7.6: Retail SMEs dynamic attributes relationships	98
Figure 7.7: Interactions between SMEs and SME-related-organisations	100
Figure 7.8: An overview of the interaction between suppliers and/or customers and SMEs	102
Figure 7.9: An overview of the interaction between insurance companies and SMEs	104
Figure 7.10: An Overview of the interaction between cleaning service providers and SMEs	106
Figure 7.11: An overview of the interaction between service providers organisations and SMEs.....	108
Figure 8.1: (a) modelled geographical environment of the Lower Don Valley of Sheffield and (b) modelled geographical environment of Tewkesbury.....	116
Figure 8.2: Flood footprints based on inundation data, Lower Don Valley of Sheffield geographical area.....	118
Figure 8.3: Manufacturing and retail SMEs modelled as agents in Lower Don Valley of Sheffield modelled geographical environment area	120
Figure 8.4: Typical simulation duration	121
Figure 8.5: Flood footprints based on inundation data, Tewkesbury geographical area	122
Figure 8.6: Manufacturing and retail SMEs modelled as agents in Tewkesbury's geographical area.	124
Figure 8.7: Manufacturing and retail SMEs operational disruption	126
Figure 9.1: The process undertaken to compute the cumulative average of the moderately flooded manufacturing SMEs in the Sheffield geographical area	145
Figure 9.2: Cumulative average of production level of 256 flood-affected manufacturing SMEs located in Sheffield versus time over 10 simulation runs	147

Figure 9.3: The <i>overall absolute operational disruption</i> of the lightly, moderately, and severely flooded manufacturing SMEs located in Sheffield geographical area	148
Figure 9.4: Cumulative average of production level of 16 flood-affected manufacturing SMEs located in Tewkesbury over time located	178
Figure 11.1: Summary of the work.....	206

List of Tables

Table 1.1: Previous research	4
Table 1.2: Business statistics (Rhodes, 2018)	5
Table 2.1: Business by industry (Rhodes, 2018)	14
Table 2.2: Impacts of flooding on SMEs (Wedawatta, 2013).....	19
Table 4.1: An overview of SME-related organisations.....	49
Table 6.1: Address layer options (Ordnance Survey, 2019).....	62
Table 7.1: SMEs pre-flood behaviours and durations.....	71
Table 7.2: SMEs post-flood behaviours and durations	76
Table 7.3: SMEs precautionary measures.....	86
Table 7.4: Manufacturing and retail SMEs attributes.....	93
Table 7.5: SME-Related organisations attributes	110
Table 7.6: Old and updated ODD protocol elements (Grimm et al., 2010)	112
Table 8.1: A breakdown of SMEs in the Lower Don Valley of Sheffield modelled geographical environment area	119
Table 8.2: A Breakdown of SMEs in Tewkesbury geographical area	123
Table 8.3: Manufacturing SME 'A' production level	129
Table 8.4: Manufacturing SME 'B' production level	130
Table 8.5: Mapping of simulation experiment questions.....	135
Table 8.6: Simulation experiments	139
Table 8.7: SME-related organisations simulation experiments	140
Table 9.1: Manufacturing and retail SMEs located in the Lower Don Valley of Sheffield categorised on the basis of the floodwater level reached in their premises	146
Table 9.2: Lightly flooded (68) manufacturing SMEs located in Lower Don Valley of Sheffield	150
Table 9.3: The results of Mann–Whitney U test applied to the lightly flooded (68) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11	164
Table 9.4: Simulation data for the moderately flooded (115) manufacturing SMEs located in Lower Don Valley of Sheffield	167
Table 9.5: The results of Mann–Whitney U test applied to the moderately flooded (115) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11	170
Table 9.6: Simulation data for the severely flooded (73) manufacturing SMEs located in Lower Don Valley of Sheffield	173
Table 9.7: The results of Mann–Whitney U test applied to the severely flooded (73) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11	176
Table 9.8: Manufacturing and retail SMEs located in Tewkesbury categorised on the basis of the floodwater level reached in their premises.....	177
Table 9.9: Simulation data for the severely flooded (6) manufacturing SMEs located in Tewkesbury	179

Table 9.10: The results of Mann–Whitney U test applied to the severely flooded (6) manufacturing SMEs located Tewkesbury and simulated in E1 – E11.....	181
Table 9.11: The overall cumulative average of manufacturing SMEs simulated in E1 to E11	186

List of Abbreviation

SME	Small and M edium-Sized E nterprises
ABM	A gent- B ased M odelling
ABMS	A gent- B ased M odelling and S imulation
CA	C ellular A utomata
MSM	M icro S imulation M odel
SDM	S ystem D ynamics M odel
Repast	R ecursive P orous A gent S imulation T oolkit
Repast J	R epast for J ava
Repast Py	R epast for P ython S cripting
Repast S	R epast S imphony
ROAD	R epast O rganization for A rchitecture and D esign
MASON	M ulti A gent S imulation o f N eighbourhood
GIS	G eographical I nformation S ystem
QGIS	Q uantum G eographical I nformation S ystem

Nomenclature

B_i^E	Number of employees required to enact a specific behaviour with priority i
$B_{E\ i}^E$	Number of employees working on behaviour with priority i
B_i	Behaviour with priority i
d_n	Simulation day
E	Ratio of the number of production employees working on production (E_p^p) to the total number of production employees (E_t^p)
E_a	Total number of employees available in an SME's premises
E_a^c	Total number of employees working on customer service
E_a^c	Total number of employees available in a retail SME's premises
E_a^p	Total number of production employees available in an SME's premises
E_b	Total number of employees working on behaviours
E_E	Percentage of total number of employees available in an SME's premises
E_p^p	Total number of production employees working on production
E_r^p	Percentage of production employees repairing machines
E_t	Total number of employees including (production and non-production)
E_t^{np}	Total number of non-production employees
E_t^p	Total number of production employees
E_t^p	Total number of production employees
EC	Percentage of the work environment conditions are in a state suitable for the SME to operate
G_e	Generic behaviour or attribute
H	Total number of man hours required to repair machines
M	Ratio of an SME's available machines (M_a) to the total percentage of machines (M_t)
M_a	Percentage of SME's available machines
M_d	Percentage of an SME's machines damaged
M_e	Multi employees required to enact a specific behaviour

$M_{partner}$	Percentage of production machines allocated at partner's location
M_t	Percentage of production machines owned by an SME
OD_{ABC}^{none}	Non-operation absolute operational disruption
$OD_{ABC}^{overall}$	Overall absolute operational disruption
OD_{ABC}^{post}	Post-flood absolute operational disruption
OD_{ABC}^{pre}	Pre-flood absolute operational disruption
OD_{none}	Non-operation operational disruption
$OD_{overall}$	Overall operational disruption
OD_{post}	Post-flood operational disruption
OD_{pre}	Pre-flood operational disruption
P	Power supply
P_a	Amount of products available at an SME's premises
PL	Percentage of manufacturing SMEs' production level
Pr_i	Precautionary measure number i
P_t	Type of products: e.g. light, medium or heavy
RM	Sum of raw material units stored on ground level and above ground level
RM_{ag}	Percentage of raw material above ground level
RM_{og}	Percentage of raw material on ground level
SC	Percentage of retail SMEs' service capability
SE	Percentage of sales equipment available
S_e	Single employee required to enact a specific behaviour
S_i	Interview transcript i
S_p	Specific behaviour or attribute
ST	Percentage of an SME's available stock
t_c	Clock time
t_s	Simulation time step or tick
t_0	It refers to the start of the simulation in which case the PL or the SC is 100%
t_1	The time at which an SME receives and acts on a flood alert or warning from the EA

t_2	The time at which the flood event (i.e. non-operation) enters premises in which case the <i>PL</i> or the <i>SC</i> remains at zero before being resumed at t_3
t_3	The time at which <i>PL</i> or the <i>SC</i> being resumed
t_4	The time at which the <i>PL</i> or the <i>SC</i> being restored to 100%
t_5	It corresponds with the end of the simulation
W_d	Level of flood water reached in an SME's premises

Chapter 1

Introduction

Flooding can result in significant financial losses to a nation's economy due to the disruption caused to businesses (Jonkman et al., 2008; Khalili et al., 2015). In the United Kingdom (UK), Small and Medium-sized Enterprises (SMEs) are essential to the economy as they account for 5.7 million businesses, which represents 99.9% of all businesses with the remaining 0.1% being large businesses (Rhodes, 2018). However, the definition of what constitutes an SME varies depending on the country of origin (Hallberg, 1999). For example, in the UK, the term SME refers to any business that has fewer than 250 employees (Lukács, 2005) whereas in the USA and Australia it is fewer than 500 and 100 respectively (Ayyagari et al., 2003). In relation to the UK definition, SMEs are categorized as micro, small or medium according to their number of employees. That is, a micro-sized business has 1 to 9 employees, a small business has 10 to 49, and a medium-sized business has 50 to 249 (DBEIS, 2018; Rhodes, 2018). In recognizing the economic importance of SMEs, it has been seen in recent years that these businesses can be vulnerable to the effects of extreme weather events (Crichton, 2006; Wedawatta et al., 2010). This vulnerability has been reported as being due to their limited resources (Sullivan-Taylor & Branicki, 2011; Van Gils, 2005) and their tendency to lack disaster mitigation plans (Jones & Ingirige, 2008). Flooding, in particular, has caused significant financial losses to SMEs in the UK and remains a serious threat (Wedawatta, 2013). According to the Environment Agency (EA), UK businesses' losses due to flooding in 2007 were estimated to be in the region of £740 million (Chatterton et al., 2010). In England, it is projected that the annual loss suffered by residential and business properties due to flooding is over £1 billion (Leinster, 2009). Thus, mitigating the potential risk and disruption caused to SMEs by flooding has become an issue of key significance (Wedawatta & Ingirige, 2012).

SMEs' preparation for, response to and recovery from disruptive events, such as flooding, depend on a myriad of complex and interdependent processes (Wedawatta, 2013). Agent-based modelling is widely recognized as an effective tool to apply to such complex problems in business and social science (Dawson et al., 2011; Dignum & Tick, 2007; Gilbert & Terna, 2000; North & Macal, 2007; Prasad & Chartier, 1999). Agent-based models (ABMs) are computational constructs used to simulate the actions and interactions of autonomous agents in order to evaluate their impacts on the system as a whole (Axelrod, 2005). Furthermore, such autonomous agents can represent individuals, businesses and organizations with personal attributes and behavioural possibilities, as well as rules for interacting with other agents and their surrounding environment (North et al., 2013). Clarke (2014) indicated that ABMs are preferred when the model's goal is the simulation of a behavioural unit and when the model represents interactions among one or more types of agent. It has been demonstrated that ABMs are predictive and analytical research tools that can provide insights into complex social behaviour and generate new theory (Johnson, 2015). Chappin et al. (2007) pointed out that, while ABMs originate from research domains such as artificial intelligence and social science, they are flexible enough to be used in a wide range of applications.

The research presented in this thesis reports on the development and use of an agent-based modelling and simulation (ABMS) framework with the aim of investigating the effects on recovery of a range of flood related precautionary measures and behaviours implemented by SMEs in the manufacturing and retail sectors. The ABMS framework involves linking a modelled geographical environment (MGE), flood-event simulation and ABMS. The MGE consists of three layers of OS MasterMap®, namely the *Topography* layer, *Integrated Transport Network (ITN)* layer, and *Address* layer (Ordnance Survey, 2019). Using these data layers enables a specific geographical area to be modelled in which the location of each individual business can be identified. In addition, within the MGE, flood event modelling and simulation generates inundation data at regular time intervals (half hour) such that the water depth at all locations throughout the area modelled, some of which coincide with the location of an SME's premises, is known. ABMS involves autonomous agents representing manufacturing and retail SMEs exhibiting a range of pre- and post-flood behaviours and able to administer a number of potential flood precautionary measures.

In addition to manufacturing and retail SMEs, related organizations are modelled such as customers, suppliers, insurance companies, the Environment Agency (EA), cleaning service providers, electricians, plumbers, and IT specialists to support SMEs' operation and recovery.

1.1 CONTRIBUTION OF THIS THESIS

Despite SMEs being the most prominent type of business in developed countries, and thus having a significant influence on their respective nation's economy, limited research has been conducted in silico using agent-based modelling and simulation to evaluate their immediate response to and short-term recovery from disruptive events, such as flooding. Consequently, there exists a need for research to be carried out into modelling and simulating SMEs to study business continuity when faced with a disruptive event – flooding in particular.

The research reported in this thesis builds on earlier work (Coates et al., 2014; Coates et al., 2016; Li & Coates, 2016; Li et al., 2015) with the aim to develop an agent-based modelling and simulation (ABMS) framework to investigate the effect of SMEs' behaviours, and flood precautionary measures that can be put in place, to maintain business continuity and speed-up short-term recovery from flooding. In terms of the previous studies, which the present research is built on, no study provide a rationale for practical applications of ABMS frameworks with the exception of (Coates et al., 2016). This is due to researchers mainly focusing on conceptualizing ABMS framework design rather than developing practical flood-prevention initiatives, while Coates et al. (2016) provide preliminary simulations for two manufacturing SMEs in order to assess their recovery from flooding. Table 1.1 provides a scope-focused summary of the research upon which the present research builds on.

No.	Paper	Scope
1.	Coates et al. (2014)	Creates a virtual geographic environment (VGE) consolidated with inundation data from the Lower Don Valley region of Sheffield in the UK to identify flooded and non-flooded organisations.
2.	Li et al. (2015)	Provide an overview of the potential design of ABMS framework to assess SMEs' responses to flooding.
3.	Li and Coates (2016)	Provides more detailed information on a potential ABMS-based framework and provides a generic performance evaluation metric of SMEs that can be used to measure the impact of flooding on SMEs' performance.
4.	Coates et al. (2016)	Illustrates a number of preliminary simulations for two manufacturing SMEs (e.g. both with and without potential

No.	Paper	Scope
		behaviours) to assess their recovery from flooding. For the SME with potential behaviours, only a small range of pre-flood behaviours are included, such as lifting-up IT equipment, and raising the level of machines and electrical sockets.

Table 1.1: Previous research

The research reported in this thesis extends the previous work summarised in Table 1.1 and achieves the following aims of the agent-based modelling and simulation framework:

1. enable organisations affected by a simulated flood event within a specific geographical area to be identified;
2. model manufacturing and retail SMEs (and other related organisations, such as suppliers, customers, the Environment Agency (EA), insurance companies, and mutual aid partners) as agents with specific behaviours and attributes as well as a set of precautionary measures within specified geographical areas to enable the simulation of these businesses in the pre- and post-flood, immediate response, and short-term recovery stages;
3. model the interactions between SMEs and SME-related organisations (which aim to provide assistance or a service, e.g.. electrical repairs), to support SMEs' operation and recovery; and
4. investigate how SMEs' behaviours and precautionary measures, and combinations of them, impact SMEs' immediate response and post-flood, short-term recovery.

Based on the four aims stated, the following research questions can be posed:

1. To what extent can the immediate response to and short-term recovery from flooding of manufacturing and retail SMEs be improved through the use of computational modelling?
2. What is meant by the immediate response and short-term recovery?
3. What performance measure should be used to assess the immediate response and short-term recover of manufacturing and retail SMEs?
4. What type of computational modelling approach should be considered?

5. What are the main components required to develop an ABMS framework that can investigate manufacturing and retail SMEs' immediate responses to and short-term recovery from flood events?

1.2 MOTIVATION FOR THE RESEARCH

SMEs constitute a large percentage of the UK market; there are currently 5.7 million SMEs (2018) which represent 99.9% of all businesses (Rhodes, 2018). SMEs also account for 60% of private-sector employment, providing jobs for more than 16.2 million individuals. Further, SMEs account for 52% of private-sector turnover amounting to nearly £2 trillion. According to the Annual Business Population Estimation for the UK and regions (2018), micro-businesses account for approximately 96% of all businesses, 33% of total employment, and 21% of total turnover, whereas small businesses account for approximately 4% of all businesses and 15% of total employment and turnover. Similarly, medium-sized businesses account for 1% of all businesses, 13% of total employment, and 15% of turnover. In Table 1.2, it is noted that the total percentages of businesses are greater than 100%. This is due to rounding as presented in (Rhodes, 2018).

Sector	Business (%)	Employment (%)	Turnover (%)
Micro	96	33	21
Small	4	15	15
Medium	1	13	15

Table 1.2: Business statistics (Rhodes, 2018)

Despite SMEs' importance to the UK economy, and, the fact that undoubtedly, any threat or disruption to their operational ability could potentially lead to serious consequences for the UK economy as a whole (Ingirige & Russell, 2015), recent years SMEs have proven vulnerable to the effects of disruptive events, such as extreme weather events (EWEs) (Crichton, 2006; Wedawatta et al., 2010) and poorly prepared for recovery following a natural disaster (Yoshida & Deyle, 2005). SMEs are vulnerable to severe consequences once affected by a disruptive event and especially EWEs all over the world. For example, in Pakistan, for the 2010 flood event, Asgary et al. (2012) indicated that 64.3% of the sampled businesses reopened three months after the flood event whereas 5% of the sample businesses remained out of businesses for more than five months. In terms of the UK following the Cumbrian floods in 2009,

Wiseman and Parry (2016) indicated that 37% of the sample businesses returned to normal operation after two to three months and 13% remained out of business for longer than a year. The economic impact linked to the closure of these businesses is significant; undoubtedly a cumulative loss of SMEs will lead to a substantial impact on the economy (Yoshida & Deyle, 2005). Therefore, the significant risk that flood events pose to the UK's SMEs means that managing and mitigating the potential for flooding to impact the economy is an issue of great importance.

1.3 RESEARCH METHODOLOGY

The research presented in this thesis has been carried out in accordance with the methodology outlined in Figure 1.1.

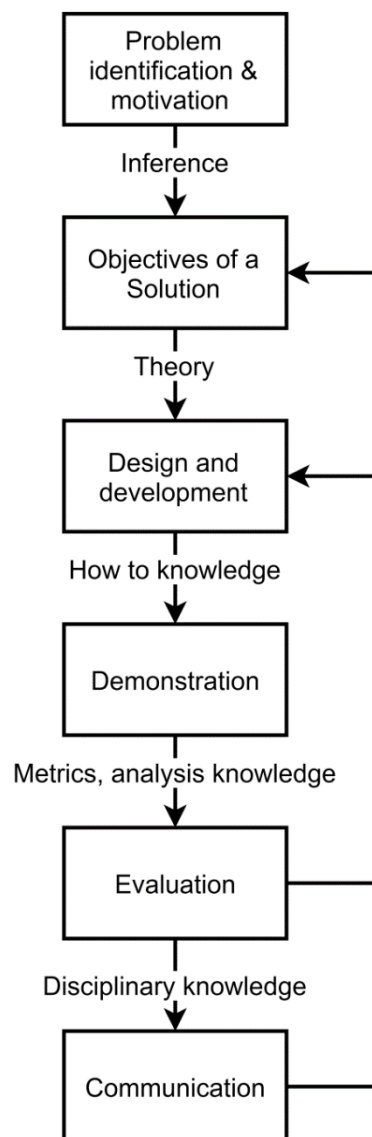


Figure 1.1: Overview of the research methodology (Peppers et al., 2007)

Figure 1.1 presents six activities in a nominal sequence. First, the *problem identification and motivation activity* defines and formulates the research problem along with the motivation for the research. Secondly, the *objectives of a solution activity* identifies the requirements of the solution (e.g. model, framework, or approach) for the identified problem. In order to move from the *objectives of a solution activity* to the *design and development activity*, prior theory of the selected solution is required. Next, the demonstration activity refers to the application of the developed model or method to the case study considered. For the evaluation activity, it measures how well the developed model or method was developed. This is achieved by comparing the actual results of the developed model or method with the objectives of a solution. Finally, communicating the defined problem along with the developed solution to researchers and other relevant audiences (i.e. writing-up and publishing this work).

1.4 ORGANISATION OF THE THESIS

The purpose of this thesis is to achieve the aim of developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flood events.

1.4.1 Problem Identification and Motivation (Chapters 2 and 3)

- Chapter 2 provides the various definitions of SMEs across several countries as well as the specific characteristics of SMEs. Following this, Chapter 2 presents an overview of disruptive events affecting businesses, focusing on extreme weather events (EWEs), especially flooding. It also presents a literature review encompassing relevant research to investigate SMEs with respect to flooding. Finally, the existing definitions of immediate response to and short-term recovery from flooding are discussed.
- Chapter 3 presents a literature review of the relevant research associated with computational models of SMEs and flooding to provide a deeper understanding and greater insight into the impacts of such events and provides an overview of how SMEs and flood events were modelled and simulated. As a result, the data gathered in the literature review leads to the identification of the key elements

of an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding.

1.4.2 Objectives of a Solution (Chapter 4)

- Chapter 4 identifies and discusses the requirements of the ABMS framework with respect to the key elements identified in Chapters 2 and 3 to provide an explanation of how to incorporate these key elements in an integrated and connected framework.

1.4.3 Design and Development (Chapters 5 - 7)

- Chapter 5 presents an overview of the developed ABMS framework to model SMEs' immediate response to and short-term recovery from flooding. The framework consists of three components: (i) flood event simulation, (ii) modelled geographical environment (MGE), and (iii) agent-based modelling and simulation. Parts of this chapter have been published and presented at (i) the 29th European modeling and simulation symposium (Alharbi & Coates, 2017), (ii) the 6th international conference on flood and urban water management (Alharbi & Coates, 2018), (iii) the 16th international conference on information systems for crisis response and management (Alharbi & Coates, 2019a), (iv) the international journal of simulation and process modelling (Alharbi & Coates, 2019b), and published in (v) the international journal of engineering applications of artificial intelligence (Coates et al., 2019b).
- Chapter 6 describes how the three ABMS framework components are linked and implemented, focusing on the framework's MGE component.
- Chapter 7 presents details of the ABMS framework developed to model and simulate SME's immediate response to, and short-term recovery from, a flood event. In this chapter, SMEs are modelled according to their pre-flood and post-flood behaviours, and attributes, along with a set of precautionary measures. It also presents how SME-related organisations are modelled and how they communicate with SMEs to provide them with assistance to support SMEs' operation and recovery. Parts of Chapter 7 have been published and presented at (i) the 29th European modeling and simulation symposium (Alharbi & Coates, 2017), (ii) the 6th international conference on flood and urban water

management (Alharbi & Coates, 2018), (iii) the 16th international conference on information systems for crisis response and management (Alharbi & Coates, 2019a), (iv) the international journal of simulation and process modelling (Alharbi & Coates, 2019b), (v) the international journal of engineering applications of artificial intelligence (Coates et al., 2019b), and published in (vi) the philosophical transactions A, royal society journal (Coates et al., 2019a).

1.4.4 Demonstration (Chapters 8 and 9)

- Chapter 8 presents the application of the ABMS framework to two UK-based case studies: (a) the Lower Don Valley region of Sheffield in South Yorkshire and (b) Tewkesbury in Gloucestershire. Also, it sets out a number of simulation experiments related to manufacturing and retail SMEs. Each of the defined experiments is distinct in that they employ different combinations of precautionary measures to investigate how SMEs' behaviours and precautionary measures, and combinations of them, impact pre-flood immediate response and post-flood short-term recovery. For the Lower Don Valley region of Sheffield, parts related to this case study have been published and presented at (i) the 29th European modeling and simulation symposium (Alharbi & Coates, 2017), (ii) the 6th international conference on flood and urban water management (Alharbi & Coates, 2018), (iii) the international journal of simulation and process modelling (Alharbi & Coates, 2019b), and published in (iv) the international journal of engineering applications of artificial intelligence (Coates et al., 2019b). In terms of the Tewkesbury case study, this has been published and presented at (i) the 16th international conference on information systems for crisis response and management (Alharbi & Coates, 2019a), and (ii) the philosophical transactions A, royal society journal (Coates et al., 2019a).
- Chapter 9 presents the results of modelling and simulating a proportion of manufacturing and retail SMEs identified in (a) the Lower Don Valley region of Sheffield and (b) Tewkesbury. Manufacturing and retail SMEs are investigated over three stages, namely pre-flood, flood (non-operational), and post-flood. In addition, this chapter presents the results of SME-related organisation's effect on SME's pre-flood immediate response to and post-flood short-term recovery from flooding. Parts of Chapter 9 have been published and

presented at (i) the 29th European modelling and simulation symposium (Alharbi & Coates, 2017), (ii) the 6th international conference on flood and urban water management (Alharbi & Coates, 2018), (iii) the 16th international conference on information systems for crisis response and management (Alharbi & Coates, 2019a), and published in (iv) the international journal of simulation and process modelling (Alharbi & Coates, 2019b).

1.4.5 Evaluation (Chapter 10)

- Chapter 10 evaluates the ABMS framework in relation to the requirements stated in Chapter 4 by examining its application to the case studies presented in Chapter 9. In particular, it highlights the achievements and weaknesses of the developed ABMS framework in terms of the requirements identified in Chapter 4.

1.4.6 Conclusion (Chapter 11)

- Finally, Chapter 11 concludes the work carried out in this thesis and outlining the unique contribution of the research. Specifically, it illustrates the work presented in this thesis and shows how the chapters are linked and integrated. Furthermore, the relevant chapters and parts of the thesis are cross-referenced to each aspect of the work.

Chapter 2

Business and Disruptive Events

This chapter defines the characteristics of SMEs and explains SME's importance to the UK's national economy. It also presents an overview of disruptive events with the focus on extreme weather events (EWEs), especially flooding.

Section 2.1 presents a set of definitions of SMEs and outlines their characteristics as well as their importance to the economy. Next, Section 2.2 presents an overview of disruptive events, EWEs, and flooding. Section 2.3 reviews several flooding and SME-related studies to highlight the impacts of flooding on SMEs and national economies and identify some or all of the key elements required to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. Following this, Section 2.4 discusses the emergency disaster risk management cycle. Finally, Section 2.5 discusses the existing definitions of immediate response to and short-term recovery from flooding before presenting the definitions employed in this thesis.

2.1 SMALL AND MEDIUM-SIZED ENTERPRISES (SMES)

Prior to investigating SMEs' immediate response to and short-term recovery from flooding and outlining the previous research in this area, it is important to gain a comprehensive understanding of how SMEs are defined and characterised. Initially, a definition of what constitutes an SME will be provided before presenting SMEs' characteristics and their importance to a nation's economy. Following this, a brief overview of the UK's SME sectors will be presented.

2.1.1 Definition of Small and Medium-Sized Enterprises (SMEs)

The literature on SMEs fails to provide any consensus on a common definition of an SME (Gunningham, 2002; Lauder et al., 1994) because the definition of what constitutes an SME varies depending on the country of origin (Hallberg, 1999). For example, in the UK, the term SME refers to any business that has fewer than 250 employees (Lukács, 2005), which is the same as the European definition (European Commission, 2015). However, in the USA and Australia, SME refers to any business that has fewer than 500 and 100 employees, respectively (Ayyagari et al., 2003). In relation to the UK definition, SMEs are categorised as micro, small or medium according to their number of employees. That is, a micro-sized business has 1 to 9 employees, a small business has 10 to 49, and a medium-sized business has 50 to 249 (Rhodes, 2018).

2.1.2 Characteristics of Small and Medium-Sized Enterprises (SMEs)

SMEs are characterised as: (i) independence, (ii) individual administration, and (iii) a restricted market share (Wedawatta, 2013). Also, SMEs vary in terms of size and other dimensions such as annual turnover (Tonge, 2001), and they represent a heterogeneous market sector (Hallberg, 1999) including a diverse range of firms; from handicraft producers to computer software companies (Lukács, 2005). However, each SME has its unique organisational culture emerging from the homogeneity between its ownership and management that characterises most SMEs (Macal & North, 2010). This statement has motivated some authors such as Bannock (2004) to confirm that each SME is distinctive in its own right. Also, since most SMEs are owned by individuals or families, owners' personal values are likely to influence the businesses' organizational structure (IFF, 2008).

It has been claimed that the vast majority of SMEs suffer from a lack of both managerial and technical skills (Jones & Tilley, 2003), however, they tend to be more flexible in terms of their operation and response to customer needs than larger firms (OECD, 2000). This flexibility and responsiveness are due to SMEs' limited internal resources, especially in terms of finance and management resources and their knowledge base, compared to other large businesses (North et al., 2001; Omar & Fraser, 2010). SMEs also rely on a small number of customers and operate within

limited markets (Löfving et al., 2014) because their operations are rooted mainly in local communities (Bannock, 2004).

In addition to the aforementioned characteristics, a number of SME characteristics have been discussed in other studies. For example, Curran and Blackburn (2000) highlight three characteristics of SMEs (also proposed by Wynarczyk et al. (1993)), namely, uncertainty, innovation, and evolution. Firstly, uncertainty is associated with SMEs being price-takers, meaning that small businesses must accept the prevailing prices in the market in which it trades. Uncertainty also refers to having a restricted customer base, and a lack of resources. Furthermore, SMEs are innovative because they often emulate large firms' products or services. SMEs have made notable progress in this aspect (Act, 2008) although they tend not to be as research-based businesses compared with large firms (Storey, 2016). Finally, evolution denotes the magnitude of experience that small businesses may gain while growing. In relation to this, five stages of growth have been highlighted: inception, survival, growth, expansion, and maturity (Scott & Bruce, 1987).

2.1.3 Business Sectors

Private-sector development plays a key role in creating economic growth. For example, the UK private sector is made up of about 5.7 million businesses of which 99.9% are SMEs, and since 2000, this number has increased by 2.2 million businesses (Rhodes, 2018). Furthermore, businesses are classified into four industries, namely agriculture, mining and utilities; manufacturing; construction; and services businesses.

The agriculture, mining and utilities sector accounts for 192,000 businesses, representing 3% of all UK businesses (Rhodes, 2018). Also, this sector accounts for 3% of total employment and 6% of all turnover in 2018. Furthermore, in the same year, the manufacturing sector accounts for 290,000 businesses, i.e. 5% of all UK businesses, and provides 10% of total employment and 14% of all UK turnover. The construction industry accounts for 992,000 businesses in 2018, which represents 17%, of all UK businesses and provided 8% of total employment and turnover. Service-sector businesses account for three-quarters of all UK companies, (4.2 million businesses), encompassing 12 different sectors (see Table 2.1). Among these, the professional, scientific, and technical industry sectors are marked as the largest,

representing 14% of all businesses. Furthermore, the retail sector is the second largest sector among the service industry, representing 10% of all businesses and has the largest turnover of any UK sector at 34%. In Table 2.1, it is noted that the total percentages of all employment and turnover of all sectors mentioned are greater than 100%. This is due to rounding as presented in (Rhodes, 2018).

Industry	Sector	Businesses		Employment (%)	Turnover (%)
		Number (000s)	(%)		
Agriculture, mining and utilities		192	3	3	6
Manufacturing		290	5	10	14
Construction		992	17	8	8
Services	Retail	556	10	19	34
	Transportation	326	6	6	5
	Accommodation & food	186	3	9	3
	ICT	363	6	5	7
	Financial and insurance	87	2	4	-
	Real estate activities	116	2	2	2
	Professional and scientific	817	14	10	9
	Administrative & support service	491	9	11	7
	Education	283	5	2	1
	Health and social work	360	6	7	2
	Arts and recreation	276	5	3	3
	Other service activities	334	6	3	1

Table 2.1: Business by industry (Rhodes, 2018)

2.2 DISRUPTIVE EVENTS

Disruptive events are actions that disrupt the completion of ordinary routines; they may last for hours or even days (Alsaedi et al., 2017; Guha, 2016; Howick et al., 2009). Disruptive events can manifest in the form of extreme weather events (e.g. flooding, heavy rain, wind, fog, storm, high waves, heat waves, or extreme cold), energy loss (e.g. blackouts, power loss, fire, electricity supply issues, water supply problems, or gas leaks), communication failure (e.g. signal loss, communication loss, or transmitter breakdown) (Alsaedi et al., 2017), or transportation issues (e.g. public transport problems, traffic jams, accidents, crashes, long delays, services breakdowns, hazardous conditions, blocked roads, or cancellations). If any of these disruptive events occur to an SME, it may have a negative impact on its ordinary routine, such as a drop or even stop (cessation) in production in manufacturing SMEs. The next section presents an overview of EWEs, and flooding in particular, given that the focus of this

research is investigating SMEs' immediate response to and short-term recovery from flooding.

2.2.1 Extreme Weather Events (EWEs)

The impacts of unforeseen natural events on human endeavours have always presented challenges for organisations' decision-makers and directors (King, 1995; Linnenluecke & Griffiths, 2010; Weick & Sutcliffe, 2001). Over recent years, unanticipated climate change has disrupted global economic systems and has led to increased consideration of risk and crisis mitigation strategies globally (Islam & van Amstel, 2018; Weyant, 2017). However, few climate-change phenomena have demonstrated as much potential for widespread and long-lasting destruction as those connected with EWEs, and specifically, flooding (Barnett, 2001; Linnenluecke & Griffiths, 2010).

In relation to the definition of EWEs, these events are defined as meteorological conditions that are uncommon for a specific place or season (Francis & Hengeveld, 1998). The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a change in the state of the climate that can be identified, e.g., by using statistical tests, by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (Solomon et al., 2007, p. 943).

EWEs can be in a form of precipitation, floods, droughts, windstorms, extreme temperatures (Meehl et al., 2000) cyclones, heatwaves and extreme cold weather (Mirza, 2003). These extreme events are also classified as extreme weather hazards and extreme weather conditions. Extreme weather hazards are defined as damaging extreme weather events that may lead to social and economic disruption as well as loss of life, financial loss, or property loss (Hallett, 2013). However, EWE is a wider term that encompasses all the weather-related hazards and conditions. EWEs can manifest in the form of different types of hazards or conditions (McGregor et al., 2005).

In relation to the risk associated with EWEs, Curtis et al. (2017) have indicated that recently a large number of EWEs have frequently occurred in the UK; for example, the summer 2007 flood event (Lane, 2008) and the heavy snowfall in the winters of 2009 and 2010 (Prior & Kendon, 2011). These extreme events led to adverse economic

consequences, for example, the UK economy suffered over £3 billion of damage from the 2007 flood. Also, the severe winter weather of 2010 reduced the UK's GDP by 0.5% whereas the associated network disruption cost the UK economy £280 million per day (HCTC, 2011). The average annual cost of EWEs is estimated to account for approximately 0.5-1% of the world's GDP by the middle of the 21st Century (Stern & Stern, 2007). Thus, because resilience to EWEs has become an international issue, the threat of EWEs is a risk that must be managed by communities including businesses and homeowners across the world.

2.2.2 Flooding

Flooding is one of the main EWEs that can negatively affect a nation's economy (ABI, 2007). According to the Association of British Insurers (ABI), worldwide floods are the second-highest cost, weather-related disaster after windstorms (ABI, 2005). For example, in Europe, floods appear to be increasing dramatically in frequency and severity, and projections demonstrate that this increase is anticipated to grow significantly (Kundzewicz, 2005). In terms of the UK economy, the 2007 floods caused over £3 billion worth of damage to approximately 48,000 homes and 7000 businesses (Chatterton et al., 2010; Pitt, 2008; Wedawatta & Ingirige, 2012). According to the ABI, the received claims exceeded 165,000, estimated at £3 billion (ABI, 2007). In the context of businesses, UK businesses' losses were estimated to be in the region of £740 million (Chatterton et al., 2010; Dlugolecki, 2008).

Recent flood events in the UK have created remarkable disruption to businesses, particularly SMEs that are less prepared for the consequences of flooding than larger companies (Crichton, 2006; Wiseman & Parry, 2011). It is projected that in England, the annual loss attributed to residential and business properties due to flooding will be over £1 billion (Leinster, 2009; Wedawatta & Ingirige, 2012). Thus, adaptation to the risks presented by flooding has accordingly become an issue of key significance to SMEs in order to mitigate the potential risk and disruption to their business.

2.3 SMALL AND MEDIUM-SIZED ENTERPRISES (SMES) AND FLOODING

This section reviews several flooding-related studies to highlight the impacts of flooding on SMEs and national economies in addition to investigating SMEs in the

context of flooding. It is acknowledged that this research investigates SMEs' immediate response to and short-term recovery from flooding rather than for all businesses in general; however, this section includes studies conducted on businesses of all sizes including SMEs and large businesses. This is to provide a deeper understanding and greater insight into the effects caused by flooding to all businesses and draw together some of the requirements required to develop an effective ABMS framework to investigate SME's immediate response to and short-term recovery from flood events.

2.3.1 Impacts of Flooding on Small and Medium-Sized Enterprises (SMEs) and National Economies

Flooding represents an EWE that has been given special attention in the literature because of its potential to cause devastating impacts on most nations' economies. Flood impacts are generally classified into two categories, namely tangible and intangible impacts (Hammond et al., 2015). Tangible impacts can be measured in financial terms, such as damage to property, equipment, and loss of profit (Smith & Ward, 1998). However, the intangible impacts are those cannot be measured financially, such as the negative impacts on humans (e.g. loss of life, injuries) and on the environment (e.g. contamination).

Flood damage is also classified into further categories, direct and indirect damage (Ingirige et al., 2012; Wijayanti et al., 2017). Direct damage is defined as any damage resultant from the first physical contact of floodwater with property or equipment, whereas indirect damage refers to any damage occurring beyond the immediate limits of a specific flood event. Further, Jonkman et al. (2008) define direct flood damage as the damage occurring within a flooded area, whereas indirect damage is that which occurs outside the flooded area. Messner (2007) refers to direct damage as the damage occurring to the value of physical stock, whereas indirect damage relates to interruptions to product flows and trade linkages.

What is evident is that a flood's impact on businesses increases both direct and indirect losses (Tierney & Bruneau, 2007). For example, damage occurring to a business leading to its closure may consequently lead to a loss of jobs. However, the literature provides little consensus on a common definition of direct and indirect losses

due to flooding (Hammond et al., 2015). For instance, Willner et al. (2018) define indirect losses as relating to the loss of production within the affected companies in addition to the production losses of their suppliers and customers. However, Van der Veen et al. (2003) divide indirect losses into primary and secondary losses: primary indirect losses are business disruption costs that relate explicitly to flooded businesses, whereas secondary indirect losses are those affecting the economy. On the other hand, Rose and Lim (2002) refer to primary losses as the disruption to production affecting businesses.

Table 2.2 lists five studies that have assessed the impacts of flooding on SMEs and highlights which of these impacts were defined by SMEs as the most serious. According to Woodman (2008), 53% of respondents concur that ‘staff unavailable for work’ is the most common impact of flooding whereas ‘loss of power, telecommunications’ is 11%. Next, EKOS Consulting Ltd (2008) reports that 80-100% of small businesses agree that ‘flooded premises’, ‘damage to premises (structural or otherwise)’, ‘damaged or lost stock’, ‘damaged or lost business equipment’, and ‘loss of income, reduced profit’ are the most common impacts of flooding on businesses. In contrast, Norrington and Underwood (2008) report that 38% of businesses indicated that ‘damage to premises (structural or otherwise)’ and ‘damaged or lost stock’ are the main impacts of flooding. In Wiseman and Parry (2011)’s study, ‘Travel difficulties for customers accessing the business’ and ‘Travel difficulties for staff’ were selected as the most serious impacts of flooding (27% and 25%, respectively, among the other impacts). Finally, Wedawatta and Ingirige (2012) point out that ‘loss of trade, production’, ‘loss of income, reduced profit’, ‘travel difficulties for customers accessing the business’, and ‘increase in costs’ are the common impacts of flooding as they represent 91% of the total impacts SMEs cited.

Impacts	Woodman (2008)	EKOS Consulting Ltd (2008)	Norrington and Underwood (2008)	Wiseman and Parry (2011)	Wedawatta and Ingirige (2012)
Flooded premises	38%	80%-100%		5%	82%
Damage to premises (structural or otherwise)		80%-100%	38%	3%	66%
Damaged or lost stock		80%-100%			84%
Damaged or lost business equipment		80%-100%			61%
Move to temporary business premises				1%	34%
Loss of trade, production		60%-80%		10%	91%
Loss of income, reduced profit		80%-100%	13%		91%
Supplies to the business delayed (due to travel difficulties)		60%-80%		24%	73%
Suppliers affected by problems other than travel	27%			7%	
Deliveries to customers delayed (due to travel difficulties)		60%-80%		14%	75%
Travel difficulties for customers accessing the business			22%	27%	91%
Customers affected by problems other than travel difficulties				8%	89%
Staff unavailable for work	53%				
Travel difficulties for staff				25%	75%
Forced reduction in number of employees		60%-80%			
Other problems for staff, including anxiety		60%-80%		15%	
Decided to move premises		60%-80%			
Loss of power, telecommunications	11%			11%	86%
Loss of water supplies					
Increase in costs					91%
Increase in insurance premiums		60%-80%			73%
Increase in trade/demand for services, positive impact	24%		8%		
Other adverse impacts				6%	64%

Table 2.2: Impacts of flooding on SMEs (Wedawatta, 2013)

As presented in Table 2.2, flood events' direct and indirect impacts can have devastating consequences for local and national economies, the environment, and people; due to these consequences, a number of studies have investigated the context and background of flood impacts mostly in terms of the effects on businesses (Asgary et al., 2012; Wedawatta et al., 2014; Zaman, 2012).

Asgary et al. (2012) carried out a research project to identify the impacts of a 2010 flood in Pakistan on small businesses and the factors that influenced these businesses' disaster-recovery performance. The study involved a questionnaire of 500 small businesses affected by flooding across different districts in three areas of Pakistan. Asgary et al. found that the vast majority (90%) were able to re-open within six months after the flood event. However, most of these SMEs then operated at a loss, while only a small number of SMEs were able to perform at the same pre-flood level or slightly better. The study also found that only a small number of SMEs (n=4) were insured against natural disasters. In response to questions regarding the factors that contributed to the flood damage, about 22% of respondents confirmed that their business's properties themselves were the most affected. Further, 19.7% pointed out that road networks were also significantly affected by the flood event. However, the remaining respondents varied in terms of which factors they identified as most affected by the flooding (e.g. shelf items, tools and equipment, machines and computers, loss of sales, business records/data, disruption to supply chain, and unavailability of transport). Asgary et al.'s study highlights a number of variables that had significant impacts on the businesses recovery time, such as access to financial resources, availability of human resources, availability of skilled labour, restoration-critical infrastructure, customer retention, recovery of logistics/supply chain, and availability of technical support. Furthermore, this research demonstrates that governmental and/or non-governmental support, such as the provision of insurance, may speed up small businesses' recovery.

In the same vein, Zaman (2012) research project investigates the impact of flooding from December 2010 to January 2011 on small businesses in Rockhampton, Australia. The study involves a survey of 100 small businesses to identify the relationships between the impact of flooding and the businesses in terms of location, number of employees, weekly turnover, and the year the business was established. The

findings show that the locations of businesses, weekly turnover, and businesses with smaller numbers of employees all have a direct impact on small businesses' rate of recovery, although the age of a business does not correlate with the severity of flood impacts.

In line with the studies mentioned (Asgary et al., 2012; Zaman, 2012), Wedawatta et al. (2014) presented a paper examining the full range of effects experienced by SMEs located in Cockermouth, UK, following the floods of 2009. The study involved a questionnaire completed by employees at both flood-affected and non-flood-affected SMEs. In response to question items about the most common impacts that SMEs experienced in relation to flooding, respondents reported that these included: a loss of operation and trading, the flooding of premises, damaged or spoiled stock/products, additional costs, travel difficulties for customers, and the loss of electricity and other services. The authors classified the impacts of the flooding into direct impacts (such as damage to premises or stock) and indirect impacts (such as travel difficulties for customers and suppliers and a significant increase in insurance premiums). Thus, this research project encourages SMEs to adopt property-level flood measures and other risk management/business continuity measures to reduce their vulnerability to future flood events.

Drawing on previous studies (Asgary et al., 2012; Wedawatta, 2013; Wedawatta et al., 2014; Zaman, 2012), the studies investigated a range of flood impacts encountered by businesses and confirmed the need for businesses to prepare for such events. It is noted that businesses were varied in terms of the level of flooding impacts they experienced and these impacts may affect business operation for different periods (i.e. days, months or even years).

2.3.2 Investigating Small and Medium-Sized Enterprises (SMEs) in the context of Flooding

A considerable number of studies investigate the provisions businesses make for flood events (Bhattacharya-Mis & Lamond, 2014; Henderson & Whittam, 2016; Kreibich et al., 2007; Kreibich et al., 2011; Mis et al., 2015; Pathak & Ahmad, 2016).

In terms of commercial properties' flood-preparedness, Kreibich et al. (2007) investigated companies' potential for improving their flood management practices by

focusing on the August 2002 flood in Saxony, Germany. This study involved a survey of 415 companies from various sectors and of various sizes, and showed that companies' level of preparedness and precautions against flooding were limited. The survey covered questions on various aspects, such as (i) flood warnings (e.g. source of warning); (ii) emergency measures (e.g. efficiency of safeguarding equipment and products or stock); (iii) clean-up (e.g. duration and number of people involved and clean-up); (v) characteristics of and damage to contents (e.g. total amount of damage to equipment); and (vi) recovery (e.g. duration of interruption until resumption of normal business operations). It also included questions about preparedness level, such as (i) financial precautionary measures (e.g. flood insurance); (ii) behavioural precautionary measures (e.g. emergency exercise and emergency plans); and (iii) building-specific precautionary measures (e.g. availability of water barriers). In relation to Kreibich et al. (2007) key findings, about half of the companies did not receive any flood warnings, and thus, the vast majority were unable to perform emergency measures successfully. The study reports that precautionary measures related to physical buildings were the most frequently implemented while behavioural measures were the least-implemented. This study also demonstrated that the precautionary measures adopted by companies depend specifically on companies' situations. For example, companies that do not deal with hazardous substances are not required to undertake special safeguarding measures to deal with these substances. The study also revealed that most companies improved their flood preparedness and precautionary measures after the flood event. Further, the findings indicated that businesses still fail to consider appropriate flood-precaution measures.

Linked to the 2007 study, Kreibich et al. (2011) conducted another research project to examine private households' and businesses' flood preparedness along the Elbe River, Germany, in 2002 and 2006. It included telephone interviews conducted with 1697 private households and 415 businesses following the 2002 flood. After the 2006 flood event, a total of 461 private households and 227 of businesses telephone interviews were conducted. In terms of the 2002 flood event, the study showed that neither private households or businesses nor the authorities expected a flood risk in the Elbe catchment area prior to 2002 because of their lack of experience; thus, they were poorly prepared and many governmental flood-risk programs were launched thereafter. For the 2006 flood event, the adaptation of precautionary measures by

private households increased significantly after the 2002 flood event. However, about 29% of businesses failed to learn any lessons from the 2002 flood event, and thus, failed to implement any precautionary measures. In particular, the use of water barriers significantly increased, whereas the use of flood-proof storage improved by just 1%; however, surprisingly, the uptake of flood insurance decreased by 6%. This is attributable to rising premiums for insurance coverage after the 2002 flood. Following the 2002 flood event, a large number of households and businesses became aware of the appropriate actions required when they received flood warnings. However, no significant increase in implementing emergency measures was evident (e.g. protecting building contents, equipment, goods, products or stock by moving them to flood-safe areas).

Two further studies (Bhattacharya-Mis & Lamond, 2014; Mis et al., 2015) reviewed and used the same case studies (Sheffield and Wakefield) to investigate businesses' and households' preparedness for flood events. Firstly, Bhattacharya-Mis and Lamond (2014) focused on analysing businesses' preparedness and recovery patterns using two case studies, namely Sheffield and Wakefield. The research project involved a self-administered questionnaire of 69 businesses. The questionnaire covered a variety of topics such as flood damage, preparedness measures implemented, sources of recovery, and property characteristics. In terms of the key findings, the Environment Agency's flood warnings, property and business insurance, and temporary preparatory measures (i.e. short-term solutions for risk mitigation) were the most popular measures implemented by businesses. In relation to the financial cost of recovery, respondents were prompted to assign a rank to this factor between 1 and 5 (1 = no cost incurred and 5 = highly expensive). The results showed that disruption of sales represented the highest costs (13%), followed by clean-up charges (12%). Other factors, such as machinery repair, supply disruption, and work-hour loss, represented the third-highest costs (10%). This study showed that 30% of businesses recovered immediately, 38% within 3 days, 16% within a week, 7% within two weeks, 3% in a month, and 6% in over a month. The research also indicated that there was an obvious lack of preparatory measures to counter the indirect effects of flooding such as taking into account the impacts on employees' jobs and suppliers.

Another study by Mis et al. (2015) collected data using a questionnaire of homeowners and businesses who had experienced flood damage to their properties in

Sheffield and Wakefield following the summer floods of 2007. The results of the residential property survey showed that about 35% of homeowners had moved their high-value items to upper floors and 33% had registered for flood warnings as non-structural measures. For the resistance measures, which intended to prevent the *entry* of floodwater into premises, about 39% of homeowners had been able to place sandbags in doorways and 20% of them had put silicon around openings. However, only 15% of homeowners had been able to cover airbricks, and 4% had non-return valves installed. In terms of the resilience measures, which intended to limit the *effect* of floodwater entering a premises, 28% of homeowners had flood tiles put in place, whereas 26% had raised the level of electrical sockets above the flood line. In relation to the commercial property survey, Mis et al.'s research shows that about 20% of respondents agreed that the most common impact of flooding was travel difficulty for customers. Similarly, 17% selected operational disruption as the most common impact of flooding. However, few businesses selected closing during the flood, damage to stock, damage to machinery, damage inside buildings, and structural damage as the most common impacts. In terms of the resistance measures, the study reveals that 23% of the businesses had property insurance in place, 20% had implemented temporary measures, such as placing sandbags at doorways, 18% had registered for EA warnings, and 13% had backed up their data and had emergency plans in place. However, only 10% of businesses moved to an alternative location, had an alternative power source and had alternative business plans in place. The results of Mis et al.'s study showed that the homeowners and businesses decision-makers were more likely to implement non-structural measures (such as registering for flood alert warnings, than other measures) due to the lower costs involved. It also shows that the uptake of other measures, such as resistance and resilience, was very low.

Ingirige and Russell (2015) investigated SMEs' resilience to flooding, sampling seven affected SMEs as experts in different flood-resilience measures in Braunton, UK. The authors present a number of physical strategies to improve businesses' preparedness levels, such as installing flood barriers at doorways, sealing under-floor drains, and purchasing flood-proof furniture. In terms of flood recovery, the authors recommend that SMEs have insurance in place.

Another relevant study by Henderson and Whittam (2016) investigates small businesses' flood resilience in Scotland using semi-structured interviews with a

sample of six small business owners. The paper reports that all six of the businesses maintained preparation for flooding, such as moving stock to safety and erecting flood defences, such as floodgates, while the floodwaters were rising. Further, it was reported that all the businesses interviewed had their own strategies, such as keeping stock upstairs, for coping with flooding in addition to their own prevention measures, such as implementing sandbags or floodgates at doorways. The results also showed that every business has implemented different coping strategies in preparation for the event. The first business kept its stock upstairs and its bottom shelves were kept empty and that was achieved within an hour. In the second business, plastic buckets were used to cover the stock, which might be effective for a low level of floodwater. The third business used a raised area at the back of the shop for stock storage during the flood, whereas the fourth business permanently raised its stocks above ground level. The fifth business lifted up its near-ground level stock onto tables as a temporary measure, whereas the sixth business, which had not yet experienced a flood, trained employees to move everything upstairs (which could take up to 3 hours with just 3 employees).

Pathak and Ahmad (2016) investigated the flood-recovery strategies adopted by manufacturing SMEs, focusing on the coping strategies implemented by flood-affected SMEs in Thailand. The study employed both qualitative and quantitative methods: questionnaires, interviews, and focus group discussions. The results reveal that SMEs need to be motivated to implement preparedness and mitigation measures, including both structural and non-structural measures. The results also show that a lack of insurance was a key factor affecting SMEs' recovery time. Furthermore, a lack of government planning, policy implementation, and managerial disaster recovery tools led to obvious gaps in the disaster-management and recovery strategies adopted. Thus, this research project shows that the current coping mechanisms were incapable of reducing the recovery period, and there is an obvious need for a more in-depth investigation of the factors contributing to SMEs' vulnerability to flood events.

Several previous studies (Bhattacharya-Mis & Lamond, 2014; Henderson & Whittam, 2016; Kreibich et al., 2007; Kreibich et al., 2011; Mis et al., 2015; Pathak & Ahmad, 2016) investigated businesses' responses to and/or recovery from flooding and presented a range of flood precautionary measures and behaviours. These could be considered in terms of an ABMS framework to investigate SME's immediate

response to and short-term recovery from flooding. For example, Kreibich et al. (2007) presented a set of business-focused financial precautionary measures, behavioural precautionary measures, and building-specific precautionary measures. Also, other studies (Bhattacharya-Mis & Lamond, 2014; Henderson & Whittam, 2016; Mis et al., 2015; Pathak & Ahmad, 2016) demonstrated a range of preparedness measures implemented by businesses.

2.4 EMERGENCY/DISASTER RISK MANAGEMENT CYCLE

A disaster is defined as an unexpected extreme event which causes excessive harm to human beings, plants, and animals (Khan et al., 2008). Disasters can be either a natural or man-made (Heaslip et al., 2010). In recent years, natural disasters have notably increased in frequency due to changes in socioeconomic, environmental, and climatic patterns (European Environment Agency, 2011; UN, 2009b). In particular, such disasters have occurred as a result of hydro- meteorological hazards (Prenger-Berninghoff et al., 2014). For example, the flooding that struck in August 2005 in the Targaniczanka stream catchment area in Poland; flood events caused by the peak discharge of the Ubaye River in May 2008 in France; a flood event in 2005 that affected the Nehoiu Valley in Buzău County in Romania; and the flood event in the Fella Basin in August 2003 in Italy and caused damage valued at hundreds of millions of Euros.

Disaster Risk Management (DRM) strategies and measures are applied to reduce the potential risks and the overall threats caused by an EWE (Paul, 2011). Measures are actions implemented following the direction of such policies to accomplish the main goal (Prenger-Berninghoff et al., 2014). In terms of DRM, it is a process designed mainly to improve the understanding of disaster risk, reduce potential losses, and to control and limit risks (Field et al., 2012; Graham et al., 2009; UN, 2009a). DRM involves four phases: (i) mitigation/prevention, (ii) preparedness, (iii) response, and (iv) recovery (Jha et al., 2013) as shown in Figure 2.1.

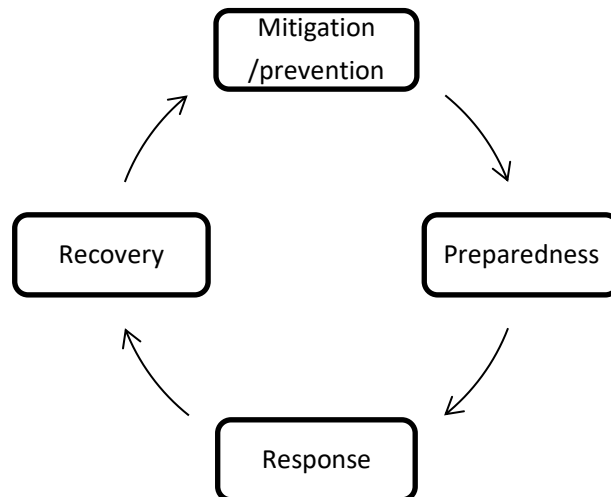


Figure 2.1: Phases of disaster risk management (Jha et al., 2013)

Mitigation/prevention is defined as structural and non-structural measures implemented to reduce or prevent the threat of the potential disaster consequences (Alexander, 2002; Coppola, 2006; Hübl et al., 2005; López-Peláez & Pigeon, 2011). Preparation refers to actions taken to reduce the impact of a potential disaster. Response refers to decisions and actions taken during the impact of a disaster and in the short-term aftermath (Alexander, 2002; HM Government, 2013). Recovery is defined as the process undertaken to repair damage, restore services, and reconstruct facilities in the aftermath (Medd et al., 2015). According to Prenger-Berninghoff et al. (2014), the response and recovery phases often are given greater action and policy attention in decision-making. Also, the preparedness phase is usually given greater attention than prevention because it requires immediate actions. Finally, *response* and *recovery* alone are insufficient in managing disasters without *preparedness* and *mitigation* activities (Coppola, 2006).

2.5 IMMEDIATE RESPONSE AND SHORT-TERM RECOVERY

Response activities are defined as the immediate actions taken and the decisions made to deal with the immediate impact of a hazardous event (Alexander, 2002; HM Government, 2013). The actual response may begin well before the disaster actually occurs or immediately after the disaster's impact (Coppola, 2006). Furthermore, response activities are likely to be short-term and last for hours or days.

In relation to recovery activities, these are mainly focused on reconstructing infrastructure and returning the social and economic life of the community to normal, with the integration of mitigation measures as its main goal (TEMA, 2006). Emergency Response and Recovery guidance for the UK government outlines that the recovery activities may take months or even years to achieve (HM Government, 2013). However, Waugh (2000) defined the recovery activities as those activities carried out shortly after a disaster occurs to restore lifelines, e.g. providing temporary shelter and restoring power (Waugh, 2000). Therefore, some authors such as Baird (2010) divided the recovery activities into two periods – short-term and long-term (Baird, 2010).

According to the National Governors' Association (NGA) report in 1979, short-term recovery focuses on returning businesses to minimum operating standards with employing some essential activities, such as cleaning up premises (NGA, 1979). Furthermore, the National Response Framework (NRF) published by the U.S. Department of Homeland Security in 2008 reports that the short-term recovery represents immediate actions after a disaster has occurred and overlaps with the response, such as restoring interrupted utilities and other essential services and it may last for weeks (NRF, 2008). Furthermore, the Disaster Recovery Plan for the State of Tennessee reported that the short-term recovery includes returning important services, such as power, communications, water and sewage (TEMA, 2006).

Long-term recovery focuses on returning the operation levels to normal or perhaps a better level than before the disaster occurred (e.g. using redevelopment loans and legal assistance (NGA, 1979). Long-term recovery activities could take many years to achieve and comprise of permanent measures (structural/non-structural) that may include long-term prevention measures (Prenger-Berninghoff et al., 2014). Also, long-term recovery may include actions that could be required for a number of months or years (e.g. completing the redevelopment of damaged areas) (NRF, 2008).

Following this discussion, the immediate response and short-term recovery terms adopted in this thesis are defined as follows:

- Immediate response refers to preparation measures or actions undertaken from the time a disaster is expected until the disaster occurs; and

- Short-term recovery refers to recovery measures or actions undertaken from the time the disaster ends until an organisation or business returns to its normal level of operation (i.e. pre-disaster level).

2.6 SUMMARY

This chapter has discussed the existing definitions of SMEs and highlights that there is no universal consensus about how SMEs are defined. However, in the UK, the upper limit for SMEs is fewer than 250 employees. In terms of SMEs' importance, SMEs represent 99.9% of all the UK businesses, and thus, any disruption to this important type of business may cause a major economic down turn. This chapter has discussed EWEs along with their associated risks to nations' economy, such as reducing GDP. It also discussed risks associated with flooding (e.g. loss of trade and production, and loss of power and telecommunications). Furthermore, several flooding- and businesses- related studies have been reviewed and subsequently, the key elements that could be considered in terms of an ABMS framework to investigate SME's immediate response to and short-term recovery from flooding are:

- SME precautionary measures, i.e. actions and measures that could be undertaken in advance before anticipating or knowing that a disaster was imminent.
- SME behaviours, i.e. actions and measures that could be undertaken after anticipating or knowing about the occurrence of a disaster.

Finally, the chapter provided an overview of the existing definitions of immediate response to and short-term recovery from flood events.

Chapter 3

Computational Models of SMEs and Flooding

This chapter reviews the existing literature associated with computational models of SMEs and flooding to provide a deeper understanding and greater insight into the design of these computational models and the effects caused by flood events. Also, this literature review aims to identify the key elements required to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding.

Section 3.1 reviews several studies that have used ABMs in the context of flood events while Section 3.2 discusses studies related to modelling SMEs. Finally, Section 3.3 summarises the identified key elements of an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding and closes the chapter.

3.1 AGENT-BASED MODELLING AND RELATED FLOOD EVENTS

This section reviews several studies that have used ABMs in the context of flood events (for more information about ABMs, please see Appendix A). This is to enable the identification of all or some of the key elements that can be incorporated in modelling SMEs and flood events given that the focus of this research is developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. In terms of flood-related studies, a considerable number of papers discuss the process of modelling businesses in the context of flooding (Coates et al., 2014; Coates et al., 2016; Li & Coates, 2016; Li et al., 2015), assessing flood

losses with household responses (Yang et al., 2018), analysing flood risk communication strategies (Haer et al., 2017), evolving community flood risk (Tonn & Guikema, 2018), assessing surface water flood risk and management strategies (Jenkins et al., 2017), assessing flood risk and insurance (Dubbelboer et al., 2017), and evacuations (Dawson et al., 2011; Liu & Lim, 2018; Liu et al., 2009).

In relation to modelling SMEs in the context of flooding, Coates et al. (2014) reported on the use of ABMS to identify flooded and non-flooded businesses in a case study in Sheffield, UK. The authors used GIS to couple the inundation data with Ordnance Survey (OS) information to identify at-risk businesses. This dataset on the flooded and non-flooded businesses was used by a series of studies, such as Coates et al. (2016). Linked to the previous study, Li et al. (2015) and Coates et al. (2016) focus on assessing businesses' responses to flooding and describes a potential agent-based modelling design and its agents, attributes, and rules controlling agents' behaviours. Li et al. (2015) provide an overview of how SMEs are modelled, including their pre-flood behaviours (such as lifting up equipment and stock to higher levels), and post-flood behaviours (such as claiming insurance and searching for clean-up contractors). Furthermore, Li et al.'s paper shows the need to model the interaction between SMEs and other organisations, such as customers, suppliers, and service companies (i.e. plumbers, electricians, and mutual aid partners).

Li and Coates (2016) provide an overview of the proposed ABMs model's design. The model is constructed using three components: (i) pre-processing, (ii) agent-based modelling and simulation, and (iii) post-processing. In terms of the pre-processing component, this includes the virtual geographical environment that enables the identification of the flooded and non-flooded SMEs. The agent-based modelling and simulation component includes the process of modelling agents along with the relevant interactions between them. In the post-processing component, the output information and data analysis are used to define the level of effects of different behaviours on business operations. The authors also provide a performance evaluation of SMEs in the simulation that can be used to measure the impact of flooding on SMEs' performance. The authors use operational level (OL) as a measure to evaluate SMEs' performance in ABM simulation; specifically, the total number of completed man-hours of tasks over the total number of man-hours required.

Yang et al. (2018) and Haer et al. (2017) focused on agent-based modelling households with respect to flooding. Even though these papers focus on modelling domestic contexts, they are included in this literature review to provide insights into how properties, which could be SMEs' premises, are modelled. Firstly, Yang et al. (2018) study uses ABMs to simulate flood-response preferences and activities taken within individual households to decrease potential flood losses. The model simulates the impacts of the interaction of inundation and human responses. It consists of three components: (i) inundation data, defined in terms of intensity and duration; (ii) a hydrodynamic model, constructed using *Topography* data, and (iii) simulation and modelling, including household agents that respond to flooding according to a set of behavioural rules. The inundation data and *Topography* data form the inputs to the hydrodynamic model to generate flood scenarios, which enables agents to respond accordingly (i.e. agents only respond if a flood warning is received). In relation to the model design, the model environment is constructed using *Topography*, river data, and household and road locations. These elements were combined using a grid projection in which each cell features a slope. This was used to determine the expected water flow, which, in turn, enabled the identification of 3294 households. The households were modelled along with a set of attributes (e.g. household's location and duration of inundation) and behaviours (e.g. investment in their property in response to the potential flood event). The reported model also consists of flood response measures, which are divided into four categories: (i) far-sighted precaution; (ii) close-to-event measures based on forecasting and warning; (iii) flood-fighting actions, and (iv) recovery actions after an event. Finally, Yang et al.'s study shows that an accurate flood-warning system can reduce flood losses by 30–40% and that investing during the early-response-measures stage is more cost-effective than taking action after a flood event. It also shows that the time at which a warning is received is directly correlated to the level of flood damage, providing that the early warning provides ample time to prepare for flooding.

In terms of flood risk analysis, Haer et al. (2017) developed an agent-based model that combines human decision-making in flood risk analysis. Specifically, the model investigates household investments in loss-reduction measures for three economic decision models: expected utility theory; prospect theory; prospect theory model. To enable this analysis, the agent-based modelling is implemented in the

context of the Heijplaat neighbourhood in Rotterdam, the Netherlands. Haer et al. indicate that this case study was selected due to the extreme flooding this area frequently experiences. In terms of the developed model, the authors indicate that the damage model includes three components: (i) a series of flood inundation maps; (ii) maps illustrating every individual property to signify exposed assets; (iii) a depth damage model. In terms of the illustration of the maps, the authors used a series of flood inundation maps coupled with land-use maps to (i) produce a visualisation of the flood risk area, and (ii) identify depth-damage curves that signify proportion amount of total possible damage. In Haer et al.'s reported model, several agents were modelled (i.e. insurance companies and households) along with their behaviours. The interactions between human and environmental systems are also modelled. This is done to incorporate human behaviour into a flood risk analysis. As a result, the study reveals that the dynamic adaption of households to changing flood risk has the potential to decrease the anticipated flood risk from between 19% to 56%.

To study the evolution of community flood risk, Tonn and Guikema (2018) developed an agent-based modelling to assess the effect of flood protection measures, individual behaviour, and the incidence of floods on community flood risk. The model concentrates on disseminating flood management information, implementing community flood protection measures, elevating the level of houses, and enabling households to raise mechanical equipment. This was applied to a case study in Fargo, North Dakota, USA. In the model, households are modelled as agents that can take individual actions, such as lifting up items and influencing community actions such as building dams and diversions. The developed model consists of three steps. In the first step, the annual flood elevation is simulated; next, each of the modelled agents can take actions. Finally, the community can take actions such as implementing an information campaign. For every agent modelled, the risk perception and coping perception values are calculated for every simulation step (i.e. every simulation step accounts for one year). In terms of the results, the study reveals that the simulation experiments related to community mitigation show lower total damage than those without community mitigation. This is due to the damage events activating community action.

Jenkins et al. (2017) developed an agent-based modelling to assess surface water flood risk and management strategies for future climate change whereas Dubbelboer

et al. (2017) investigated the dynamic emergence of flood risk and insurance mechanisms in London. In the former, Jenkins et al. (2017) aimed to investigate the impact of the new flood insurance pool (called Flood Re) in addition to its possible incorporation with flood-risk management options. This study investigated the London Borough of Camden, an area at high risk of surface water flooding. In terms of the model's development, six agent types were modelled: (i) persons (classified as a homeowner, buyer or seller); (ii) insurer (modelled to provide homeowners with flood insurance); (iii) developer (modelled to build and sell houses); (iv) local government (modelled to protect people from floods by investing in surface water flood reduction projects); (v) houses; and (vi) banks (modelled to foreclose houses when homeowners could not pay their house fees for three successive years). Each of these agents was modelled with a set of attributes and behaviours to govern their interactions. In terms of the interactions, all the modelled agents interact with each other. For example, persons and banks, as well as developers, can interact with the housing market to buy and sell houses. In terms of the analysis, a probability-damage curve is estimated annually for every house modelled and presented graphically, and thus, the average surface water flood risk was calculated for each of the experiments as the area under the curve. As a result, Jenkins et al.'s study shows that the new Flood Re scheme does not improve the policy link between the insurance scheme and the policymakers in the provision of flood risk management policies.

In relation to Dubbelboer et al. (2017) study (which is linked to Jenkins et al. (2017) study), the model concentrates on modelling and investigating the role of flood insurance and the UK government. Similar to Jenkins et al. (2017) model, Dubbelboer et al. (2017) model consists of six agent types, namely people, houses, an insurer, a bank, a developer and a local government department. Each of these agents was modelled with a set of behaviours (such as persons deciding to buy or sell properties) and attributes. Furthermore, Dubbelboer et al.'s model provides a visualisation map created using GIS data such as surface water flood depth maps. This is to illustrate the boundary of the Borough area and the location of the residential houses and thus 95,561 houses were highlighted. In terms of the results, the study reveals that investment in flood-protection measures is helpful for reducing surface-water flood risks.

Du et al. (2017) developed an ABM to assess the role of social media in evacuation processes during flooding. In this study, households were modelled as agents with a set of attributes and behavioural rules, such as choosing the appropriate information sources and learning attitudes. Subsequently, agents are modelled with (a) flood risk-tolerance threshold and (b) decision opinion. Both (a) and (b) were modelled as a binary decision [0,1] and thus, an evacuation decision is made if the value of the opinion of flood risk [0,1] exceeds the value of the risk-tolerance threshold [0,1]. Furthermore, Du et al. presented an equation to calculate the information obtained from social networks for every agent. This was modelled as a weighted average of information collected from all the related-agents. As a result, Du et al.'s study suggests that communication via social media reduces variation among individuals' opinions and leads them to undertake actions at a similar pace. Also, the study shows that less-accurate flood warnings can result in low evacuation rates. This confirms the need to improve the quality of flood warnings and transportation infrastructure during flooding events.

In terms of flood-related evacuations, a study by Liu et al. (2009) is aimed at the evacuation aspect of flood risk assessment. The authors present a multi-agent-based evacuation simulation model including hydraulic model data on the Oike underground space in Kyoto, Japan. The model integrates three functions, namely survivability, vitality, and communication, to interpret flood evacuation strategies. The survivability function uses inundation depth data to measure the hazard level whereas the vitality function is defined to measure the flood water's physical energy, which decreases over time. In terms of the communication function, this enables evacuee agents to communicate across the surrounding environment and allows nearby evacuee agents to obtain information to enable them to evacuate successfully. For the simulation, two types of agents were defined: (i) static agents (e.g. staircase, wall, and corridor), and (ii) dynamic agents, such as evacuees. Each of the dynamic agents (e.g. evacuees) was modelled with a set of attributes, such as location, age, height, and health and mobility status. In terms of the environment, a 2m x 2m grid was created in which each agent occupied a 0.4m X 0.4m space. Liu et al.'s study revealed both the effectiveness and the weaknesses of their evacuation strategy and emphasised the need for more in-depth information about adaptive strategies to cope with sudden serious cases of flooding and present this knowledge to local residents to improve their adaptive capabilities.

Another relevant study was conducted by Dawson et al. (2011) to analyse the risks of flooding to people. The authors adopted a risk-based approach to evaluate the benefits of flood-incident management response measures and outline a simulation-based approach to estimate the extent of properties' exposure to flooding. Dawson et al.'s model involves a sequence of interactions between individuals and organisations; thus, ABMS was adopted to support this feature. In particular, the Towyn (UK) case study was selected for this research project and was represented using information on *Topography*, integrated transport network, building locations, and an inundation model raster grid. People and organisations were modelled as agents. People were modelled using a probabilistic finite state machine in which a state could be either home or work to enable their movements while evacuating to be modelled. In terms of analysis, Dawson et al. used the exposure functions to quantify the flood risk to people and indicated that receiving flood warnings has the potential to significantly reduce the population's exposure to flooding.

Similarly, Liu and Lim (2018) developed an agent-based evacuation model to assess the evacuation process using 2011 flood data from Brisbane, Australia, as a case study. In particular, the developed model incorporates an evacuation simulation model with the output of a flood inundation model to enable the analysis of the effects of floodwater levels and related warning times on evacuation results. Liu and Lim used MIKE 21 software to model the two-dimensional (2D) inundation event; this is coupled with the *Topography* Mission Digital Elevation Model (SRTM DEM) data, which provides a spatial resolution of 30 m. This was used to predict flooding extent in the modelled case study area. The environment was represented in a grid space using Repast software to enable the simulation. Further, four entities were simulated: road network, flood inundation extent, shelters, and escaping vehicles. The first three entities (road network, flood inundation extent, and shelters) were coupled to enable the map visualisation, whereas the escaping vehicles were modelled as agents. These agents were modelled along with a set of behavioural rules to regulate their movements. The movements and the interactions between agents were visualised using NetLogo software because the authors indicated that Repast is relatively poor in terms of visualisation. In relation to the simulation scenarios, floodwater was classified into three levels: minor, moderate, or major. At the minor floodwater level, the vast majority of evacuees are assumed to arrive at shelters safely. In this study, two

parameters were analysed: (i) the relationship between departure times and flood-level warnings; (ii) the communication between informed and regular evacuees. In terms of the results, the study reveals that more evacuees arrive at the shelters in the scenario when the flood warning has been received or when the flood level is less severe.

Many previous studies (Coates et al., 2014; Coates et al., 2016; Dawson et al., 2011; Dubbelboer et al., 2017; Haer et al., 2017; Jenkins et al., 2017; Li & Coates, 2016; Li et al., 2015; Liu & Lim, 2018; Liu et al., 2009; Tonn & Guikema, 2018; Yang et al., 2018) have highlighted a range of key elements that can be incorporated in developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. First, it can be recognised that some of the studies reviewed modelled agents with a set of attributes and behaviours (Coates et al., 2016; Du et al., 2017; Dubbelboer et al., 2017; Jenkins et al., 2017; Li & Coates, 2016; Li et al., 2015; Yang et al., 2018). This is to define agents' identities and regulate their interactions with the other agents modelled. Also, several studies (Coates et al., 2014; Dubbelboer et al., 2017; Haer et al., 2017; Liu & Lim, 2018; Yang et al., 2018) have coupled inundation data with other data, such as *Topography* and road data. This is either to identify the flooded and non-flooded organisations (Coates et al., 2014; Yang et al., 2018) or to visualise the modelled environment (Dubbelboer et al., 2017; Haer et al., 2017; Liu & Lim, 2018). Next, some of the reviewed studies (Dawson et al., 2011; Haer et al., 2017; Jenkins et al., 2017; Li & Coates, 2016; Li et al., 2015; Liu & Lim, 2018; Yang et al., 2018) have reported on the interactions between agents. For example, Haer et al. (2017) reported on the interactions between insurance companies and households in the context of flooding. In the same vein, Li et al. (2015) reported on the need to model the interactions between SMEs and other organisations, such as customers, suppliers, and service companies (i.e. plumbers, electricians, and mutual aid partners). Finally, all the presented studies have implemented a specific metric to measure their model's performance. For example, Li and Coates (2016) implemented the operational level (OL) metric to evaluate SMEs' performance whereas Jenkins et al. (2017) used the probability-damage curve to assess the average surface-water flood risk for every experiment conducted.

3.2 AGENT-BASED MODELLINGS AND SMALL AND MEDIUM-SIZED ENTERPRISES (SMEs)

A number of studies report on the process of modelling SMEs in different domains (Arvitrida et al., 2017; Barenji et al., 2017; Blackmore et al., 2003; Chen et al., 2008; Holm et al., 2016; Pablo-Martí et al., 2013; Qiuyan, 2009; Sauser et al., 2018; Tounsi et al., 2012). Specifically, these papers model SMEs in the context of SMEs' evolution (Blackmore et al., 2003), SMEs' growth systems (Qiuyan, 2009), and predictions on the impact of public policies on SMEs (Pablo-Martí et al., 2013), community impact on resilience (Sauser et al., 2018), consumer-to-business electronic commerce (Chen et al., 2008), market analysis (Holm et al., 2016), supply chain analysis (Arvitrida et al., 2017; Tounsi et al., 2012), and dynamic re-scheduling (Barenji et al., 2017). It is acknowledged that the reviewed papers are from different domains; however, they are included in this literature review as they are considered to provide information on the key elements that may be used in developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding.

In relation to SMEs' evolution, Blackmore et al. (2003) reported on the use of ABMS in which retail SMEs were modelled with a set of behaviours, such as aggressiveness, product mix, and awareness. For each SME modelled, each of these behaviours changed during the course of the simulation from high, medium, or low. SMEs were also modelled with a set of attributes, such as cash level, stock ID, stock level, product longevity, profits from last sale, average profit, and information flow measures. In terms of products, these were modelled with a number of parameters, such as ID, type, quality, cost per unit, and cost entry. Similarly, consumers were modelled with a set of parameters, such as ID, product, quality, price, and conservatism. In terms of interactions, SMEs could buy products and sell them to customers based on customers' demands. Changing products and receiving demand information was implemented using information flow, which was measured in the SME-agent's state. This measurement was carried out by subtracting the amount spent on a product from the amount received from sales to consumers. The authors provided a set of rules used to govern the interaction between these agents. Blackmore et al.'s study focused on conceptualizing ABMS design rather than developing a practical

work. This is to provide a deeper insight into the structure of SME populations and the interactions among them.

A study carried out by Qiuyan (2009) constructed a systematic analysis framework using an agent-based modelling framework to analyse SME's growth systems. Similar to Blackmore et al. (2003), Qiuyan outlined the process of how agents were modelled and interact. However, the focus of Qiuyan's research is different. The modelled agents were classified into three types: active agents of SMEs, active agents of the ecological environment, and active agents of the regional environment. The active agents of the SMEs represent the modelled SMEs, whereas the active agents of the ecological environment represent the supplier, consumer or demanding enterprises, competitors, and complementary enterprises. The active agents of the regional environment comprise the regional government, universities, and research institutes. The authors provided a set of rules that can be used to govern the interaction between these agents in order to increase the growth area, promote innovation competence, produce new products, and meet customers' demands via cooperation and competition. Qiuyan concluded his study by discussing the characteristics of the agent-based complex and SME's adaptive growth system (e.g. the complexity of the relationship between agents and the dynamics of the systematic structure), providing that SMEs can be observed as self-learning, self-organising, actively adaptive agents.

Pablo-Martí et al. (2013) predict and simulate the impact of public policies on SMEs using an agent-based modelling. The developed model represents the dynamics of behaviours and the decisions of agents as well as their interactions to predict the evolution of an economic system over a specific timeframe. Specifically, firms (SMEs) and households were modelled as agents that interact among themselves. SMEs were modelled with a set of behaviours and individuals, such as workers, technicians, managers, directors, and owners. This is to enable every individual in the firm to make decisions. This is in line with the theories on human resources and knowledge management in addition to the agency problem or theory. Pablo-Martí et al. (2013) outlined the relationship structure between agents and their activities, such as production, innovation, and sales strategy. Subsequently, firms can sell their products on the market and choose the cheapest suppliers. Furthermore, firms may change in size during a simulation due to their interaction with other firms. In terms of interactions, firms post their products on the market and buyers select their preferred

supplier from among these sellers. Pablo-Martí et al.'s study focused on conceptualizing ABMS design and structure rather than developing a practical work.

ABMS has been used to investigate SME's resilience to business challenges (Sauser et al., 2018) and businesses' interactions (Chen et al., 2008). For the former, Sauser et al. (2018) carried out a study to assess SMEs' resilience to community impacts using an agent-based modelling. The authors aimed to investigate the behaviour of a community consisting of small and medium businesses after a disaster in terms of three aspects (type of customer, resilience, and community sensitivity). As reported, a grid of 51 by 51 patches was designed using the NetLogo agent-based modelling environment version 5.3.1. SMEs were modelled as agents and placed in this grid with a maximum of one agent per patch and with each agent having up to eight neighbours. However, the size of enterprises was not considered, assuming that each enterprise is either small or medium in size. Each agent was modelled as either local or global in terms of its type of customer (local or global customers) and this was determined randomly. The local SMEs were modelled to serve local customers, whereas the global businesses could serve both local and global customers. Sauser et al.'s developed model is based on the interaction between SMEs themselves and SMEs and customers. For example, SMEs interact with their neighbours to determine their opening hours based on the community sensitivity or belonging thresholds. In terms of the results, Sauser et al.'s study shows a positive correlation between the severity of a disaster and its impact on the local community exists while the damage to the community remains below 50%.

In relation to customer-business interactions, Chen et al. (2008) reported on the use of an agent-based modelling to assess the online interaction between consumers and businesses, a rarely explored topic. As reported, a set of agents was modelled (e.g. coordinator, negotiator, search agent, client agent, and supplier agent). These agents aimed to initiate a group buying plan, searching for qualified sellers, collecting preferences, inserting product information into usable forms, bargaining with sellers, and making their final decision, respectively. The authors define the bargaining strategy briefly; they assume that both negotiation parties will make concessions by reducing the benefit from their initial offers and look for another satisfactory offer to both parties through an iterative negotiation process. For the interaction, the authors provide a number of rules applied to enable the interaction between these agents and

used the messaging protocol to enable the asynchronous communication between agents; this approach is in line with (Blackmore et al., 2003) paper. Chen et al. indicated that their study is an attempt to promote collective purchasing (i.e. online purchasing from consumers to businesses) to the E-commerce community.

In terms of market analysis, Holm et al. (2016) report on the use of ABMS to investigate the wood market in Switzerland to identify factors influencing the availability of wood on the market. In the developed model, several entities are modelled as agents (e.g. private forest owners, public forest managers, bundling organisations, traders, wood fuel market, sawmills, particleboard factories, pulp mills, and paper mills). The private forest owners and public forest managers are modelled into agents as suppliers, whereas sawmills act as consumers in the market. Each of these agents is modelled with a set of attributes, such as location (x, y coordinates) and a portfolio of goods that they buy or sell, and a set of behaviours, such as buying and selling products. Interactions are initiated by the requester (e.g. the buyer or seller), who sends a request along with the associated information (e.g. price and amount) to the other party. The receiver can either accept or decline the request or reply with a counteroffer; then the first requester can either accept or decline.

In relation to supply-chain analysis, Tounsi et al. (2012) adopted a multi-agent model and simulation of SMEs' mechatronic supply chain to model and analyse supply chains in the context of SMEs. This study focused on analysing organisational features, behaviours, and performance considerations. The authors indicated that supply chains are modelled as agents to enable the interaction between them to achieve the overall aim and objective of the model. Furthermore, the environment was modelled to allow agents to behave and interact via a structured exchange of messages; this is similar to Blackmore et al. (2003) and Chen et al. (2008), in which agents interpret received messages based on communicative action. Further, performance metrics are developed to evaluate the performance of SMEs within the developed environment.

In relation to the collaboration duration of supply chains, Arvitrida et al. (2017) investigated the impact of duration of collaboration on suppliers from a market perspective using an agent-based modelling. The authors report that suppliers, customers, and manufacturers are modelled as agents to enable partnerships between manufacturers and suppliers. Customers are modelled to represent retailers or

warehouses in which each customer has a fixed set of preferences for products. However, they may change their preferences to a certain degree. Similarly, manufacturers can select their suppliers; they can also change their preferences to adjust them in line with the available suppliers. Suppliers are modelled to attract manufacturers to cooperate with them, whereas manufacturers continue to obtain more customers. Furthermore, manufacturers and suppliers are modelled to have no trust in/loyalty to each other, and thus, suppliers may vanish if they cannot link up with a manufacturer. This model is measured by the rate of demand accomplished and the number of suppliers that can exist in the market. Furthermore, these agents are modelled with a set of behavioural rules, which in turn govern agents' interactions. In terms of the interactions, a two-dimensional strategic space was designed as the environment to allow agents to interact. Thus, each customer is modelled to build a link up with a manufacturer, whereas every manufacturer modelled aims to collaborate with one supplier or a set of suppliers. In terms of the results, Arvitrida et al.'s study reveals that the duration of collaboration between supply chains themselves has no substantial influence on their demand fulfilment and survivability.

In terms of dynamic re-scheduling, Barenji et al. (2017) developed a multi-agent-based dynamic scheduling system for manufacturing flow lines with a focus on dynamic customer orders using the Prometheus Methodology (PM). This study was implemented on a real manufacturing flow line of an SME specialising in unplasticized polyvinyl chloride (uPVC) doors and windows. In terms of the PM's design stages, the model is divided into three stages. First, the system specification phase defines the system's goals, functionalities, inputs, and outputs. Based on the output of the system specification stage, the architecture design stage decides the type of agents and the level of their interactions. Finally, the detailed design stage is concerned with the internal design of each agent including their attributes and behavioural rules. In terms of the agents, five software agents were modelled, namely manager agent, shop manager agent, cell agent, material handling systems agent, and scheduler machine agent. In specific, a material handling system resource agent and a machine resource agent were modelled as interface agents. In terms of interaction, agents can receive messages from each other (such as updating and enquiring about orders). The multi-agent system scheduling and conventional scheduling approaches were used to measure the performance of the reported model. In terms of the results, two scenarios

were defined: the first scenario assesses the response of the system with regard to the dynamic customer demands whereas the second scenario is concerned with the quantitative indicators based on various production performance measures.

Based on the studies reviewed in this section (Arvitrida et al., 2017; Barenji et al., 2017; Blackmore et al., 2003; Chen et al., 2008; Holm et al., 2016; Pablo-Martí et al., 2013; Qiuyan, 2009; Sauser et al., 2018; Tounsi et al., 2012), a range of key elements were identified that can be incorporated to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. Similar to the studies presented in Section 3.1, SMEs have been modelled along with a set of attributes and behaviours (Arvitrida et al., 2017; Barenji et al., 2017; Blackmore et al., 2003; Holm et al., 2016; Pablo-Martí et al., 2013; Qiuyan, 2009; Sauser et al., 2018). Furthermore, all the studies presented in this section (Arvitrida et al., 2017; Barenji et al., 2017; Blackmore et al., 2003; Chen et al., 2008; Holm et al., 2016; Pablo-Martí et al., 2013; Qiuyan, 2009; Sauser et al., 2018; Tounsi et al., 2012) reported the interaction between SMEs and other related organisations. Specifically, some of these studies (Barenji et al., 2017; Blackmore et al., 2003; Chen et al., 2008; Tounsi et al., 2012) used the messaging protocol to enable asynchronous communication between agents. For instance, Barenji et al. (2017) reported that SMEs and customers can exchange messages to enquire about placed orders. Next, some studies (Arvitrida et al., 2017; Blackmore et al., 2003; Tounsi et al., 2012) modelled one or more metric/s to measure the performance of their model, which in turn, enables the analysis to take place. For example, Blackmore et al. (2003) developed a metric that relied on the products and demands information to measure the performance of the developed model. Similarly, Arvitrida et al. (2017) measured the performance of their model via the relationship between demand accomplished and the number of suppliers that can exist in the market.

3.3 SUMMARY

This chapter has presented a review of the literature on using ABMs in modelling flooding and SMEs. The key elements of an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding involved are identified as follows:

- **Geographical environment**, i.e. modelling geographic environments and flood event simulations to (i) identify each individual organisation flooded over the timeline of simulated flood events, and (ii) provide a visual representation of the modelled geographical area.
- **Modelling SMEs**, i.e. SMEs were modelled with a set of attributes, behaviours, and pre-defined precautionary measures in a specified geographical area.
- **Modelling SME-related organisations**, i.e. related organisations include electrical, plumbing, IT, and cleaning service providers; suppliers; customers; EA; insurance companies; mutual aid partners; and refurbishment companies. These are modelled to provide assistance or a service to SMEs to maintain their operation and support their immediate response to and short-term recovery from flooding.
- **Modelling interactions between SMEs and SME-related organisations**, i.e. modelling a specific technique to enable the interactions between SMEs and related organisations to support an SME's response to and recovery from flooding.
- **Modelling performance metrics**, i.e. these metrics are modelled to assess SMEs' performance before, during, and after a flood event.

The five key elements identified in this chapter are partly comprised of the two key elements (SMEs' precautionary measures and SMEs' behaviours) identified in Chapter 2. Thus, these five key elements are the foundation for the requirements for modelling SMEs' immediate response to and short-term and recovery from flood events as presented in Chapter 4.

Chapter 4

Requirements of Agent-Based Modelling and Simulation Framework

The aim of this chapter is to identify the requirements of the ABMS framework based on the key elements identified in Chapters 2 and 3.

Section 4.1 provides an overview of the key elements identified in Chapter 2 and 3 and clarifies the originality of this research. Section 4.2 to 4.6 presents the key elements involved in developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. Finally, Section 4.7 summarises the necessary requirements of developing ABMS framework and closes the chapter.

4.1 OVERVIEW

Based on the literature review presented in Chapters 2 and 3, to date, no study has incorporated all the key elements to successfully develop an ABMS framework that investigates SMEs' immediate response to and short-term recovery from flood events. Therefore, the current key elements remain unintegrated (i.e. not linked together within a unified framework) because the studies reviewed in Chapters 2 and 3 provide insufficient knowledge in respect of how to:

- model geographical environments appropriately to enable the identification of flooded and non-flooded SMEs and provide a visual representation of the modelled geographical area;

- model SMEs appropriately with a set of attributes, behaviours, and pre-defined precautionary measures in a specified geographical area;
- model SME-related organisations such that they can provide assistance or a service to SMEs appropriately to maintain their operation and support their immediate response and short-term recovery;
- model the interaction (i.e. communication protocol) between SMEs and SME-related organisations to support the communication and cooperation between agents; and
- measure SMEs performance, especially if they are from more than one sector.

Therefore, there is scope for a more highly integrated and comprehensive ABMS framework to include the key elements in investigating SMEs' immediate response to and short-term recovery from flooding. This chapter aims to provide an explanation of how to incorporate these key elements within a connected, comprehensive framework.

4.2 MODELLING THE GEOGRAPHICAL ENVIROMENT

The geographical environment has been discussed in terms of enabling the identification of flooded and non-flooded organisations and producing a visual representation of the modelled geographical area. Enabling the visual representation of a geographical environment involves the appropriate spatial information to be synthesised and modelled. Specifically, there is a requirement to couple the spatial information with the inundation data, which represents the water depths throughout the area modelled at specific intervals. Thus, knowledge of how to successfully achieve such coupling is required as well as knowledge of GIS software to enable the spatial information to be edited in terms of their visual representation. This will allow the appropriate visualisation enhancements to be applied.

4.3 MODELLING SMALL AND MEDIUM ENTERPRISES

Developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding requires SMEs to be modelled as agents. This involves a set of SMEs' behaviours, attributes, and precautionary measures.

4.3.1 Behaviours

Behaviours should be identified from reliable sources, such as academic literature, technical documents, and/or a series of semi-structured interviews with SMEs involved in flood-related events and/or located in flood-prone areas. In order to model SMEs' behaviours in a structured and logical order, their dependency relationships, number of employees required to enact them, priority of execution, classification (i.e. a generic behaviour or specific behaviour) and duration range need to be established and managed. An emphasis is placed on managing the dependencies between behaviours to ensure the preservation of the logical order in which they should be enacted and completed.

Knowledge of behaviours' dependencies, the number of employees required to enact them, priority of execution, classification, and duration all need to be represented such that once defined, they can be maintained and managed. That is, behaviours can be enacted appropriately if all behaviours upon which they are dependent have been completed. The complexity of this process is exacerbated by the fact that multiple behaviours must be enacted before the completion of other behaviours.

4.3.2 Attributes

In addition to modelling behaviours as well as related information (e.g. the number of employees required to enact them, priority of execution, and classification), there is also a need to model a set of attributes to define SMEs' identities, which in turn, enable the identification of each SME among those modelled. That is, there is a requirement to investigate every SME individually over the course of a simulation. Since modelling SMEs' attributes is a requirement, there is a need to establish which specific attributes can remain static or may vary during the course of a simulation.

4.3.3 Precautionary Measures

SMEs' precautionary measures should be modelled such that they should have direct or indirect impacts on SMEs' immediate response to and short-term recovery from flooding. Thus, knowledge of precautionary measures should be gained to enable modelling their impacts on SMEs' performance. Also, precautionary measures should be classified in terms of their impact (e.g. resistance or resilience precautionary

measures) on SMEs. This enables the simulation experiments to be set out in terms of the precautionary measure classifications, which in turn enables an investigation of SMEs' immediate pre-flood responses and post-flood short-term recovery to be carried out based on this classification.

4.4 MODELLING SME-RELATED ORGANISATIONS

Modelling SME-related organisations enables SMEs to interact with a range of organisations/businesses throughout the course of a simulation of a flood event. Table 4.1 provides an overview of SME-related organisations, which support SMEs' operation and recovery along with their period of interaction with SMEs. This table also indicates whether these services are 'internal' (in which case an SME's employees can perform them) or 'external' (in which case SMEs must allocate specialists from outside the company to perform them). Furthermore, Table 4.1 provides an overview of SME-related organisation's potential locations, namely regional or national. The regional SME-related organisations are located in the same geographical area as the SMEs whereas the national SME-related organisations may be located anywhere within the UK. Finally, Table 4.1 also provides a brief overview of the SME-related organisation's respective functions.

SME-Related Organisation		Period of Interaction	Internal/External	Regional/National	Function
Suppliers		Pre- and post-flood	External	Regional	Provide SMEs with raw material or stock.
Customers		Pre- and post-flood	External	Regional/National	Take delivery of products from manufacturing SMEs.
Environment Agency		Pre-flood	External	National	Send alerts and warnings to SMEs that have registered for these services.
Insurance companies		Post-flood	External	Regional/National	Provide insured SMEs with assistance in the form of a cleaning service, if insured sufficiently, in addition to financial compensation.
Service provider organisations	Electricians	Post-flood	External	Regional/National	Provide the necessary repairs to support SMEs' recovery.
	Plumbers	Post-flood	External	Regional/National	
	IT specialists	Post-flood	External	Regional/National	
	Refurbishment companies	Post-flood	Internal/External	Regional/National	Provide renovation and redecoration for retail SMEs' premises.
Cleaning service providers		Post-flood	Internal/External	Regional/National	Provide a cleaning service to SMEs.
Mutual aid partners		Post-flood	External	Regional	Share a certain percentage of its own production machines with its pre-defined mutual aid partner when requested.

Table 4.1: An overview of SME-related organisations

4.4.1 Environment Agency

The EA should be modelled to send flood alerts and warnings to EA-registered SMEs. More specifically, the EA should predict the flood commencement times for the geographical area modelled so that it can send alerts and warnings to SMEs registered for these services in those areas. Thus, knowledge about EA alerts and warnings service should be gained to enable them to be modelled appropriately.

4.4.2 Suppliers and Customers

Suppliers should be modelled to supply SMEs with raw materials and stock, at regular intervals respectively. Customers are modelled to take delivery of products and goods from SMEs at regular intervals. This interaction between SMEs, and suppliers and customers should occur in both the pre- and post-flood stages.

4.4.3 Insurance Companies

Insurance companies should be modelled to support SMEs' recovery from flooding. Thus, every insurance company modelled should maintain a list of SMEs it insures to provide services, such as compensation and cleaning services, to them when required depending on the insurance type (e.g. basic or comprehensive). Subsequently, insurance companies should interact with cleaning service providers to request such services for its insured SMEs, if insured sufficiently, when required. Thus, knowledge of insurance-provided services should be gained to be modelled with insurance companies.

4.4.4 Cleaning Service Providers

Cleaning service providers should be modelled to support SMEs' recovery in the aftermath of a flood event. In each geographical area, the appropriate number of cleaning service providers should be modelled as *regional* whereas a larger number of cleaning service providers should be modelled as *national*; these two categories of cleaning services providers should differ in number and arrival time in terms of service. Thus, information about the total number of cleaning service providers in every geographical area as well as their arrival time of service providers is required.

Cleaning service providers should interact with (i) SMEs to provide cleaning services when requested, and (ii) insurance companies to provide cleaning services to their insured SMEs, if sufficiently insured. Thus, there is a requirement to consider the issue if a cleaning service provider is working for a non-contracted SME and it is requested by an insurance company with which it has a pre-defined contract.

4.4.5 Service Provider Organisations

Service provider organisations include electricians, plumbers, IT specialists, and refurbishment companies that should interact with SMEs in the post-flood stage. Similar to the cleaning service providers, these organisations should be modelled both regionally and nationally, as appropriate. Furthermore, the arrival time of service providers should also be considered as well as the total number of service provider organisations in the modelled geographical area.

4.4.6 Mutual Aid Partners

Mutual aid partners should be modelled to interact with manufacturing SMEs during the recovery period. Manufacturing flooded SMEs can have a pre-defined contract with a non-flooded manufacturing SME in which both parties agree on a proportion of work that could be carried out at the partner's premises.

4.5 MODELLING INTERACTIONS BETWEEN SMES AND SME-RELATED ORGANISATIONS

Recovery requires interaction and decision-making among a set of groups and organisations (Mileti, 1999). In terms of ABMS, it is important to understand and define how individuals entities interact with each other (Axelrod, 2005). Thus, after modelling SMEs and SME-related organisations as agents, the communication protocol between these entities should be defined and modelled to enable them to interact, communicate, and cooperate appropriately.

4.6 MODELLING PERFORMANCE METRICS

Measuring businesses' performance is required to enable the investigation of SMEs operation over a specific timeframe (Blackmore et al., 2003; Linnenluecke & Griffiths, 2010; Tounsi et al., 2012). SMEs can enact a certain set of (i) pre-flood

behaviours to reduce the risk associated with flooding, and (ii) post-flood behaviours to speed-up their short-term recovery. However, enacting these behaviours requires a proportion of employees to enact them. This will cause a disruption to SMEs' production or service tasks respectively. Thus, the expected performance of each SME needs to be modelled and established. SMEs' performance metrics can be either generic, which can be used to measure a larger set of SME sectors or specific, which can be used to measure a specific sector.

4.7 SUMMARY

The purpose of this thesis is to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flood events, and thus the specific requirements of developing ABMS framework are identified as:

- Geographical Environment
 - enable the identification of flooded and non-flooded organisations;
 - produce a visual representations of the modelled geographical area.
- Modelling SMEs
 - model SMEs' behaviours including their dependency relationships, the number of employees required to undertake the tasks related to these relationships, priority of execution, classification, and duration range;
 - modelling a set of attributes to define SMEs' identities;
 - model precautionary measures to improve SMEs' immediate response to and short-term recovery.
- Modelling SME-related organisations:
 - EA to send flood alerts and warnings to EA-registered SMEs;
 - suppliers and customers to support SMEs' operational continuity;
 - insurance companies to support SMEs' recovery from flooding with financial compensation or the provision of a cleaning service provider, if sufficiently insured;

- cleaning service providers to support SMEs' recovery in the flood aftermath phase where this proportion of organisations or businesses should be modelled in terms of their locations (i.e. regional or national);
 - service provider organisations (i.e. electricians, plumbers, IT service providers, and refurbishment companies) are also modelled as *regional* and *national* organisations;
 - Mutual aid partners that interact with manufacturing SMEs during the recovery period to assess the affected partner according to their contract.
- Modelling interactions between SMEs and SME-related organisations
 - define the communication protocol between SMEs and SME-related organisations to enable the interaction and communication between them.
- Modelling performance metrics
 - measure businesses' performance in order to analyse their operation over the course of a simulation of a flood event.

Chapter 5

Overview of Agent-Based Modelling and Simulation (ABMS) Framework

This chapter presents an overview of the ABMS framework that aims to investigate SMEs' immediate response to and short-term recovery from flood events. This framework consists of three components, namely flood event simulation, Modelled Geographical Environment (MGE), and agent-based modelling and simulation. In this chapter, an overall description of the processes involved in each of these components is presented.

Section 5.1 presents an overview of the ABMS framework developed. Sub-Section 5.1.1 presents the framework's flood event simulation component, i.e., the dynamic inundation data. Following this, sub-Section 5.1.2 presents the MGE component of the ABMS framework. This consists of three layers of Ordnance Survey (OS) MasterMap® (e.g. the *Topography layer*, *Integrated Transport Network (ITN)*, and *Address layer*). Next, sub-Section 5.1.3 presents an overview of the agent-based modelling and simulation component. Section 5.2 summarises the ABMS framework components and closes the chapter.

5.1 AGENT-BASED MODELLING AND SIMULATION FRAMEWORK

An ABMS framework is developed in order to evaluate which precautionary measures, or combinations of them, can be employed to improve SMEs' immediate response to and short-term recovery from disruptive flood events. In particular, the developed ABMS framework aims to investigate flood-affected manufacturing and

retail sector SMEs' immediate response and short-term recovery. To achieve this aim, manufacturing and retail SMEs, which include a set of pre- and post-flood behaviours, attributes, and pre-defined precautionary measures, are modelled along with SME-related organisations such as electrical, plumbing, and IT cleaning service providers, refurbishment companies, suppliers, customers, the Environment Agency (EA), insurance companies, and mutual aid partners.

As indicated in Figure 5.1, within the developed ABMS framework, a geographical environment is modelled that takes dynamic inundation data as its input from the simulation of a flood event. The MGE uses Ordnance Survey (OS) data (e.g. the *Topography*, *Integrated Transport Network (ITN)*, and *Address* layers) combined with inundation data to (i) identify each individual organisation flooded over the timeline of the simulated flood event, and (ii) provide a visual representation of the modelled geographical area. Subsequently, a proportion of flooded-affected organisations, in addition to those unaffected by flooding and other related organisations, are to be modelled as autonomous agents and simulated before, during, and after a flood event.

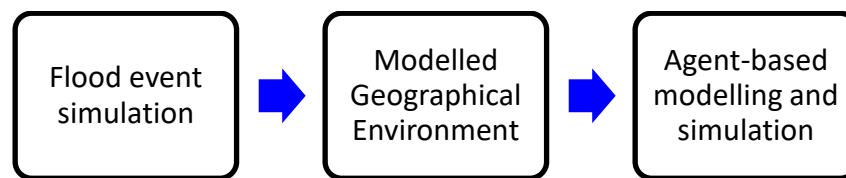


Figure 5.1: ABMS framework overview

5.1.1 Flood Event Simulation

The flood event simulations generate a series of inundation data files, each of which represents the water depths throughout the area modelled at specific time intervals (at 30-minute intervals). As presented in Figure 5.2, each inundation data file consists of a series of values, in which each of these values represents the depth of floodwater at a specific location in the MGE. In particular, the inundation data (i.e., the depth of floodwater at locations in the geographical area modelled) vary dynamically and supplies the input to the MGE. This is to be combined along with the MGE's three OS MasterMap® layers, which in turns enables the visual representation

and the identification of each individual organisation over the timeline of the simulated flood event.

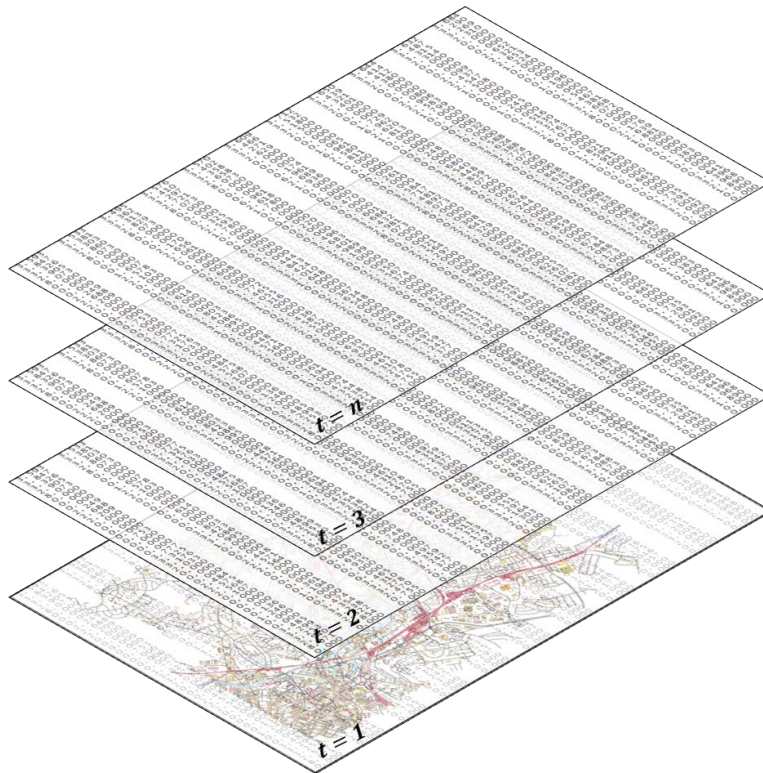


Figure 5.2: Series of inundation data files for a specific geographical area

5.1.2 Modelled Geographical Environment

The MGE is made up of three layers of OS MasterMap® (Ordnance Survey, 2019) as follows:

- *Topography* layer, provides data on individual buildings including business premises;
- *Integrated Transport Network (ITN)* layer, contains data related to the road network (i.e. such as road codes); and
- *Address* layer, provides data related to commercial properties including business name, precise location, and classification, as well as other attributes such as the number of floors at the premises.

The MGE was constructed to (i) enable the identification of the flooded and non-flooded organisations in the modelled geographical area, and (ii) provide a visual

representation of a series of floodwater footprints in the geographical areas to help the reader gain a better understanding of the modelled geographical area.

In relation to the identification of the flooded and non-flooded organisations, this is carried out by coupling the *Address* layer and the inundation data. However, the visual representation of the modelled geographical area is represented by coupling *all* the OS MasterMap® layers (*Topography*, *ITN*, and *Address*) along with the inundation data. Therefore, the *Topography* and *ITN* layers are incorporated with the *Address* layer and inundation data to provide a visual representation of the simulated geographical area whereas the *Address* layer and inundation data are coupled to enable the identification of the flooded and non-flooded organisations.

In terms of the visual representation, Kornhauser et al. (2009) indicate that visualizations provide greater insights and a more meaningful illustration of the modelled phenomenon. Furthermore, they emphasised that an effective visualisation helps users to understand the purpose of the model visually.

5.1.3 Agent-Based Modelling and Simulation

An agent-based modelling has been developed and used to simulate and investigate the potential effects a range of precautionary measures deployed by SMEs in the manufacturing and retail sectors on the immediate response to, and short-term recovery from, flooding. As indicated in Figure 5.3, manufacturing and retail SMEs were modelled as autonomous agents with a set of attributes, behaviours, and pre-defined precautionary measures, whereas SME-related organisations (suppliers; customers; electrical contractors, plumbers, IT service contractors; cleaning service providers; the Environment Agency; mutual aid partners; refurbishment companies; and insurance companies) were modelled with only a set of attributes and behaviours. In terms of the interactions among them, both types of agent (SME agents and SME-related organisation agents) can interact with each other to ensure and support SMEs' operational continuity and recovery. Furthermore, both types of agent (SME agents and SME-related organisation agents) interact with the modelled geographical environment.

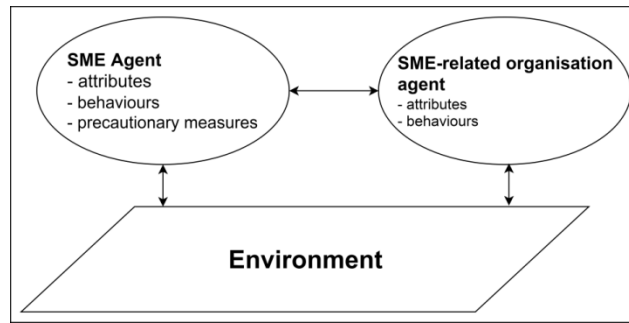


Figure 5.3: Overview of the agents' design (Tran et al., 2015)

In terms of attributes, these are modelled to define SMEs and are classified as:

- static attributes, which are used to define an agent's identity; and
- dynamic attributes, which change during the course of a simulation and used to determine SMEs' performance.

In terms of behaviours, these are actions that can be completed over different time durations and are classified as:

- pre-flood behaviours, which can be enacted from the time an SME receives an EA alert and/or warning until the flood event occurs; and
- post-flood behaviours, which can be enacted from the time the water recedes from an SME's premises until the time an SME returns to normal operation.

Precautionary measures are implemented by an SME prior to (i) receiving an EA flood alert or warnings, and (ii) a flood event occurring and are classified as:

- property-level precautionary measures;
 - flood resistance precautionary measures, which are deployed to prevent the *entry* of floodwater into premises;
 - flood resilience precautionary measures, which are implemented to limit the *effect* of floodwater entering a premises; and
- business continuity/risk management precautionary measures.

Behaviours and attributes, as well as the pre-defined precautionary measures considered in this thesis, were collected from various sources: (i) transcripts of semi-

structured interviews with SMEs having experience of flooding or being at risk of flooding, (ii) EA guidance, (iii) academic literature, and (iv) *Address* layer dataset. In terms of the transcripts of interviews, these data are drawn from a total of 63 in-depth interviews. Subsequently, they are presented anonymously as S_i ($1 \leq i \leq 63$).

5.2 SUMMARY

The ABMS framework consists of three components as follows:

- Flood event simulation, which generates inundation data at regular time intervals (half hour).
- Modelled Geographical Environment (MGE), which consists of three OS MasterMaps® layer, namely the *Topography* layer, *Integrated Transport Network (ITN)* layer, and *Address* layer. This enables a specific geographical area to be modelled in which the location of each individual business can be identified.
- Agent-based modelling and simulation, which involves autonomous agents representing manufacturing and retail SMEs exhibiting a range of pre- and post-flood behaviours and able to administer a number of potential flood-preparedness precautions. In addition to manufacturing and retail SMEs, related organizations are modelled such as customers, suppliers, insurance companies, the Environment Agency (EA), cleaning service providers, electricians, plumbers, and IT specialists.

The overview provided in this chapter aims to expand the reader's understanding of the research reported in this thesis. Further details on SMEs' behaviours (including pre- and post-flood) and precautionary measures are provided in Chapter 7.

Chapter 6

Modelled Geographical Environment (MGE)

This chapter presents how the OS MasterMap® *Topography*, *ITN*, and *Address* layers are coupled along with flood event simulation (i.e. inundation data) to model the geographical environment.

Section 6.1 outlines how the OS MasterMap® layers were pre-processed before being coupled along with the inundation data to form the MGE of the developed ABMS framework. Section 6.2 illustrates how the OS MasterMap® layers are coupled along with the inundation data. Next, Section 6.3 explains how the flooded and non-flooded SMEs were identified while Section 6.4 provides information on how the visual representation of the MGE was modelled. Finally, Section 6.5 summarises the processes followed and concludes the chapter.

6.1 MODELLED GEOGRAPHICAL ENVIRONMENT (MGE) LAYERS

This section explains how the OS MasterMap® layers were pre-processed before being coupled along with the inundation data to form the MGE of the developed framework. Firstly, Figure 6.1 (a) presents the flood event simulation, which generates a series of inundation data files, each of which represents the water depths throughout the area modelled at specific intervals over a certain timeframe. Next, Figure 6.1 (b) presents the OS MasterMap® layers (*Topography*, *ITN*, and *Address*). For the *Topography* and *ITN* layers, these layers were imported into Quantum Geographic Information System (QGIS) software, as proposed by Digimap® Maps, to enhance their visual representation (see appendix B). This is because the *Topography* and *ITN*

layers were downloaded from EDINA Digimap® (www.edina.ac.uk) with the Geography Markup Language GML extension format, which does not hold any visualisation styles, such as colours. Confirming this, Gudmundsson and Mohajeri (2013) indicated that the GML extension format represents the geographic data content rather than the *style* in which the data should be presented. Subsequently, as indicated in Figure 6.1 (b), both layers were exported to (i) a shapefile extension format (a Repast-compatible extension format), which stores the overall information, such as road codes and properties' coordinates, and (ii) a Styled Layer Descriptor (SLD) file extension format which maintains the style format, such as attribute colours and sizes. According to Crooks (2008), shapefiles are compatible with Repast due to their capability to store the converted layers' geographical coordinates along with the corresponding attributes of each feature (e.g. roads and buildings). Furthermore, shapefiles enable the GIS feature to access and display their content.

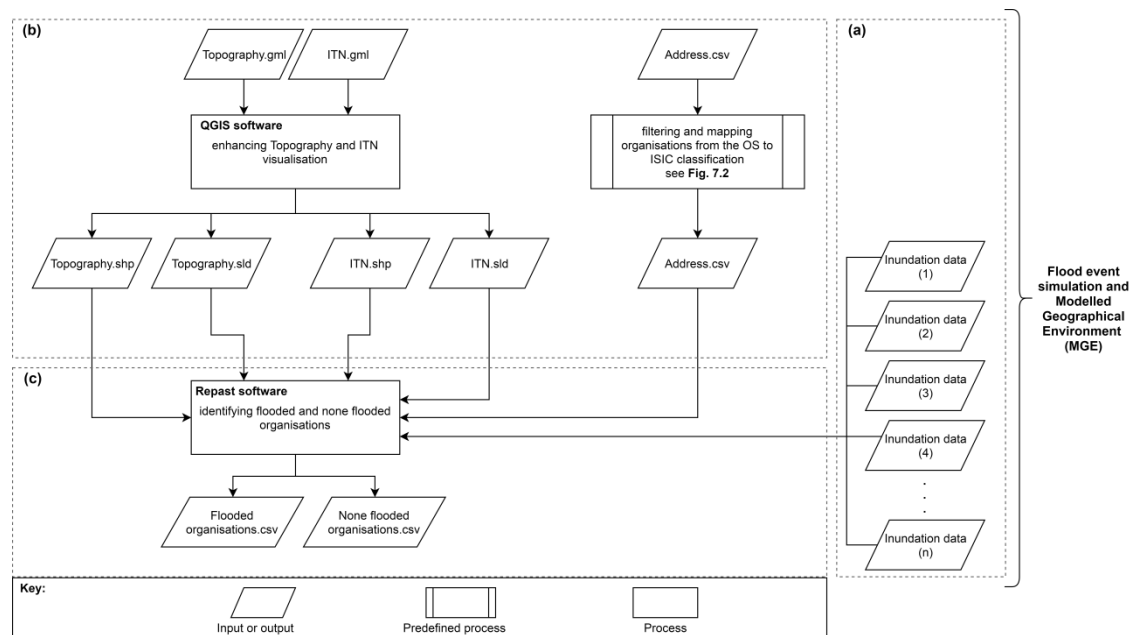


Figure 6.1: MGE elements

In relation to the *Address* layer, as indicated in Figure 6.1 (b), it is a dataset that provides information about every individual organisation within a particular area. Three different *Addressing* products are available: *AddressBase*, *AddressBase Plus*, and *AddressBase Premium*. Each of these OS products provides a different collection of features as presented in Table 6.1. Since the *AddressBase Plus* product incorporates both the *AddressBase* product features as well as the features of the current *Address*

of the local authority, it was selected for this research. It is acknowledged that the *AddressBase* Premium package offers extra features, such as alternative Addresses and lifecycle data; however, these features are unnecessary in this research.

	AddressBase	AddressBase Plus	AddressBase Premium
UPRN – basic analysis	✓	✓	✓
PAF Address – Royal Mail addresses	✓	✓	✓
PAF UDPRN – Royal Mail's delivery reference system	✓	✓	✓
Classification	✓	✓	✓
Local Authority Current Address	✗	✓	✓
Cross reference with third-party datasets	✗	✓	✓
Alternative Addresses	✗	✗	✓
Lifecycle data	✗	✗	✓

Table 6.1: Address layer options (Ordnance Survey, 2019)

In *AddressBase Plus*, the data is structured in a CSV file extension format that includes data on organisations and Addresses sourced from 380 local authorities across the UK (Ordnance Survey, 2019). These data were mapped from the OS classifications onto the International Standard Industrial Classification of all Economic Activities (ISIC) given this is a more recognisable sector categorisation (United Nations, 2008). Furthermore, while a range of these records are residential and some of them fall outside of this research's remit, the dataset was filtered based on locations and classifications (i.e. organisations or residential properties) to enable flooded and non-flooded organisations to be identified within the geographical areas examined.

In relation to the filtering process, a Java program was written to enable the process of filtering the *AddressBase Plus* product. This initially removed all the records (properties or organisations) that fall beyond the northing and easting provided by the MGE, given that the *AddressBase Plus* uses a CSV extension format. Furthermore, the Java program removed all the records of the residential properties within the selected geographical area. This process is illustrated in Figure 6.2.

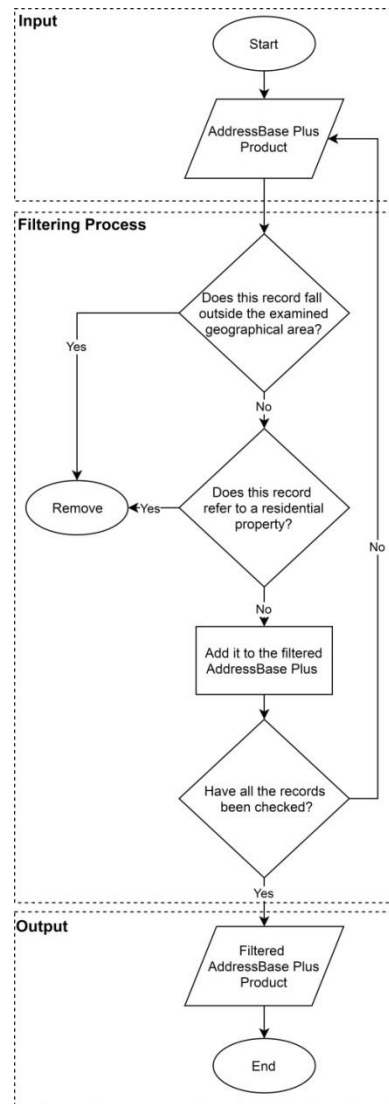


Figure 6.2: Address layer filtering process

After filtering the *AddressBase Plus* layer and visually enhancing the *Topography* and *ITN* layers, they were coupled along with the inundation data using the Repast software toolkit to: (i) identify the flooded and non-flooded organisations, and (ii) provide a visual representation of the flood event in the selected geographical area (see Figure 6.1 (c)). As a result, two CSV files were exported; the first consists of the flooded organisations along with their inundation data throughout the course of the simulation while the second consists of the non-flooded SMEs.

6.2 CONSTRUCTING THE MODELLED GEOGRAPHICAL ENVIRONMENT (MGE)

In relation to coupling OS MasterMap® layers along with the inundation data presented in Figure 6.1 (c), every water depth value within the inundation data files had to be mapped to its corresponding location on the OS MasterMaps® layers. However, the location coordinates of these values were not provided. Thus, these location coordinates were identified according to the relationship between the provided inundation data dimensions (the total number of rows (R_{max}), and the total number of columns (C_{max})) and the provided northing and easting coordinates of the selected geographical area (N_{max} and N_{min}) and (E_{max} and E_{min}) of the inundation data, respectively, as follows:

$$N = \frac{N_{max} - N_{min}}{R_{max}} \quad (6.1)$$

$$E = \frac{E_{max} - E_{min}}{C_{max}} \quad (6.2)$$

where N and E are the northing and easting mapping values used in equation (6.3) and (6.4) to identify the northing (V^N) and easting (V^E) coordinates associated with every floodwater depth value, as follows:

$$V^N = N_{min} + (C \times N) \quad (6.3)$$

$$V^E = E_{min} + (R \times E) \quad (6.4)$$

The column number (C), as well as the row number (R) of every inundation value was available. To provide an example, using the first case study reported in this thesis (the Lower Don Valley of Sheffield) the geographical area was defined using the coordinates 390837.5 and 386937.5 (N_{max} and N_{min}) and 440210.0 and 434720.0 (E_{max} and E_{min}), whereas the corresponding inundation data was defined using 1098 C_{max} and 780 R_{max} . The northing and easting mapping values can be identified using equation (6.1) and (6.2) as $N = 5$ and $E = 5$. Subsequently, the northing and easting coordinates of the first value ($C = 0$ and $R = 0$) of the inundation data files can be calculated using equation (6.3) and (6.4) as $V^N = 386937.5$ and $V^E = 434720.0$. Similarly, the northing and easting coordinates of the second value of the inundation data files ($C = 1$ and $R = 0$) are $V^N = 386942.5$ and $V^E = 434720.0$.

6.3 IDENTIFYING FLOODED AND NON-FLOODED SMES

After coupling the OS MasterMap® layers with the inundation data, every SME was modelled at its precise location according to its associated northing and easting coordinates. As indicated in Figure 6.3, at every simulation tick and throughout the course of a simulation, every SME modelled had to store its corresponding inundation data (water depth values) in the associated list; these values change at every simulation tick. This enables the identification of flooded SMEs by checking the stored inundation data values to see if any of these values is greater than zero (in which case the organisation is considered flooded). The process involved in identifying the flooded and non-flooded organisations is presented in Chapter 9 (Case Studies and Simulation Experiments).

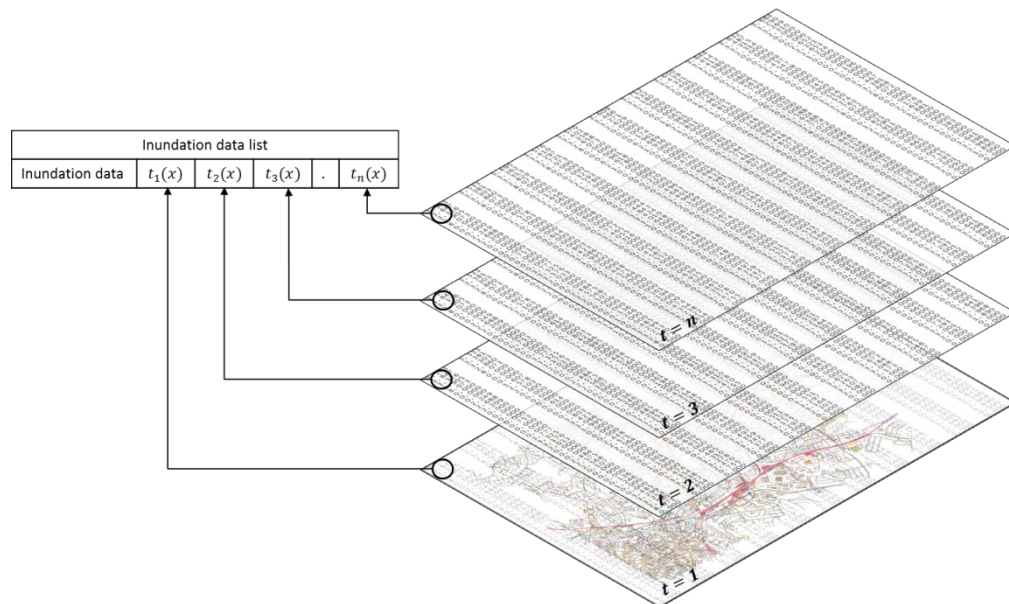


Figure 6.3: Overview of how inundation data was stored into a structured list

6.4 VISUAL REPRESENTATION OF THE MODELLED GEOGRAPHICAL ENVIRONMENT (MGE)

The visual representation process implemented in the MGE is different from the process of identifying the flooded and non-flooded SMEs. After coupling the OS MasterMap® layers along with the inundation data (which vary dynamically at every simulation tick) every inundation data value greater than zero was modelled as an agent ‘floodwater agent’ and visually represented at its precise location. Thus, at every

simulation tick, the number of floodwater agents change based on the inundation data values greater than zero. This technique enables the dynamic visualisation of the floodwater on top of the OS layers (see Figure 6.4). In terms of modelling floodwater agents, they were simply modelled with two attributes (i.e. northings and eastings).

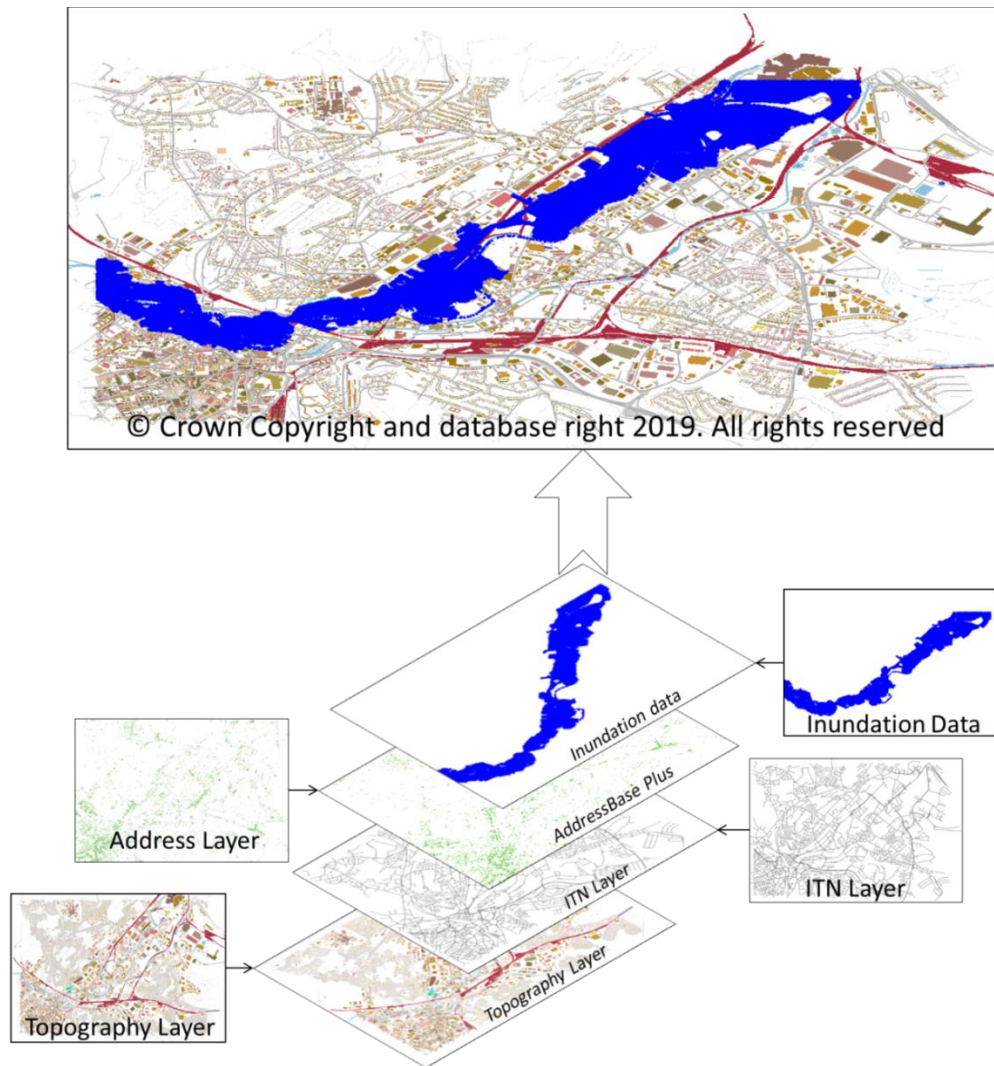


Figure 6.4: Coupling the inundation data with the OS MasterMap® layers

6.5 SUMMARY

The MGE was constructed using OS MasterMap® Topography, ITN, *AddressBase Plus* layers to (i) identify the flooded and non-flooded organisations, and (ii) provide a visual representation of the flood event in the selected geographical area. In terms of the identification of organisations, this was mainly dependent on the *AddressBase Plus* layer and inundation data. Subsequently, every water depth value within the inundation data was mapped to its appropriate location on the *AddressBase Plus* layer, which in turn, enabled the identification of the flooded and non-flooded organisations.

Chapter 7

Agent-Based Modelling and Simulation

This chapter presents the process followed to develop the agent-based modelling component of the ABMS framework to model and simulate SME's immediate response to, and short-term recovery from, a flood event. After identifying specific flooded and non-flooded organisations, the flooded manufacturing and retail SMEs were selected to be modelled as autonomous agents. Specifically, the SMEs are modelled according to their pre-flood and post-flood behaviours and attributes along with a set of precautionary measures. This component involves interactions between SMEs and SME-related organisations such as suppliers, customers, electrical service providers, plumbing service providers, IT service providers, cleaning service providers, refurbishment companies, mutual aid partners, the Environment Agency, and insurance companies. Each of SME-related organisations provides SMEs with assistance to support their operations, such as suppliers and customers, and/or short-term recovery, such as electrical and plumbing service providers.

Section 7.1 presents the model development process including SME's behaviours and precautionary measures and how these influence SME's immediate response to and short-term recovery from flooding. It also outlines how manufacturing and retail SMEs are modelled as agents and how their performance is measured. Next, Section 7.2 describes how SME-related organisations are modelled. Section 7.3 presents an overview of how the model's efficacy is validated before presenting the Overview, Design concepts, and Details (ODD) protocol, on which the validation of this agent-based framework is based. Finally, Section 7.4 summarises and closes the chapter.

7.1 MODEL DESIGN AND DEVELOPMENT

Manufacturing and retail SMEs are modelled as autonomous agents with a set of static and dynamic attributes, behaviours, and pre-defined precautionary measures. SMEs' behaviours can be carried out pre- and post-flood whereas SMEs' precautionary measures are implemented by SMEs prior to a flood event taking place.

This section presents the process of designing and developing the agent-based modelling and simulation (ABMS) component that aims to investigate SMEs immediate response to and short-term recovery from flooding. Specifically, this section describes how manufacturing and retail SMEs' pre- and post-flood behaviours, along with pre-defined precautionary measures, are derived and modelled. As indicated, two SME sectors (manufacturing and retail) are included in this research, and thus, behaviours are classified as either *generic* (i.e. applied to both sectors) or *specific* (i.e. applicable to only one of the two sectors). For manufacturing SMEs, only production employees are allocated to work on behaviours. This is due to the physical nature of the work. However, retail SMEs can allocate all employees available to work on behaviours.

7.1.1 Pre-Flood Behaviours

Pre-flood behaviours are actions that can be completed before a flood occurs. Completing each of these pre-flood behaviours requires different specific duration. Enacting pre-flood behaviours has the potential to raise SME's protection level, which may reduce or prevent potential flood damage.

In Table 7.1, all the considered pre-flood behaviours for both manufacturing and retail SMEs are listed and classified in terms of the number of employees required to undertake them (i.e. a single employee (S_e) or multiple employees (M_e)), their priority execution order, their classification (i.e. a generic behaviour (G_b), specific behaviour to manufacturing SMEs (S_M), or specific behaviour to retail SMEs (S_R)), and duration range required for each behaviour. In terms of priority execution order, at times when the number of behaviours needing to be enacted exceeds the number of employees available, behaviours with a higher priority are assigned the relevant number of employees available such that they can be enacted first.

Recall, the behaviours along with their associated information modelled in this research were collected from various sources (i) transcripts of semi-structured interviews with SMEs having experience of flooding or being at risk of flooding, and (ii) EA guidance, and (iii) academic literature.

Code	Pre-flood behaviours	Employee	Priority	Classification	Duration (hours)	References	
						EA guidance and academic literature	Semi-structured interview transcripts
B₁	Place sandbags at doorways	M _e	1	G _b	3 - 6	[1, 18-20]	S ₃₃ , S ₂₀ , S ₂₇ , S ₃₄ , S ₄₅ , S ₄₉ , S ₆₃
B₂	Cover air-bricks	M _e	2	G _b	1 - 2	[21-23]	S ₄₉ , S ₅₂
B₃	Lift-up IT equipment	M _e	3	S _M	½ - 3	[24, 25]	S ₁₁ , S ₄₃ , S ₄₄ , S ₄₆ , S ₅₀ , S ₅₆ , S ₆₀
B₄	Lift-up sales equipment	M _e	4	S _R	½ - 3	[26]	S ₃₀ , S ₅₉ , S ₅
B₅	Lift-up paper documents	M _e	5	G _b	½ - 3	[22, 24, 25]	S ₅₆ , S ₅₉
B₆	Lift-up raw materials	M _e	6	S _M	½ - 3	[24]	S ₂₇ , S ₃₀ , S ₅₆
B₇	Lift-up light or medium products	M _e	7	S _M	½ - 3	[27, 28]	S ₂₇ , S ₃₀ , S ₅₆
B₈	Lift-up stocks	M _e	8	S _R	½ - 3	[19, 26]	S ₂₇ , S ₃₀ , S ₅₆ , S ₅₉
B₉	Cut-off electricity	M _e	9	G _b	½ - 2	[18, 29, 30]	S ₅₃ , S ₆₀
B₁₀	Contact customers to inform of suspension in dispatch of products from SME	S _e	10	S _M	½ - 2	[24, 25]	S ₈ , S ₁₉ , S ₄₃
B₁₁	Contact suppliers to suspend their delivery of raw materials	S _e	11	G _b	½ - 2	[22, 24, 25]	S ₃ , S ₈ , S ₆₂
B₁₂	Evacuation (immediately if floodwater enters an SME's premises)	M _e	12	G _b	½ - 4	[1, 25, 31-35]	S ₃₆ , S ₄₃ , S ₄₄ , S ₄₆

Table 7.1: SMEs pre-flood behaviours and durations

The pre-flood behaviours listed in Table 7.1 are presented in Figure 7.1, which indicates the relationships between them. It can be observed that all SMEs' pre-flood behaviours are unrelated in the sense that they do not depend on the prior completion of other behaviours; with the exception of pre-defined precautionary measures such as EA alerts and warnings. However, the ability to enact all pre-flood behaviours simultaneously and in parallel depends on the number of employees available on SMEs' premises and thus some behaviours have been assigned a higher-priority execution order. As mentioned previously, the priority execution order of pre-flood behaviours has been derived from (i) the semi-structured interview transcripts and (ii) the academic literature. For example, according to the semi-structured interview data available, SMEs have placed sandbags at doorways as an initial measure before focusing on lifting-up SMEs' equipment and paper documents. Also, Pathak and Ahmad (2016) have indicated that the coping mechanisms undertaken by SMEs, during the 2011 flood event in Thailand included placing sandbags in doorways, moving items to safer places, and finally evacuations.

In relation to Figure 7.1, if a manufacturing or retail SME receives and trusts an EA alert, it will immediately allocate employees to complete possible behaviours such as place sandbags at doorways and cover airbricks. However, if an EA alert was not received or trusted, but a warning was received, then a manufacturing or retail SME will allocate employees to complete pre-flood behaviours, although less time (3 hours prior to the expected flood commencing) would be available to enact them. For the worst-case scenario of an SME not receiving an EA alert or warning, employees would work on production for manufacturing SMEs, or customer service for retail SMEs until it was observed that flooding was imminent at which point they would evacuate, and thus, none of the pre-flood behaviours will be enacted.

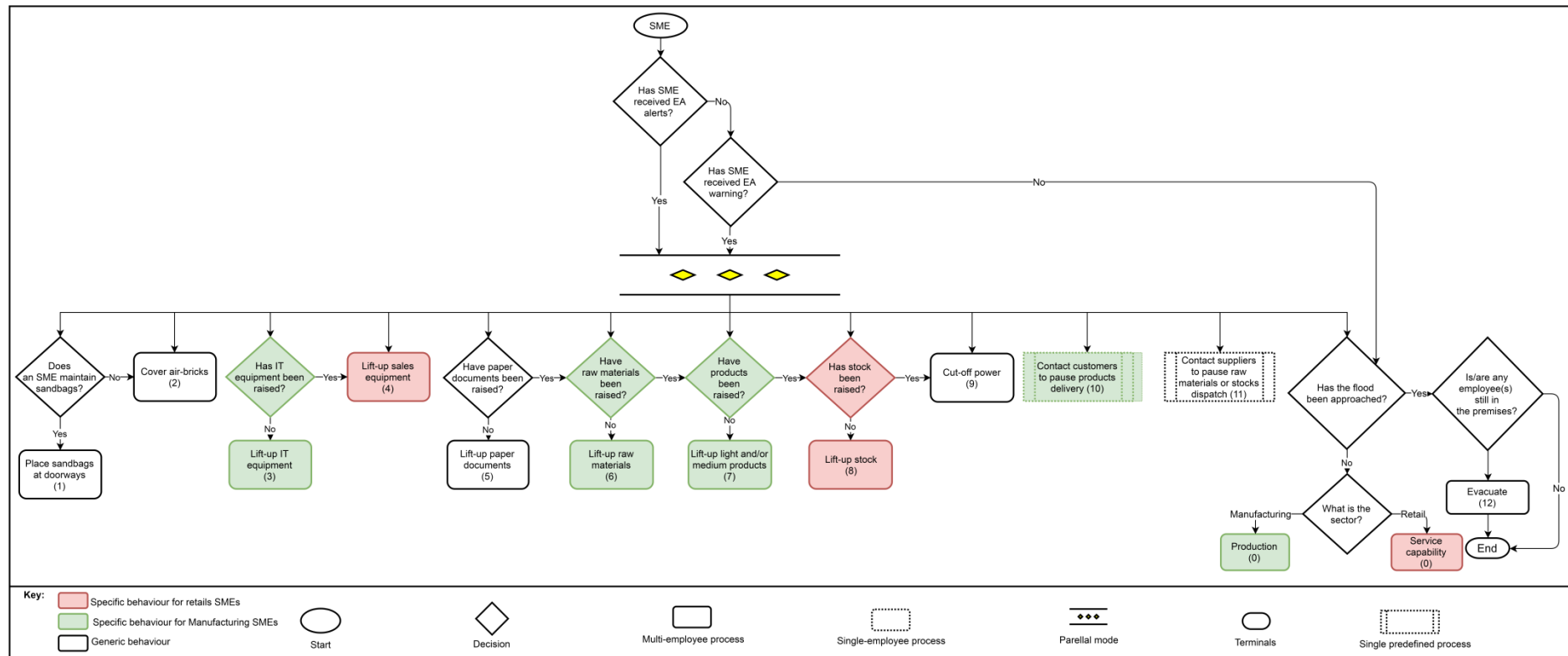


Figure 7.1: Pre-flood behaviours' relationships with sequencing order of behaviour execution indicated in the brackets in each action box

On receipt of a trusted alert or warning, manufacturing and retail SMEs will enact all or a proportion of their pre-flood behaviours based on (i) the number employees available (production employees for manufacturing SMEs), (ii) the number of pre-flood behaviours needed to be enacted, (iii) the time at which the alert or warning was received, and (v) the precautionary measures implemented. Initially, manufacturing and retail SMEs will allocate a proportion of employees (production employees for manufacturing SMEs) to place sandbags, if available, at doorways. Depending on availability, employees will be allocated to, simultaneously or sequentially, enact pre-flood behaviours, such as cover airbricks or lift-up paper documents. According to the technical report, air-bricks should be located at least 0.075 m above ground level (NHBC, 2016). Therefore, if the floodwater level outside premises exceeds 0.075 m, water will enter through the airbricks unless they are covered.

For manufacturing SMEs, a proportion of employees will be allocated to enact pre-flood behaviours, such as lift-up IT equipment, documents, raw materials, and products whereas employees in retail SMEs will be allocated to lift-up sales equipment, documents, and stock. According to Keogh et al. (2011) prior to the evacuation people are prompted to move documents and valuable items onto tables. Similarly, interviewees S₈, S₉, S₁₁, S₂₇, S₄₃, S₄₄, S₄₈, S₅₇, and S₆₀ had items, such as IT equipment, sales equipment, documents, raw materials, products, and stock located on the ground, and then, on receipt of a flood alert or warning, a proportion of employees were allocated to lift them up onto desks.

S₈: “... so all we had time to do really then was anything that was on the floor level, was just get it on the desk and then that’s it, we had to leave ...”

S₄₄: “... because we used to keep all our computers on the floor, so all the computers, everything we could lift up onto desks people started to do that. So that was done and that sort of saved us ...”

According to the Furniture Industry Research Association, the standard height for desks is 0.72 m (Furniture Industry Research Association, 2019). Once these items (IT equipment, sales equipment, paper documents, raw materials, products, and stocks) have been lifted-up, the potential for them to be damaged is reduced or removed. For

paper documents, protecting these documents allows an SME to contact customers and suppliers quicker than if these documents were damaged (Wedawatta et al., 2014)

In relation to manufacturing SMEs, SMEs are assigned a product type (i.e. light, medium, or heavy) randomly; note that heavy products cannot be lifted-up. For production machines, because machines tend to be heavier, they cannot be moved. According to interview transcript S₄, employees report that they were unable to lift-up machinery because they were too heavy to move.

7.1.2 Post-Flood Behaviours

Post-flood behaviours are performed in the aftermath of an inundation event once the floodwater has receded from an SME's premises. Enacting post-flood behaviours enable SMEs to return their normal operation. However, this may take hours or days. Table 7.2 indicates manufacturing and retail SMEs' post-flood behaviours in addition to the number of employees required to undertake them (i.e. a single employee (S_e) or multiple employees (M_e)), their priority execution order, their classification (i.e. a generic behaviour (G_b), specific behaviour to manufacturing SMEs (S_M), or specific behaviour to retail SMEs (S_R)), and duration range.

Code	Employees	Priority	Classification	Post-flood behaviours	Durations (Hours)	Resource	
						EA guidance and academic literature	Semi-structured interview transcripts
B₁₃	M _e	13	G _b	Restore power supply	½ - 2	[22, 24, 25]	S ₄₁ , S ₅₇
B₁₄	S _e	14	G _b	Contact insurance company	2 - 3	[22, 36-38]	S ₄₁ , S ₅₇
B₁₅	S _e	15	G _b	Contact electrical service providers	½ - 2	[22, 24, 25, 29, 35, 38, 39]	S ₃ , S ₁₅ , S ₂₇ , S ₄₇
B₁₆	S _e	16	G _b	Supervise power supply repairs	12 - 48	-	S ₁₁ ,
B₁₇	M _e	17	G _b	Set-up and use electricity generator	½ - 2	[18, 19, 22, 32]	S ₄₈ , S ₅₃ , S ₅₉ , S ₆₂
B₁₈	S _e	18	S _M	Contact mutual aid partner	½ - 2	[19, 24, 33, 40]	S ₉
B₁₉	M _e	19	S _M	Work at partner's location	Variable *	[19, 24, 33, 40]	S ₉
B₂₀	S _e	20	G _b	Supervise electrical sockets repairs	6 - 10	-	S ₂₇ , S ₂₈
B₂₁	S _e	21	G _b	Contact plumbing service providers	½ - 2	[18, 25, 38, 39]	S ₃ , S ₁₄
B₂₂	S _e	22	G _b	Supervise damaged pipes repairs	6 - 10	-	S ₁₄ , S ₁₅
B₂₃	S _e	23	G _b	Contact cleaning service providers	½ - 2	[24, 38]	S ₆ , S ₁₅ , S ₃₃ , S ₅₀
B₂₄	S _e	24	G _b	Supervise cleaning service	22 - 54	-	S ₆ , S ₂₆ , S ₃₃
B₂₅	M _e	25	G _b	Acquire cleaning equipment	4 - 12	[22, 29]	S ₄₅ , S ₅₉
B₂₆	M _e	26	G _b	Allocate employees to clean up	22 - 54	[20, 22, 38]	S ₄ , S ₅ , S ₅₉ , S ₆₁ , S ₆₃
B₂₇	M _e	27	S _M	Repair production machines	27 - 90	[20, 24, 28, 41]	S ₁ , S ₂₈ , S ₂₉ , S ₄₇ , S ₆₀
B₂₈	S _e	28	S _R	Contact refurbishment company	½ - 2	[26, 27, 38]	S ₄ , S ₇ , S ₂₁ , S ₆₂
B₂₉	S _e	29	S _R	Supervise premises refurbishment	5 - 48	[23]	S ₄ , S ₇ , S ₂₁ , S ₅₀ , S ₆₂
B₃₀	M _e	30	S _R	Allocate employees to refurbish SME's premises	5 - 48	[23]	S ₄₁ , S ₅₉
B₃₁	S _e	31	G _b	Contact suppliers to resume their delivery of raw materials or stocks	½ - 2	[22, 24, 25]	S ₃ , S ₈ , S ₆₂
B₃₂	M _e	32	S _M	Return lifted-up IT equipment to normal location	½ - 3	-	S ₃ , S ₄₃ , S ₄₆
B₃₃	S _e	33	S _M	Contact IT service providers	½ - 2	-	S ₆₁
B₃₄	S _e	34	S _M	Supervise IT equipment repairs	8 - 24	-	S ₄₆ , S ₆₁
B₃₅	M _e	35	S _M	Set-up IT equipment	2 - 5	-	S ₈ , S ₄₆ , S ₅₁
B₃₆	M _e	36	S _M	Recover IT data	48 - 96	-	S ₅₀ , S ₆₁
B₃₇	S _e	37	S _M	Restore back-up IT data	4 - 10	-	S ₄₆
B₃₈	M _e	38	S _R	Return lifted-up sales equipment to normal location	½ - 3	-	S ₆₂
B₃₉	S _e	39	S _R	Order new sales equipment	½ - 2	-	S ₄ , S ₆₂
B₄₀	M _e	40	S _R	Set-up sales equipment	2 - 5	-	S ₆₂
B₄₁	M _e	41	G _b	Return lifted-up paper documents to normal location	½ - 3	-	S ₁ , S ₅₀
B₄₂	M _e	42	S _R	Return lifted-up stocks to normal location	2 - 10	-	S ₂₇ , S ₃₀ , S ₅₆ , S ₅₉
B₄₃	M _e	43	G _b	Reproduce documents	48 - 96	[18, 21]	S ₁₄ , S ₄₃ , S ₅₀
B₄₄	S _e	44	S _M	Contact customers to inform of resumption of SME dispatch of products	½ - 4	[24, 25]	S ₈ , S ₁₉ , S ₄₃

* depends on allocated machines (see Section 7.2.6)

Table 7.2: SMEs post-flood behaviours and durations

The post-flood behaviours listed in Table 7.2 are related; some of them depend on the prior completion of others. Specifically, Figure 7.2, Figure 7.3, and Figure 7.4 indicate manufacturing and retail SMEs' post-flood behaviours, and the precedence relationships between them. As indicated previously, the relationships between post-flood behaviours as well as their priority execution order have been derived from (i) the semi-structured interview transcripts and (ii) the academic literature. For example, according to the interview transcript data available, some SMEs had restored the power supply themselves immediately after the flooding had receded. Also, it is indicated that some SMEs – especially those that suffered higher levels of damage – had to contact their insurers to provide them with the necessary information and financial assistance to support their recovery. Confirming this, Dhonau and Rose (2016) indicated that SMEs, if insured, need to contact their insurance providers immediately after the floodwater has receded. Furthermore, the interview transcript data available shows that some SMEs had to contact electricians and plumbers to restore the power supply and repair damage to piping, respectively, after the power supply was reconnected. With electricity restored, it is reported that while some SMEs carried out premises cleaning, those with less damage returned the lifted-up items to their normal locations. These different scenarios followed by SMEs have been considered in this research to (i) design the relationships between post-flood behaviours and (ii) establish the priority- execution order of the post-flood behaviours.

In relation to Figure 7.2, manufacturing and retail SMEs' aim is to return to normal operation as soon as possible. Thus, in the initial short-term recovery stage, the power supply must be restored or repaired as indicated in Figure 7.2. Power can be restored by an SME's employees unless damage has occurred in which case the SME is required to contact an electrician, if funds are available, to carry out the necessary repairs (see Section 7.2.5). Furthermore, SMEs that have insurance (see Section 7.2.3) will contact their insurer to obtain financial compensation for any flood damage and, if covered sufficiently, a cleaning service to attend their premises. Furthermore, if available (see the precautionary measures in Section 7.1.3), an SME may set-up and use an electricity generator as an alternative power supply until the main power is restored. This will enable a manufacturing or a retail SME to enact some of the post-flood behaviours (e.g. repairing production machines and set-up and repair IT equipment for manufacturing SMEs) before the main power is restored.

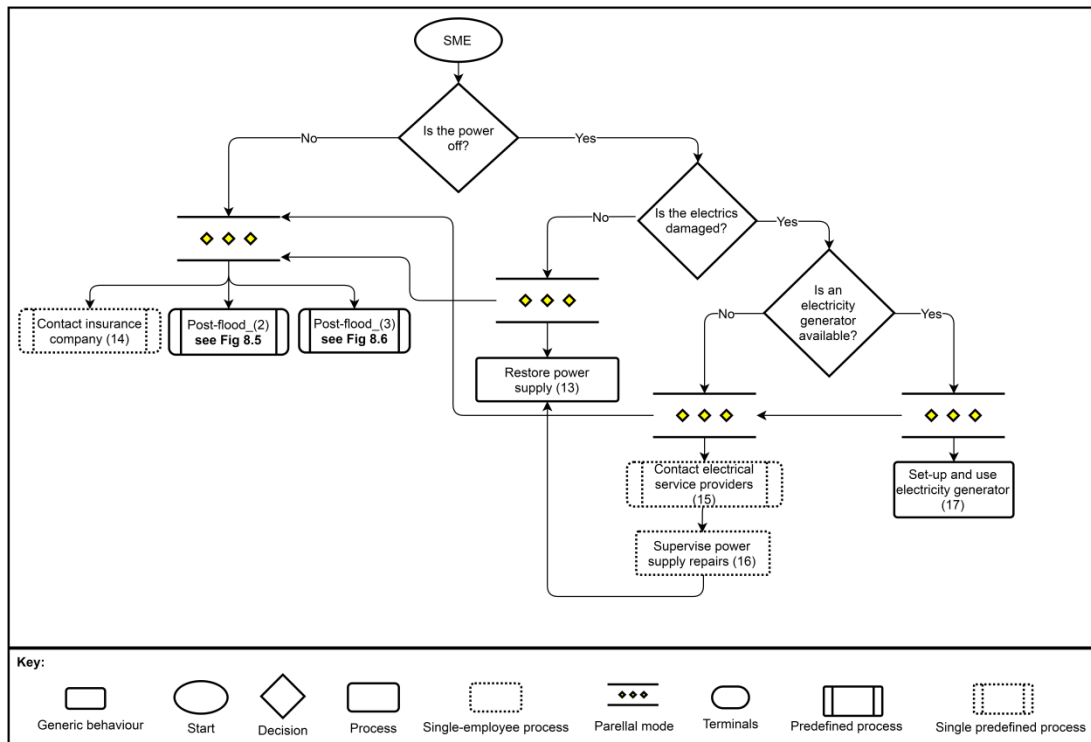


Figure 7.2: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (1)

For manufacturing SMEs, as indicated in Figure 7.3, those with pre-defined mutual aid (see Section 7.2.6) will contact their mutual aid partner to move production to a new location (partner's location) for a period of time.

For manufacturing and retail SMEs, if the floodwater level reaches electrical sockets, e.g. 0.3m if not raised or 1.5m if raised (see the precautionary measures in Section 7.1.3), they will be damaged and thus they need to be repaired by an electrician. Also, the floodwater may cause damage to water pipes in which case a plumber will be contacted to carry out repairs. For a cleaning service, manufacturing and retail SMEs, especially those without an insurance policy but with an emergency financial reserve or funds available, could contact a cleaning service provider or, alternatively, employ a proportion of their employees to clean-up the premises. However, prior to employees carrying out post-flood cleaning, a proportion of employees would be allocated to acquire the appropriate cleaning equipment. As indicated in Figure 7.3 and Figure 7.4, cleaning-up a premises must be completed before enacting some behaviours, such as returning IT equipment and paper documents

for manufacturing SMEs, and sales equipment, stocks, and paper documents for retail SMEs, that had been lifted-up pre-flood to their normal location.

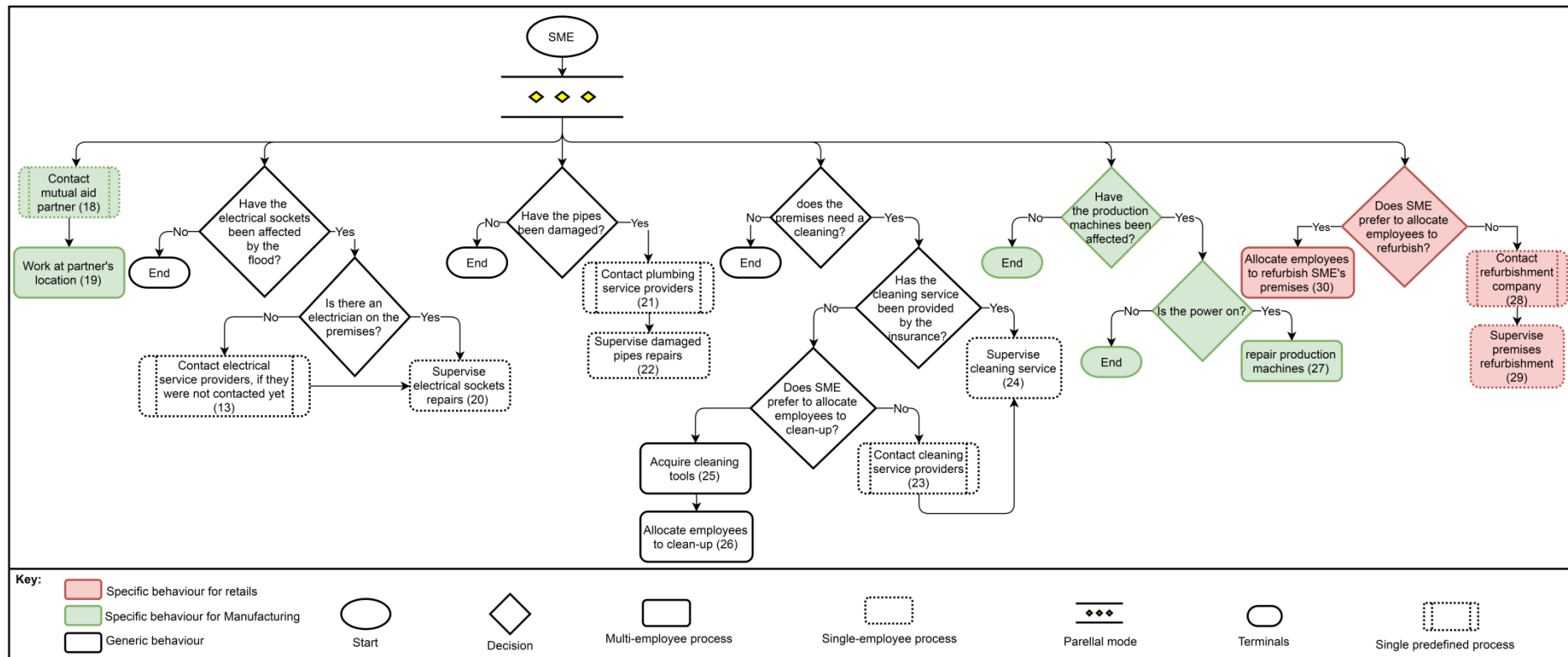


Figure 7.3: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (2)

For retail SMEs, as indicated in Figure 7.4, if sales equipment is damaged, it must be replaced. Subsequently, a single employee must be allocated to enact such behaviour.

In terms of manufacturing SMEs, as indicated in Figure 7.4, if damage has occurred to IT equipment due to flooding, an IT service provider needs to be contacted (see Section 7.2.5) and attend to carry out the necessary repairs. Once repaired, or returned to their normal location after being lifted-up pre-flood, IT equipment must be set-up by employees. After repairing IT equipment, backed-up data must be restored if available (see the precautionary measures Section 7.1.3) or recovered if not. In relation to production machines (specific manufacturing behaviour), as a percentage of those in need of repair, each production employee may fix E_r^p machines per simulation tick,

$$E_r^p = \frac{M_d}{H \times 2} \quad (7.1)$$

In equation (7.1), M_d is the percentage of an SME's machines damaged and in need of repair and H is the number of man-hours required to repair them, which is converted to the simulation tick (30-minute interval).

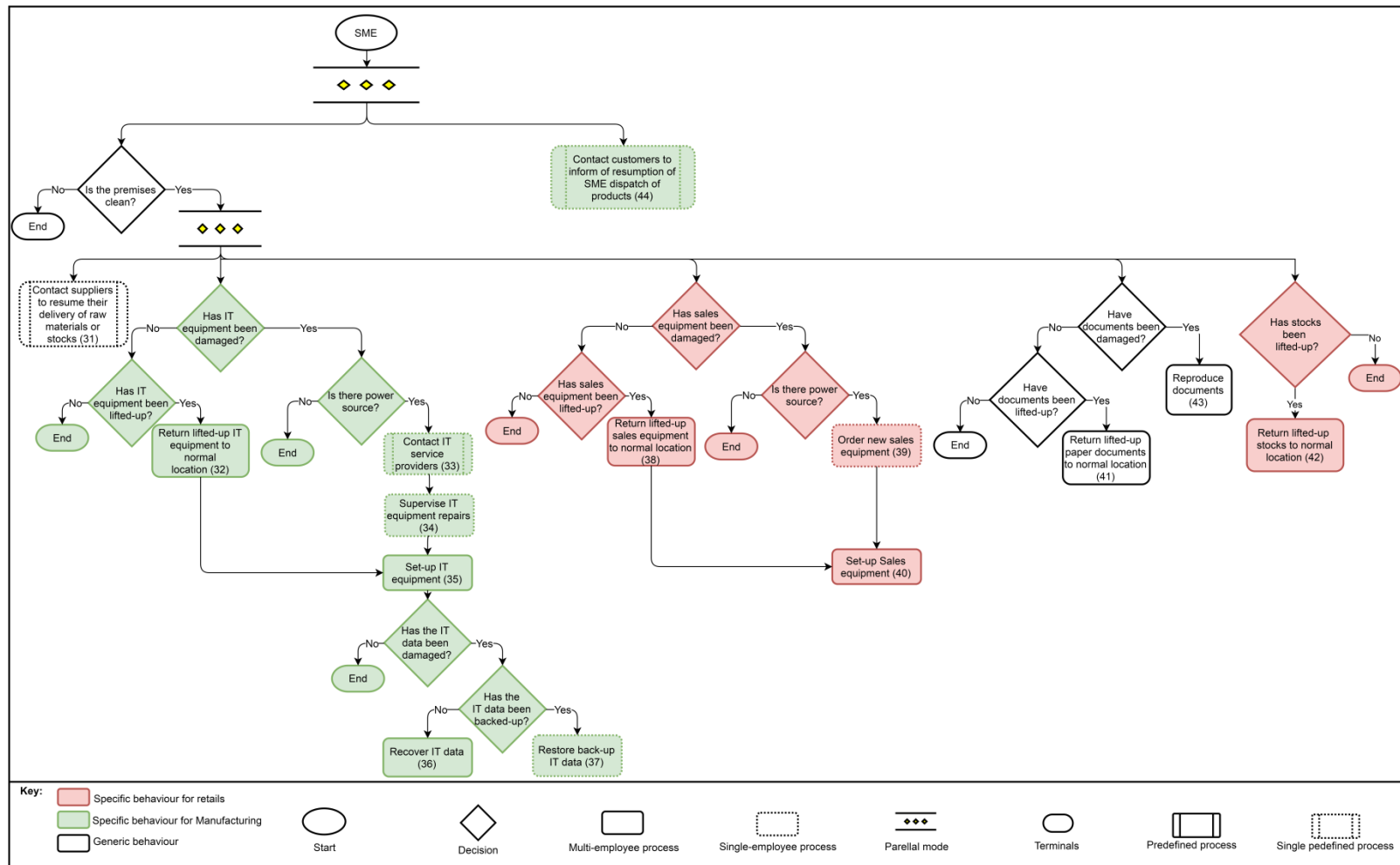


Figure 7.4: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (3)

Kreibich et al. (2007) indicate that machine repair should be influenced by the water level reached inside a premises. Therefore, in this research, SMEs are classified according to the level the floodwater reaches within their premises. According to the EA (Environment Agency, 2019b), flood depth is classified into three categories: (i) lightly flooded (if the floodwater level is less than 0.3m), (ii) moderately flooded (if the floodwater is greater than or equal to 0.3m but less than or equal to 0.9m), and (iii) severely flooded (if the floodwater is greater than 0.9m).

For manufacturing SMEs, the durations required to repair production machines, IT equipment, and clean-up a premises are divided into three thirds: each of these thirds is implemented with the corresponding floodwater category (i.e. the first third is the duration required when a manufacturing SME's premises is lightly flooded whereas the second and the third thirds are the durations required when a manufacturing SME is moderately and severely flooded, respectively).

In terms of retail SMEs, similarly, the durations required to clean-up and refurbish a retail SME's premises are also divided into three thirds: the first third is implemented when a retail SME's premises is lightly flooded while the second and the third thirds are implemented for the moderately and severely flooded SMEs' premises, respectively.

7.1.3 Precautionary Measures

Precautionary measures are implemented by an SME prior to a flood event occurring or being anticipated and are intended to: (i) prevent or reduce the amount of water entering a premises; (ii) remove the need for, or reduce the duration of, some pre- and post-flood behaviours. Table 7.3 lists the precautionary measures considered in this research which were collected from three sources: (i) semi-structured interview transcripts with SMEs having experience of flooding or being at risk of flooding; (ii) EA guidance; (iii) academic literature.

In the academic literature, precautionary measures are classified into three types: (i) property-level (Cameron & Proverbs, 2014; Joseph et al., 2015; Kazmierczak & Bichard, 2010; May et al., 2014; Treby et al., 2006); (ii) community-level (Environment Agency, 2009; Joseph et al., 2015; Treby et al., 2006); and (iii) and business continuity/risk management precautionary measures (Wedawatta & Ingirige,

2012). First, property-level precautionary measures (i.e. structural precautionary measures) are defined as building's fabric and contents designed to protect a property from extreme weather events, especially flooding (Joseph et al., 2011; Kazmierczak & Bichard, 2010). Next, community-level flood precautionary measures represent the first line of defence against flooding to reduce the risk to local communities. These include features such as storage basins, raised river embankments, and coastal defences (Bichard & Kazmierczak, 2009). Finally, business continuity/risk management precautionary measures (i.e. social precautionary measures) are those deployed more likely for businesses, such as registering for flood warnings and alerts services, seeking business interruption insurance, and business continuity planning (Wedawatta & Ingirige, 2012).

In terms of these different types of precautionary measures, SMEs are only able to adopt property-level (structural) precautionary measures and business continuity/risk management (social) precautionary measures. Community-level precautionary measures, which cannot provide protection to every property vulnerable to flooding Environment Agency (2009), are under the control of local and national authorities, and thus, are excluded from this research.

Code	Classification		Classification	Precautionary measures	Resources	
					EA guidance and academic literature	Semi-structured interview transcripts
PM ₁	Property Level	Flood Resistance precautionary measures	G _e	Build bund wall	[23-25]	S ₄₁ , S ₄₇
PM ₂			G _e	Maintain sandbags on site	[1, 18-20, 22, 33, 34, 42]	S ₁₅ , S ₃₃ , S ₄₅ , S ₄₇ , S ₄₉ , S ₆₃
PM ₃			G _e	Install flood-proof doors	[20-23, 43]	S ₅₉ , S ₄₃
PM ₄			G _e	Install flood barriers at doorways	[19, 22, 23, 26, 28, 44-47]	S ₈ , S ₁₅ , S ₂₂ , S ₃₃ , S ₅₉ , S ₆₀
PM ₅			G _e	Install flood-proof windows	[22, 23]	S ₂₇ , S ₆₂
PM ₆			G _e	Install anti-backflow valves	[18, 20, 22, 23, 35]	S ₁₅ , S ₂₈ , S ₂₉ , S ₃₁ , S ₃₄
PM ₇			G _e	Paint brickwork with waterproofing treatments	[1, 23, 25, 35]	S ₂₂ , S ₂₇
PM ₈			G _e	Install ‘below-ground’ water-proof materials	[22, 23, 48]	S ₁₈ , S ₅₁
PM ₉		Flood resilience precautionary measures	G _e	Install flood-resilient flooring	[22, 23, 45, 48]	S ₂₅ , S ₂₆
PM ₁₀			G _e	Raise consumer boards	[18, 26]	S ₂₂ , S ₂₈ , S ₂₉
PM ₁₁			G _e	Raise electrical sockets	[21, 22, 26]	S ₂₂ , S ₂₈ , S ₂₉ , S ₆₂
PM ₁₂			G _e	Raise the location at which paper documents are stored	[22, 24, 39]	S ₂₂ , S ₂₇
PM ₁₃			S _p	Raise the location at which raw material can be stored	[22, 39]	S ₂₈ , S ₁₉
PM ₁₄			S _p	Raise the location at which stocks can be stored	[22, 39]	S ₂₈ , S ₄₁
PM ₁₅			S _p	Raise the location at which production machines are placed	[22, 24, 39]	S ₂₈ , S ₉
PM ₁₆			S _p	Raise the location at which IT equipment is placed	[22, 26, 39]	S ₄₄ , S ₄₃
PM ₁₇			S _p	Raise the location at which products are stored	[22, 39]	S ₂₈ , S ₄₁
PM ₁₈			G _e	Install and use a sump pump system	[23, 29]	S ₄ , S ₅₃
PM ₁₉	Business continuity/risk management precautionary measures		G _e	Register for EA alerts	[18, 20, 42]	S ₄₃ , S ₅₄ , S ₆₂
PM ₂₀			G _e	Register for EA warnings	[20, 42]	S ₆ , S ₃₃ , S ₆₃
PM ₂₁			G _e	Obtain basic insurance	[28, 45, 49]	S ₁₈ , S ₅₇ , S ₆₁
PM ₂₂			G _e	Obtain comprehensive insurance	[28, 34, 49, 50]	S ₆ , S ₄₃ , S ₄₅ , S ₅₃ , S ₅₇
PM ₂₃			G _e	Set-up and maintain an emergency financial reserve	[20, 39]	S ₃₈ , S ₄₁ , S ₄₃
PM ₂₄			S _p	Has pre-existing mutual aid partner	[19, 33, 40]	S ₉ , S ₃₆ , S ₁₀
PM ₂₅			S _p	Identify a mutual aid partner	[19, 33, 40]	S ₉ , S ₃₆ , S ₁₀
PM ₂₆			S _p	Request a mutual aid partner	[19, 33, 40]	S ₉ , S ₃₆ , S ₁₀
PM ₂₇			G _e	Maintain an electricity generator on site	[18, 19, 22, 32]	S ₄₃ , S ₄₈ , S ₅₃ , S ₅₉ , S ₆₂
PM ₂₈			G _e	Backup IT data	[41]	S ₈ , S ₄₃ , S ₄₅ , S ₄₉

Code	Classification	Classification	Precautionary measures	Resources	
				EA guidance and academic literature	Semi-structured interview transcripts
PM₂₉		G _e	Maintain an emergency flood plan	[22, 30, 34, 44, 46]	S ₃ , S ₃₆ , S ₄₄ , S ₄₆ , S ₅₃ , S ₅₉
PM₃₀		G _e	Display an emergency flood plan	[18, 22, 35, 48]	S ₃ , S ₁₂ , S ₃₆
PM₃₁		G _e	Perform emergency flood exercise	[28]	S ₂₀ , S ₄₇ , S ₅₃ , S ₃₇

Table 7.3: SMEs precautionary measures

7.1.3.1 Property-Level Precautionary Measures

Property-level precautionary measures are effective at protecting premises from flooding (Joseph et al., 2015; Wedawatta & Ingirige, 2012), and thus, businesses are primarily encouraged to take up these structural types of measures (Pitt, 2008). There is a wide and varied range of individual property-level precautionary measures which can be implemented within a business, depending mainly on the specific type of business and the characteristics of its building(s) (Wedawatta & Ingirige, 2012). However, once appropriate property-level precautionary measures are implemented, they potentially enhance SME's long-term resistance and resilience to flooding events. Specifically, property-level precautionary measures are classified as (i) flood resistance precautionary measures, and (ii) flood resilience precautionary measures (Bowker, 2007; Cameron & Proverbs, 2014; Dhonau & Rose, 2016; Joseph et al., 2011; Mis et al., 2015; Thurston et al., 2008).

7.1.3.1.1 Flood Resistance Precautionary Measures

Flood resistance precautionary measures are intended to prevent the *entry* of floodwater into premises in order to reduce the potential risk of damage (Defra, 2005; Joseph et al., 2011; Thurston et al., 2008).

Premises can be protected from floodwater in different ways. For example, if detached, building a bund-wall around the premises or deploying sandbags could prevent floodwater entering a premises up to 1.5m (East Ayrshire Council, 2019; Environment Agency, 2019a) and 0.3m respectively (Rickard, 2009). Similarly, flood-proof doors and flood barriers are alternative protection measures that could stop floodwater entering a premises up to a level of 0.9m and 0.5m respectively (SFF, 2016; Stormguard Flood Plan, 2019). SME's premises feature multiple entry points (windows, brickwork, below ground, and drainage network or pipes) that could be protected to prevent or reduce floodwater ingress.

According to the Building Regulation Guidance, windows should be located at least 0.80 m above ground level (NHBC, 2016). Therefore, if the floodwater level outside premises exceeds 0.80 m, water will enter through the windows unless flood-proof windows are installed. In terms of brickwork, Beddoes and Booth (2011) indicate that the average leakage rate of a typical brick wall is 0.15 m³/hr.

7.1.3.1.2 Flood Resilience Precautionary Measures

Flood resilience precautionary measures are intended to limit the *effect* of floodwater entering a premises (Joseph et al., 2011; Thurston et al., 2008; Wingfield et al., 2005). These precautionary measures aim to reduce the impact of flooding, which eventually speeds-up the affected buildings' and infrastructures' short-term recovery stage (Defra, 2005). Indeed, according to a UK government panel's recommendations reviewing the lessons to be learned from the summer floods of 2007 (The Pitt Review), building regulations were reviewed to certify that all recent buildings (including residential and business) are in a flood-resilient state (Pitt, 2008).

Manufacturing and retail SMEs may install flood-resilient flooring and/or a sump pump system to speed-up the cleaning process. According to the Association of British Insurers, implementing or using resilient flooring materials accelerates the post-flood recovery process (Association of British Insurers, 2019). For the sump pump system, it removes water from premises at a faster rate than other measures (Boston et al., 2012). In this research, implementing each of these two precautionary measures reduces the duration required for cleaning up the premises by 10-30%. This selected range may vary from business to business based on the quality of the flood resilient flooring materials used and the sump pump system (DAB, 2019).

Furthermore, SMEs may raise the point at which consumer boards are located to prevent them being damaged; according to UK electrical safety experts, consumer units should be mounted between 1.35 m and 1.45 m above ground level (UK's electrical safety experts, 2019). Similarly, the locations of electrical sockets may be raised; according to the British building standards, sockets should be installed 1.5 metres above floor level (Environment Agency, 2019c, 2019d). However, with no precautionary measures implemented, British building standards indicate that electrical sockets, switches, and other electrical control devices should be installed at a minimum of 0.35 m above ground level (DIY, 2019).

As precautionary measures, manufacturing SMEs may raise the location of their items, such as paper documents, products, raw materials, IT equipment, and production machines, which may increase their level of protection. Similarly, retail SMEs may raise the location of documents and stock to reduce the impact of flooding. However,

prior to implementing these precautionary measures, manufacturing and retail SMEs may place some items at ground level as revealed in the interview transcripts.

- Documents

S1: “... some things are too big, too heavy and there is no way you could take them upstairs but I would take all the paper and anything that was on the floor, upstairs ...”

- Stock

S19: “... So the second time it happened, there wasn't...there was some stock on the floor but not very much ...”

- Raw materials

S59: “... we have learnt now about getting certain things off the floor if we can and we do ... we can get the raw materials off the floor ...”

- IT equipment

S44: “... the people here lifted all the computer stuff off the floor because we used to keep all our computers on the floor ...”

- Production machines

S1: “... I would take everything, everything, all the jobs, the paper, everything upstairs. You can't do anything about the machinery because the machines are on the floor and we can't do anything about that ...”

S46: “... we have got loads of machinery on the factory floor, this is a low-risk business ...”

Businesses and residential owners are encouraged to raise their items, such as documents and electrical equipment (IT equipment), to at least 1.5m above ground level (ABI, 2017; Benn, 2009; Go Compare Insurance, 2019). Thus, a height of 1.5m is selected, signifying that if the water level inside a premises remains below 1.5m, the raised documents, stock, raw materials, and IT equipment, will not be affected. Note that for raw materials and heavy products, the extent to which they can be raised above ground level is limited. In terms of production machines, interviewee S₉, S₂₈, and S₂₉, indicate that they plan to place machines on plinths as a flood precautionary measure.

Furthermore, Dhonau and Rose (2016) have recommended raising machines on plinths to reduce their vulnerability to flood damage. In terms of the plinth height, this is taken as approximately 0.5m (HSE, 2015). Thus, a value of 0.5m is selected signifying that if the water level inside a premises remains below 0.5m, the raised production machines will not be damaged.

7.1.3.2 Business Continuity/Risk Management Precautionary Measures

Business continuity/risk management precautionary measures include (i) generic precautionary measures, which are not implemented specifically for floods, such as obtaining an insurance plan, and (ii) flood-specific precautionary measures such as signing up for a flood warning system or having a flood plan (Wedawatta & Ingirige, 2012). Furthermore, these precautionary measures can only reduce the adverse impacts of flooded businesses and support their short-term recovery process rather than protecting premises and/or reducing the potential damage flooding may cause to a building and its resources. Indeed, Crichton (2006) indicates that businesses always aim to implement business continuity/risk management precautionary measures rather than property-level precautionary measures in preparation for flooding, although implementing these types of precautionary measures alone is insufficient (Crichton, 2006; Wedawatta & Ingirige, 2012).

As a precautionary measure, registering for an EA alert or warning may prompt an SME to prepare for a possible event by enacting pre-flood behaviours that result in reducing damage and accelerating the resumption of production or service post-flood. SMEs that have registered for EA alerts and warnings may enact pre-flood behaviours providing they are received (and the former trusted) during normal working hours. According to SEPA (2019), EA alerts can arrive 36 hours prior to the expected flood commencing whereas warnings may be received approximately 3 hours in advance (see Section 7.2.1).

SMEs with comprehensive insurance receive assistance in the form of a cleaning service in addition to financial compensation, whereas basic insurance only provides the latter (see Section 7.2.3). However, SMEs without insurance may go out of business unless they have an emergency financial reserve to draw on. According to the

interview transcripts, S₄₃ indicates that having an emergency financial reserve is an essential precautionary measure to support SME's short-term recovery.

S₄₃: "... Yes, that's one of the things, immediately you need to put in place some sort of cash reserve to be able to allow you to start meeting the funds ..."

As a precautionary measure, maintaining an electricity generator on site enables an SME to use, if needed, this alternative power supply until the main power is restored, and thus, an SME can start its short-term recovery process before the power supply is restored (FEMA, 2013). Furthermore, backing up IT data is a precautionary measure that enables an SME to restore its data if their IT equipment was damaged; otherwise, an SME may lose business-critical data which could slow-down their short-term recovery time. It is acknowledged that some SMEs may use cloud storage to store their data. However, the interview transcripts available reveal that some SMEs lose their data due to damage occurring to their IT equipment, such as computers and servers. Next, maintaining and displaying an emergency flood plan, along with performing emergency flood exercises, may reduce the duration. Confirming this, Kreibich et al. (2007) and EAP (2014) indicate that businesses with emergency plans could prepare more effectively than those without a plan in place.

7.1.4 Attributes of Small and Medium Enterprises

Attributes are modelled for manufacturing and retail SMEs to formalise their identity. Attributes are categorised as (i) generic or specific, and (ii) static or dynamic.

The attributes listed in Table 7.4 are obtained from (i) the provided *AddressBase Plus* dataset, (ii) academic papers, and (iii) transcripts from the semi-structured interviews with employees of flooded SMEs.

Type	Attributes	Brief description
Generic Attributes		
Static	SME Id	Unique identifier for every agent modelled.
	SME name	SME's name obtained from OS master map's <i>AddressBase Plus</i> product.
	Classification code	This code is associated with the SME to identify its business activity and is obtained from the <i>AddressBase Plus</i> product.
	Classification name	The name associated with each classification code to classify each SME into a group of activities.
	Northing	Geographic coordinates associated with each SME; obtained from OS master map's <i>AddressBase Plus</i> product.
	Easting	
	Longitude	

Type	Attributes	Brief description
	Latitude	
	Road code	The code of the road where the SME is located; obtained from OS master map's <i>AddressBase Plus</i> product.
	SME size	Micro, small, or medium according to the number of employees.
	Inundation data	The water depth(s) associated with every flooded SME modelled in this model.
	Total number of employees, E_t	Total number of employees working for an SME.
	Funds	True: if an SME has funds available otherwise, it is false.
Dynamic	Percentage of employees available, $E_{\%}$	Percentages of total number of employees available at an SME's premises at each tick.
	Total number of employees available, E_a	Total number of employees available at an SME's premises at each tick.
	Total number of employees working on behaviours, E_b	Total number of employees allocated to work on behaviours at every tick.
	Allocated employees to clean up	True if an SME decides to allocate employees to clean up rather than contacting a cleaning service provider or accepting any provided cleaning service from their insurer otherwise it is false.
Specific Attributes for Manufacturing SMEs		
Dynamic	Production level, PL	Percentage of production level for an SME at each tick.
	Production employees, E_a^p	Total number of production employees available at an SME's premises at every tick.
	Production employees working on production, E_p^p	Total number of production employees working on production at an SME's premises at every tick.
	Production employees repairing machines, E_r^p	Percentage of production employees repairing machines.
	Raw materials available, RM	Total amount of raw materials available at an SME's premises for production at every tick.
	Raw materials on ground level, RM_{og}	Amount of raw materials kept at ground level at an SME's premises at every tick.
	Raw materials above-ground level, RM_{ag}	Amount of raw materials kept above-ground level at an SME's premises at every tick. This storage is always limited in size.
	Production machines available, M_a	Percentage of machines available for production at every tick.
	Ratio of production machines, M	Ratio of an SME's available machines, M_a , to the total Percentage of production machines owned by an SME, M_t
	Damaged production machines, M_d	Percentage of an SME's machines damaged.
	Products available, P_a	Amount of products available at an SME's premises each tick.
	Storage of products	The current room available to store products, which is always limited in size.
	Location height of products	Height at which products are stored; this variable changes whenever the products moved.
	Location height of IT equipment	Height at which the IT equipment is stored; this variable changes whenever the IT equipment is moved.
Static	None-production employees, E_t^{np}	Total number of non-production employees for an SME.
	Capacity can be placed above ground	Maximum capacity of the above-ground space in which raw materials are stored.
	Production machines, M_t	Percentage of production machines owned by an SME.
	Type of products, P_t	Type of products: e.g. light, medium or heavy.
	Maximum capacity of storage of products	The maximum capacity of the space in which products are stored.

Type	Attributes	Brief description
Specific Attributes for Retail SMEs		
Dynamic	Sales capability, SC	Percentage of sales capability at an SME's premises at every tick.
	Environment condition, EC	Percentages of the validity of the environmental conditions for operation at an SME's premises at every tick.
	Sales equipment, SE	Percentages of working sales equipment at every tick.
	Employees working on customer service, E_c^c	A list of the available employees allocated to serve customers.
	Location height of sales equipment	Height at which the IT equipment is stored; this variable changes whenever sales equipment is moved.
	Location height of stocks	Height at which stocks stored; this variable changes whenever stock is moved.

Table 7.4: Manufacturing and retail SMEs attributes

7.1.5 Manufacturing SMEs Performance Measurement

Gomes et al. (2004) present a literature review of 154 articles related to manufacturing performance measures categorized as financial and non-financial. Financial measures, such as profit and return on investment, are reported as ignoring clients and their needs and thus can be viewed as irrelevant. With a focus on non-financial performance measurement in manufacturing companies, Abdel-Maksoud et al. (2005) identify a series of measures ordered in terms of importance including on-time delivery to customers, number of complaints from customers, number of customer returns, efficiency (standard hours produced / hours worked), defects, scrap, absenteeism, number of warranty claims, manufacturing cycle efficiency, capacity utilisation, schedule adherence, on-time production, rework, employee lateness staff turnover and employee attitudes. However, Chang (2010) stated that no common approach exists for measuring post-flood recovery. Similarly, Jordan and Javernick-Will (2013) emphasised that although researchers agree that post-flood recovery is a process that occurs over time, there is no consensus about (i) how long the recovery may take, or (ii) how to measure it.

In this research production level is used as the performance metric given the focus is investigating SMEs' immediate response to and short-term recovery from a flood event. Production level is related to the availability of production machines (M), employees (E), raw materials (RM), and power (P) at the premises. These dynamic attributes have been identified from academic literature and a series of semi-structured interviews with SMEs involved in flood-related events and/or are located in flood-prone areas. For example, Kreibich et al. (2007) indicated that disruption to business

means that no business-related activities (such as production or providing a service) are possible, due to a lack of electricity, water or communication links; damage to essential machinery or a lack of raw materials due to transport disruptions or difficulties in ancillary industries. Specifically, in the data from the semi-structured interviews, it is indicated that restoring power is required before returning to normal operation. Similarly, it is mentioned that repairing production machines is an essential requirement governing the resumption of normal operation. The data also show that raw materials must be protected due to being needed for production. The relationships between these dynamic attributes are represented in Figure 7.5, demonstrating that the availability of each is necessary for production to take place.

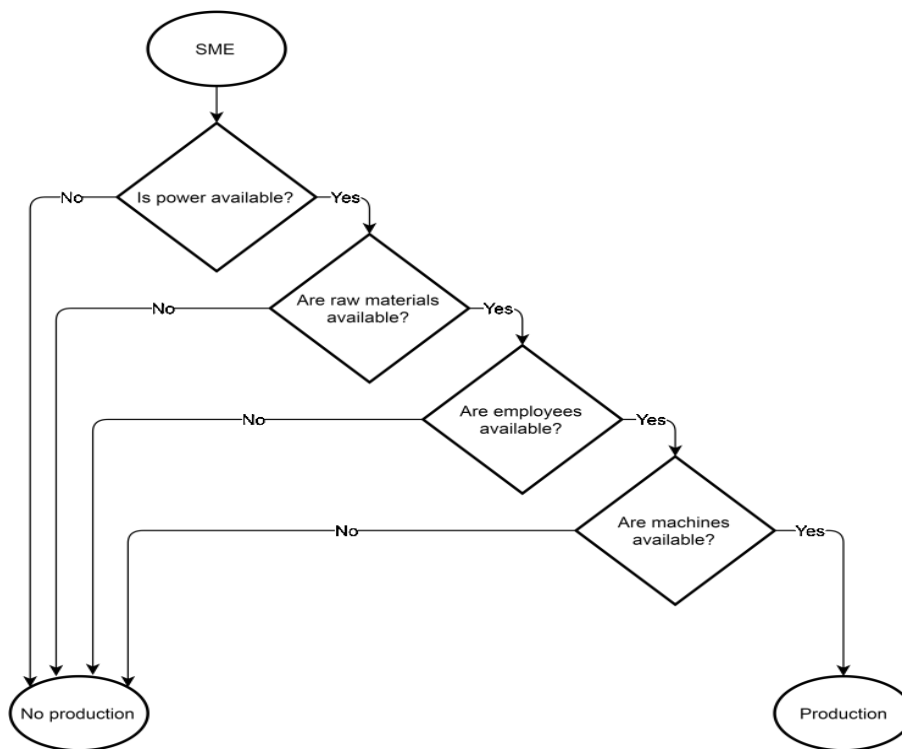


Figure 7.5: Manufacturing SMEs dynamic attributes relationships

These attributes change during the course of a simulation and contribute directly to the SMEs' performance, i.e. production level (PL). Given the flood event is simulated at 30-minute intervals, each of which corresponds to 1 simulation time step or tick (t_s), then the production level is determined at each half-hour interval (or tick) throughout the course of a simulation. Post-flood, a flood-affected manufacturing SME's production level can be resumed if:

- a) the power supply is restored to the premises, i.e. $P = 1$ ($P = 0$ indicates that an SME's premises has no power and thus cannot resume the manufacture of products);
- b) raw materials are available, $RM > 0$, where RM is the sum of raw material units stored on the ground, RM_{og} , and above ground, RM_{ag} ;
- c) machines are available, $M > 0$, where M is the ratio of an SME's available machines, M_a , to the total number of machines M_t ;
- d) production employees are available, $E_a^p > 0$, and $E > 0$ which is the ratio of the number of production employees working on production, E_p^p , to the total number of production employees, E_t^p .

In relation to (d),

$$E_t^p = [0.81 \times E_t] \quad (7.2)$$

where the total number of employees, E_t , is the sum of the total number of production employees, E_t^p , and non-production employees, E_t^{np} . In equation (7.2), the value 0.81 has been used since, according to the Department of Business Innovation and Skills (Werwick, 2010), within a *typical* manufacturing business 48.7% of employees work directly in production and 32.1% work in production-related roles. The remaining 19.2% of employees work in non-production roles such as sales and marketing. Thus, each of the manufacturing SME agents has been assigned 81% of the total employees as being related to production and 19% as being related to non-production.

In terms of the consumption of raw materials during production, if $P = 1$, $RM \geq 1$, $M = 1$ and $E = 1$, then in each 30-minute period a single unit of RM is used and, consequently, production level $PL = 100\%$. That is, in that half-hour period, the premises has power, the raw materials available exceeds or is equal to the unit to be used, all production machines are available ($M_a = M_t$), and all production employees are available and work on production ($E_p^p = E_a^p = E_t^p$). However, still with power to the premises and sufficient raw materials available, if not all machines and/or production employees are available, i.e. $M < 1$ and/or $E < 1$, then only a fraction of a unit of raw materials will be used for production and PL will be less than 100%

during the associated 30-minute period. Note that, while in all SMEs a maximum of a single unit of raw materials can be consumed in a 30-minute period, the size of a unit of raw material varies according to the total number of production employees in that SME. For example, for an SME with $E_t^p = n$, each production employee will use $1/n$ units of raw material in a 30-minute period. Algorithm 7.1 defines how the production level in a 30-minute period, i.e. a simulation tick, is determined.

```

1. if P=1 then
2.   {
3.     if raw materials at time t,  $RM_t \geq \min \{E, M\}$  then
4.       {
5.          $PL = \min \{E, M\} \times 100$ 
6.          $RM_{t+1} = RM_t - \min \{E, M\}$ 
7.       }
8.     else if  $RM_t < \min \{E, M\}$ 
9.       {
10.         $PL = RM_t \times 100$ 
11.         $RM_{t+1} = 0$ 
12.      }
13.   }
14. else if P=0
15.   {
16.      $PL = 0$ 
17.      $RM_{t+1} = RM_t$ 
18.   }

```

Algorithm 7.1: Determining production level (PL) of a manufacturing SME

In Algorithm 7.1, for each simulation tick (i) production level and (ii) raw materials available at the next tick, are determined depending on whether power is available at the SME's premises (lines 1 to 13) or not (lines 14 to 18). For situations in which power is available, and depending on the amount of raw materials available at the current tick, both (i) and (ii) are determined according to the relationship between ratios of production employees working on production to total number of employees, and machines available to total number of machines respectively.

7.1.6 Retail SMEs Performance Measurement

Retail performance measurement is measured by a range of metrics such as store traffic, labour, and sales performance (Perdikaki et al., 2012). Further, Zhu (2017) and Perdikaki et al. (2012) introduced the concept of the *conversion rate* (the ratio of the number of transactions to traffic) as a performance metric to measure businesses' performance. This metric is commonly applied to the e-commerce sector to determine online sales performance. In addition, Line (2011) used both people counting (i.e.

counting the number of people entering and exiting a store location) and conversion rates to increase sales.

Francis et al. (2016) proposed a retail metrics framework follows a logic common to retailers everywhere: “Better environments lead to better experiences for people and that leads to better economics for retailers”. Francis et al.’s proposed framework consists of three main components, namely environment, experience, and economics, in which each of these consists of a list of elements. The environment component considers ten elements (e.g. lighting, indoor air quality, thermal comfort, acoustics, interior layout, look and feel, active/inclusive design, amenities, and community space). The experience component consists of both employees (i.e. perception of the work environment) and customers (i.e. perception of the retail environment). The economics component includes both employees and customers along with the company. Employees are measured in terms of absenteeism, staff retention, medical complaints, medical costs, or physical complaints while customers are measured in terms of sales, footfall, dwell time, loyalty, and/or distance travelled. The company component is measured in terms of the brands it offers.

In this research, service capability (SC) is used to measure retail SME’s immediate response to and short-term recovery from flooding. Service capability (SC) is related to the availability of power (*P*), stock (*ST*), sales equipment (*SE*), employees (*E*), and environment condition (*EC*). This performance metric, i.e. service capability (SC), is grounded on Francis et al. (2016) proposed retail metrics framework, whereas some additional factors (e.g. power, stock, sales equipment) were identified from the semi-structured interview data available. In terms of stock and sales equipment, the data from the semi-structured interviews reported that some companies were unable to operate because of damage to their sales equipment and stock respectively.

In terms of the aforementioned retail SMEs’ dynamic attributes, the relationship between them is presented in Figure 7.6, demonstrating that the availability of each is necessary for service capability, i.e. the capability to offer a service to customers.

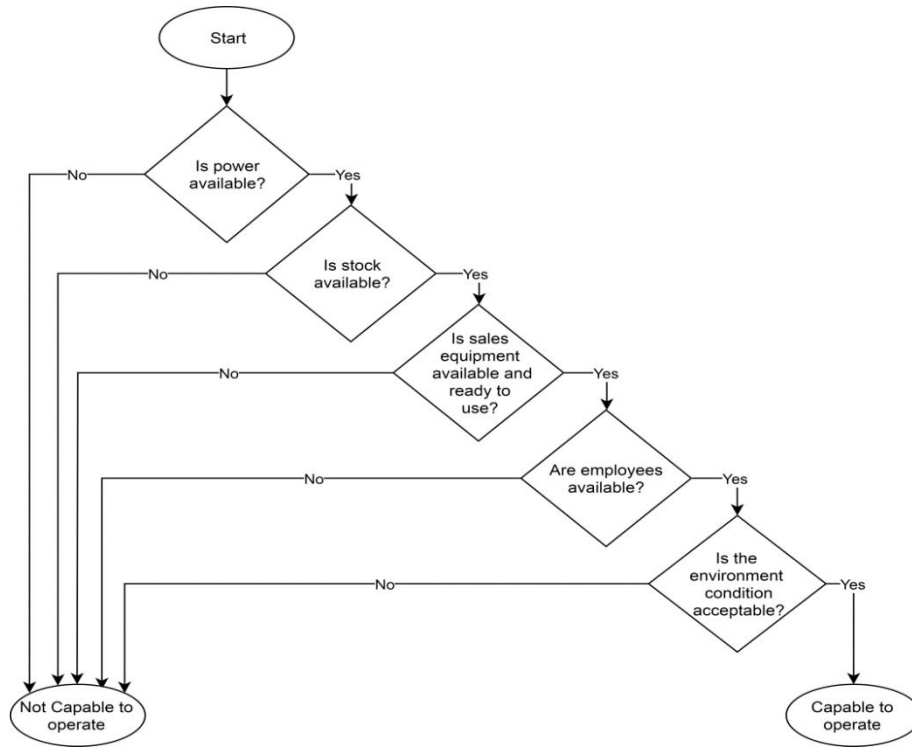


Figure 7.6: Retail SMEs dynamic attributes relationships

Retail SMEs' dynamic attributes may change during the course of a simulation and contribute directly to retail SMEs' performance, which is measured as the service capability (SC). The service capability is determined at each half hour (30-minute) interval (or tick) throughout the simulated period. Post-flood, a flood-affected retail SME's service capability can be resumed if:

- the power supply is restored to the premises, i.e. $P = 1$ ($P = 0$ indicates that a retail SME's premises has no power and thus it is unable to operate);
- stock is available, $ST > 0$, where ST is the percentage of stock available in its premises;
- sales equipment is available, $SE > 0$, where SE is the percentage of a retail SME's available sales equipment to enable transactions to take place;
- employees are available, $E_E > 0$, where E_E is the percentage of an SME's employees available to work; and

- e) environment conditions are acceptable if $EC = 1$ or not if $EC = 0$, where $EC = 0$ indicates that a retail SME's premises needs to be or is being renovated and redecorated after being flooded whereas $EC = 1$ indicates that the work environment conditions are in a state suitable for the retail SME to operate.

In relation to (c), sales equipment is replaced if damaged. Replacing damaged equipment affects the short-term recovery profile, prompting retail SMEs' status to be either in recovery, i.e. $SC = 0$, or fully recovered, i.e. $SC = 100\%$, providing the other retail SMEs' dynamic attributes are greater than zero. Algorithm 7.2 defines how the service capability (SC) in a 30-minute period, i.e. a simulation tick, is determined.

```
1. if  $P=1$  and  $EC=1$  then
2. {
3.    $SC = \min \{ST, SE, E_E\}$ 
4. }
5. else if  $P=0$  or  $EC=0$ 
6. {
7.    $SC=0$ 
8. }
```

Algorithm 7.2: Determining service capability (SC) of a retail SME

In Algorithm 7.2, for each simulation tick, service capability, is determined depending on whether power is available and environment condition is acceptable at an SME's premises ($P = 1$ and $EC = 1$) (lines 1 to 4) or not ($P = 0$ or $EC = 0$) (lines 5 to 8). For the latter, the service capability cannot be resumed (i.e. $SC = 0$). However, for situations in which power is available and working conditions are acceptable, the service capability is determined according to the relationship between (i) percentage of stock, ST , (ii) percentage of sales equipment, SE , (iii) percentage of employees available, E_E respectively.

7.2 MODELLING SME-RELATED ORGANIZATIONS

SME related-organizations, which may include other businesses, can interact with SMEs to provide assistance or a service to maintain SMEs' operation and support their immediate response to and short-term recovery from flood events. These SME related-organizations include electrical, plumbing, IT, and cleaning service providers; Environment Agency; refurbishment companies; suppliers; customers; insurance companies; mutual aid partners.

As shown in Figure 7.7, manufacturing and retail SMEs can interact with electrical, plumbing, and cleaning service providers; the Environment Agency (EA); suppliers; and insurance companies. However, manufacturing SMEs can also interact with customers, IT service providers, and mutual aid partners, whereas retail SMEs can interact with refurbishment companies. Note that, while a cleaning service can be provided to both manufacturing and retail SMEs, refurbishment occurs only in retail SMEs. This refurbishment behaviour refers mainly to renovation and redecoration of retail SMEs' premises. According to the interview transcripts available, four retail SMEs (S_4 , S_5 , S_{45} , S_{50}) had a premises refurbishment (redecoration) before restoring their services, whereas none of the manufacturing SMEs took this step.

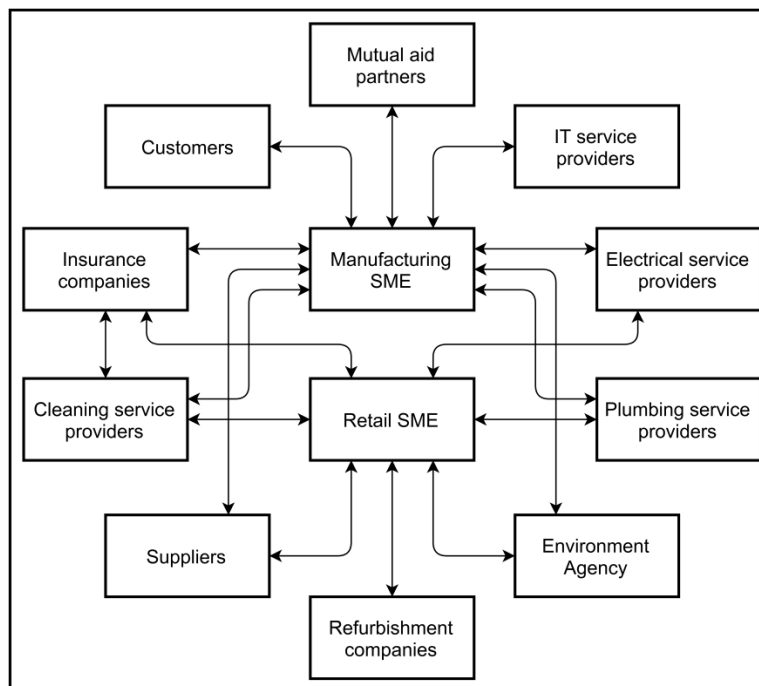


Figure 7.7: Interactions between SMEs and SME-related-organisations

7.2.1 Environment Agency

Preceding a flood event, the government-funded EA will send alerts and warnings to SMEs that have registered for these services. In particular, SMEs that have registered for EA alerts and warnings may enact pre-flood behaviours (e.g. lifting-up raw materials or stock) providing they are received (and the former trusted) during normal working hours. Alerts can arrive 36 hours prior to the expected flood commencing whereas warnings may be received 3 hours prior; SMEs trust EA warnings and so always act on them (Morrissey, 2016; SEPA, 2019).

In terms of modelling, every geographical area modelled in this framework has an associated variable, namely ‘flood-time’. This variable represents the flood-commencement time in the modelled geographical area, which in turn, enables the EA agent to send alerts and warnings to the registered SMEs at the appropriate times (i.e. 3 and 36 hours before the flood commences, respectively).

7.2.2 Suppliers and Customers

Suppliers and customers are businesses or organizations that are modelled to interact with SMEs to preserve SMEs’ operational continuity. However, they are not modelled to the same level of detail as SMEs given the focus of this research is investigating SMEs immediate response to and short-term recovery from flood events. Suppliers provide manufacturing and retail SMEs with raw material or stock respectively. However, customers, who only interact with manufacturing SMEs, take delivery of products from these businesses.

Customers only interact with manufacturing SMEs. This is because manufacturing SMEs commonly have contracts with a certain number of customers, and thus, customers’ information is available for manufacturing SMEs. In contrast, retail SMEs tend to deal with the public and are less likely to have customers’ contact information. Confirming this, the interview transcripts S1 and S56 from manufacturing SME employees report that they have a regular and known number of customers.

As indicated in Figure 7.8, SMEs interact with suppliers and/or customers via messages. In preparing for a particular flood event, SMEs’ behaviours include contacting their suppliers and customers in order to suspend manufacturing raw material or retail stock delivery, and product dispatch. However, if SMEs are not able to complete these behaviours before employees evacuate the premises, then their suppliers and customers are contacted at the beginning of the post-flood stage to inform them of the situation. Subsequently, once an SME is in a position to recommence production for manufacturing or a service for retails, (a) its supplier is contacted to resume raw material or stock delivery, which happens within 48 hours as indicated in S₁₃, and (b) customers are informed of the resumption of product dispatch, which occurs within 24 hours as in S₃₀.

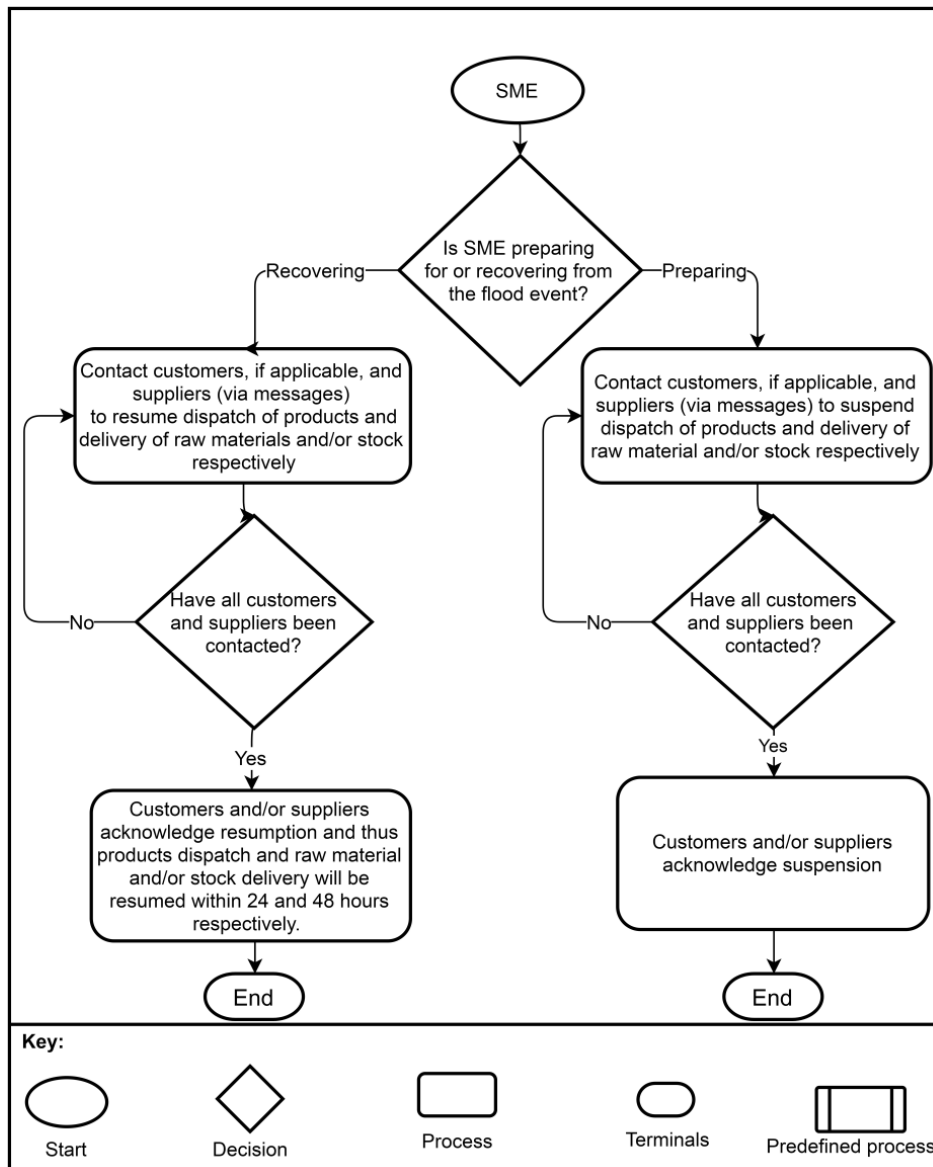


Figure 7.8: An overview of the interaction between suppliers and/or customers and SMEs

7.2.3 Insurance Companies

Insured SMEs with comprehensive cover will receive, via its insurance company, assistance from a cleaning service provider in addition to receiving financial compensation (Environment Agency, 2019d; Nidirect Government Services, 2019) and (S₆). In contrast, SMEs with basic insurance cover will only receive the latter. According to interviews undertaken with SMEs having experienced flooding, some of these businesses chose to contact their insurer (S₃₀ and S₃₈) whereas others did not (S₂₁ and S₄₇). The reason for not doing so was to avoid a potential increase in their future

insurance premium. However, in such cases, these SMEs needed and had sufficient funds to be in place to ensure business continuity

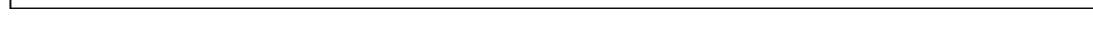
If the insurance company is contacted by an SME, a loss adjuster will be sent within seven days to assess the damage and produce a report (Association of British Insurers, 2016) followed by payment being released within five working days of the visit (Allianz, 2018). During this potential 12-day period, SMEs may choose to allocate their own employees to work on post-flood behaviours, such as clean up the premises rather than waiting for the cleaning service provided by the insurance to arrive. According to interviewee S₄, employees were allocated to clean up while waiting for their insurer's response.

S₄: "... Yeah. The staff, they came in every day just to help out for a few hours cleaning. Just getting rid of all the stuff while we waited for a response from the insurance ... we were just trying to do some cleaning and we started doing some of the decoration ourselves, cleaning out, waiting to get some money off the insurance and also ordering the equipment. That takes quite a bit of time ..."

Alternatively, if sufficient funds are available, SMEs may themselves choose to contact cleaning service providers as in S₃₃:

S₃₃: "... I had to bring about five extra staff in and a cleaning company just to get it clean ..."

Figure 7.9 provides an overview of the aforementioned scenarios followed by an SME and insurance company. It shows that SMEs with access to funds can contact service providers (electricians, plumbers, IT specialists, and cleaning service providers) immediately. However, those without access to such funds have to contact their insurer, if insured, or they may go out of business. For the insured SMEs, they have the choice either to wait for the offered cleaning service, if insured sufficiently, or they may allocate their employees to clean up their premises.



7.2.4 Cleaning Service Providers

Cleaning service providers are businesses that interact with both SMEs and insurance companies. For the latter, cleaning service providers could have a pre-defined contract with insurance companies to provide such a service to insured SMEs if required. Recall, SMEs with comprehensive insurance receive assistance in the form of a cleaning service in addition to financial compensation. Thus, a cleaning service could be interrupted while working for a non-contracted SME at any time when it is contacted by an insurance company with which it has a pre-defined contract. The affected non-contracted SME would then need to contact another service provider; otherwise, its employees may need to be allocated to clean-up.

If an insurance company requests a cleaning service for an insured SME, the requested team will arrive at the SME's premises between 2 and 24 hours. According to a specialised flood cleaning service provider, the cleaning service can be provided in just two hours from the time of the request (Ideal Response, 2019). However, due to the potential increase in cleaning service requests in the aftermath of a flood, cleaning service providers are simulated to arrive between 2 and 24 hours.

Cleaning-service providers can interact with SMEs to provide them with clean-up assistance. As indicated in Figure 7.10, SMEs will contact regional cleaning-service providers before contacting national cleaning-service providers. The latter are only contacted if an SME is unable to secure the services of a regional provider. In terms of arrival times, regional organizations arrive at the SME's premises between 2 and 24 hours whereas the national organizations arrive later (e.g. 24-48 hours) than regional service providers although they are more numerous.

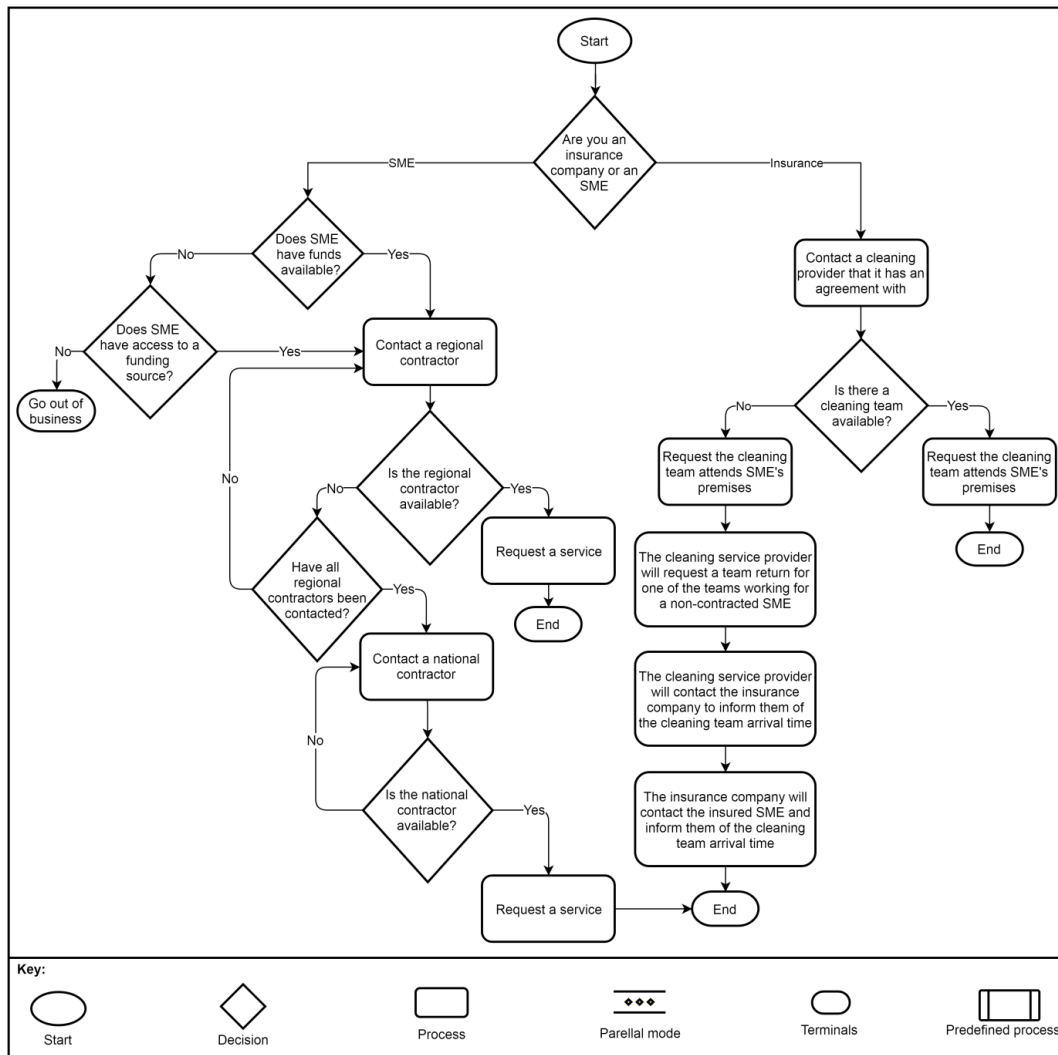


Figure 7.10: An Overview of the interaction between cleaning service providers and SMEs

In terms of the two geographical areas considered in this research (the Lower Don Valley of Sheffield, and Tewkesbury), a total of 250 and 154 commercial cleaning service providers exist in Sheffield and Tewkesbury in the UK, respectively (Yell, 2019).

7.2.5 Service Provider Organizations

Service provider organizations include electrical, plumbing, IT, and refurbishment service providers. These service provider organisations are not the same as the cleaning service providers (defined previously in Section 7.2.4). Cleaning service providers are modelled to interact with both SMEs and insurance companies whereas these service provider organisations are modelled to *only* interact with SMEs.

In terms of the interaction, the service provider organisations interact with SMEs via messages to attend at an SME's premises after a flood event. This is to assist with SMEs' to return to the normal operation (pre-flood).

Service provider organisations are modelled as either regional or national organisations as mentioned in relation to the cleaning service providers in Section 7.2.4. According to the UK Business Directory, more than 250 electrical, plumbing, IT, and refurbishment service providers exist in Sheffield (Yell, 2019). Tewkesbury has more than 250 electrical and plumbing service providers, but only 60 and 68 IT and refurbishment service providers, respectively. On request, regional service provider organizations arrive quickly (e.g. 1 – 24 hours) at an SME's premises, but are limited in terms of numbers. According to electrical and plumbing services providers, the emergency response service is available 24-hours a day and guaranteed to arrive within an hour of a request (Electric Call, 2019; Heating, 2019). However, due to the potential increase in demand for such services in the aftermath of a flood, regional organizations may not be able to arrive immediately. Therefore, SMEs will contact national organizations, which are modelled to arrive later (e.g. 24 – 48 hours) than the regional service providers but are greater in number.

As Figure 7.11 shows, SMEs must have funds available to request such services. Confirming this, interview transcript S₆₁ indicates that the recovery process is expensive and some difficulties were encountered due to insufficient funds. Funds can be derived from three defined sources: (i) insurance compensation, (ii) emergency financial reserves, or (iii) access to cash. Insurance compensation represents the most common source of funds, but an SME may have to wait for up to a potential 12 days as discussed in Section 7.2.3. In terms of emergency financial reserves and access to cash, SMEs can proceed with the short-term recovery process immediately on receipt of these.

In relation to Figure 7.11, SMEs must have funds available or access to cash, or they will go out of business. With sufficient funds available, SMEs will contact the regional service providers. However, if they are unable to secure the services of a regional provider, they will contact the national service provider organisations.

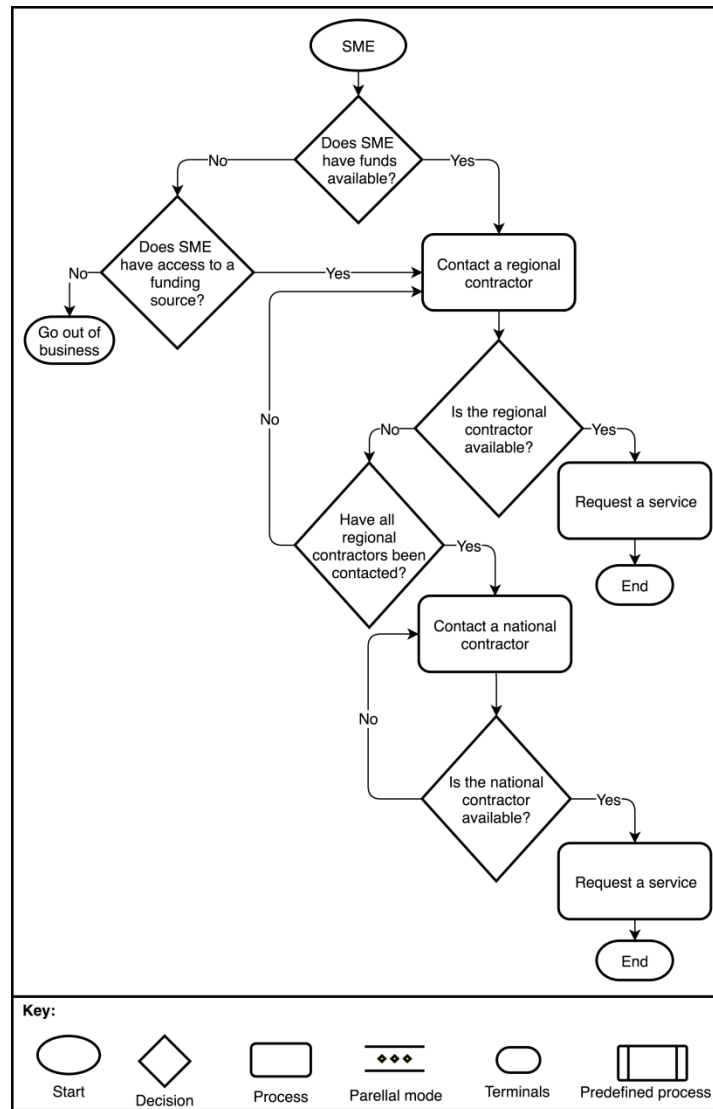


Figure 7.11: An overview of the interaction between service providers organisations and SMEs

7.2.6 Mutual Aid Partners

A mutual aid partner is a manufacturing SME that has established a contract with another manufacturing SME that is experiencing flooding and/or is located in a flood-prone area. According to the International Organization for Standardization (ISO, 2018), mutual aid is defined as a “pre-arranged understanding between two or more entities to render assistance to each other”.

According to Stier and Goodman (2007), mutual aid is defined as the sharing of suppliers, equipment, personal information, or other resources between two parties. Also, it is indicated that mutual aid is useful when local resources are insufficient to

meet a business' needs due to the disaster that has occurred (Sutton & Tierney, 2006). Furthermore, businesses are encouraged to improve their disaster response through contracts and mutual aid agreements. However, mutual aid agreements can be limited in scope, in which it is impossible to anticipate every eventuality (British Columbia, 2014).

In this research, a mutual aid contract must include a number of key conditions. Firstly, a manufacturing SME must have at least two production employees, $E_p^p \geq 2$, in order to establish a mutual aid contract. That is, during flood recovery, the flooded SME could have at least one production employee working on its premises to restore its production level while the second employee is working at the mutual aid partner's location. Furthermore, the non-affected manufacturing SME must reply instantly within the same day when the request is received from the flood-affected manufacturing SME (IPIECA, 2014). Subsequently, the non-affected mutual aid partner must allocate a proportion of its production machines to the affected SME (NENE, 2015). In this research, the allocated proportion of machines is implemented to be (1-10%). In terms of the number of production employees sent to a partner's location, this is determined as follows:

$$E_{partner}^p = \left\lfloor \frac{100}{E_t^p} / M_{partner} \right\rfloor \quad (7.3)$$

where the total number of employees that should be sent to a partner's location, $E_{partner}^p$, is determined as, $\frac{100}{E_t^p}$, to the percentage of production machines allocated to the affected SME at the partner's location, $M_{partner}$. Next, production employees start working at a mutual aid partner's location on the first day after the request is made until the time those production employees can resume work on production at their own premises. In terms of raw materials, partners must provide a sufficient amount of raw materials to the allocated machines. However, the affected SME must pay for the supplied raw materials (British Columbia, 2014).

7.2.7 SME-Related Organisations Attributes

Attributes are modelled to define the identity of the modelled SME-related organisations' agents (e.g. manufacturing and retail SMEs; suppliers; customers;

electrical, plumbing, cleaning, and IT service providers; mutual aid partners; and the Environment Agency). Similar to the SME attributes, as indicated in Table 7.5, SME-related organisations' attributes are categorised as (i) generic and specific types, and (ii) static or dynamic.

Type	Variable name	Brief description
Generic Attributes		
Static	Id	Unique identifier for every agent modelled.
	Name	The name could be an electrician, plumber, or an IT specialist, cleaning-service provider, supplier, customer, or refurbishment company.
	Northing	Geographic coordinates for every individual agent.
	Easting	
Specific Attributes for Cleaning Service Providers		
Static	Status	Could be available or busy.
	Region	Could be regional or national.
Static	Number of teams	Number of teams making up the cleaning service provider.
	Number of staff in each team	Number of staff in each team within this cleaning service provider; this number could vary between a company and another.
Dynamic	Teams' status	Statuses for every team within the cleaning-service provider signifying the current status: available or busy
Specific Attributes for Environment Agency		
Static	Flood times	Potential flood times for every geographical area. This is derived from the inundation data available for all SMEs located in the modelled geographical area.
	Inundation data	Water depth(s) associated with every SME modelled in this model.

Table 7.5: SME-Related organisations attributes

7.3 MODEL VALIDATION

Model validation is aimed at ensuring that a model is in an appropriate representation of reality (Banks et al., 2001; Gon et al., 2000; Heath et al., 2009; Law et al., 2000; Sargent, 2010). However, it has long been recognised that models do not exactly represent reality (Ashby & Stogdill, 1970; Stanislaw, 1986).

Validation is defined as the process of determining the level of similarity between a model and a real system (Goodall, 1972; Law, 2008). In relation to this, previous studies (Bianchi et al., 2007; Klügl, 2008; Niazi et al., 2017; Richiardi et al., 2006) have reported that validating ABMs is problematic. Klügl (2008) highlighted that validating agent-based simulation models is difficult due to their (i) multi-level nature with an absence of links between system levels, (ii) nonlinearities and multiple assumptions which maximize complexity, and (iii) a dearth of appropriate data.

Richiardi et al. (2006) indicate that ABMs lack of a clear communication standard upon which agents can interact, in which every designed model has its own agent-communication structure. Also, no standards exist to treat the simulated data (i.e. resulting from a simulation) to provide a description of the dynamics of a given system. Moreover, the details of ABM implementation are most likely to be misunderstood. Niazi et al. (2017) subscribe to the belief that ABMs cannot be validated in the ways other models can. That is, due to (i) the complexity of entity interaction, (ii) strong dynamics, and (iii) frequent emergence patterns in the model. However, it is also indicated that it is important to validate ABMS since the results could be influenced by any change(s) which may occur in the variables.

In relation to ABMS protocols, there is no clear agreement on a standardized protocol for developing ABMs (Cosgrove et al., 2015). Similarly, Xiang et al. (2005) confirm that no such universal validation process exists for ABMs. However, many model-validation and verification-presentation techniques exist, and therefore, it is difficult to use them all: for example, Relative Operating Characteristics (ROC) (Kocabas & Dragicevic, 2009), multi-scale land use (Kok et al., 2001), the map comparison technique (Boots & Csillag, 2006), landscape metric-based comparisons (Lei et al., 2005), and quantitative goodness-of-fit (GOF) (Hargrove et al., 2006).

According to Xiang et al. (2005), model designers have the choice to select the most appropriate techniques to validate their model. In this research, a “three-block” standard protocol for describing ABMs is used, namely the ODD (the Overview, Design concepts, and Details) protocol. This protocol was proposed by (Grimm et al., 2006; Grimm et al., 2010) to make model descriptions more understandable and less subject to criticism. Also, it aims to provide an overview of a model’s purpose, structure, process, and additional low-level details. In the same way, it defines and describes ABMs’ processes, mainly for academic publications and literature. This is to allow the reader to understand the model’s structure and details following the academic-paper style (e.g. abstract, introduction, and body). The ODD protocol was initially released in 2006, followed by an updated version in 2010 as shown in Table 7.6. According to (Grimm et al., 2010), the ODD protocol was used in 54 publications (consisting of 87 citations) by the end of 2009. However, in 2018 it has been cited more than 1980 times, and this increased volume of citations may reflect the protocol’s high applicability.

	Elements of the original ODD protocol (Grimm et al., 2006)	Elements of the updated ODD protocol
Overview	1. Purpose 2. State variables and scales 3. Process overview and scheduling	1. Purpose 2. Entities, State variables, and scales 3. Process overview and scheduling
	4. Design concepts • Emergence • Adaption • Fitness	4. Design concepts • Basic principles • Emergence • Adaption • Objectives • Learning • Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation
Design Concepts	• Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation	
Details	5. Initialization	5. Initialization
	6. Input	6. Input
	7. Submodels	7. Submodels

Table 7.6: Old and updated ODD protocol elements (Grimm et al., 2010)

As mentioned, the ODD protocol aims to present model descriptions including the model's purpose, structure, and processes in a more understandable format. It also makes writing and reading model descriptions more straightforward and efficient.

In relation to the present ABMS framework's purpose (see Section C.1, Appendix C), the developed ABMS framework aims to investigate the effect of manufacturing and retail SMEs' behaviours and flood precautionary measures that can be implemented to maintain business continuity and speed-up short-term recovery from flooding. Furthermore, the ODD protocol presents all the state variables used to develop the present ABMS framework. These include state variables related to manufacturing and retail SMEs as well as SME-related organisations (cleaning service providers, customers, suppliers, electricians, plumbers, IT specialists, refurbishment companies, the Environment Agency, insurance companies, and mutual aid partners). Following this, the ODD protocol presents an overview of the processes and scheduling that has been undertaken (see Section C.3, Appendix C). In this section, the ODD protocol outlines the time when the SMEs' and SME-related organisations' state variables are updated, as well as an overview of the implemented processes. At

each time step (i.e. a 30-minute period), SME and SME-related organisation agents execute a set of different actions based on SMEs' status (before flooding, flooding, after flooding). Please note that the implemented actions are highlighted in bold font.

In relation to the Environment Agency (EA), this agent **sends** alerts and warnings to the registered SMEs at intervals before the onset of a flood event. For manufacturing and retail SMEs, the **record information** action will be initially executed to update the simulation's current information, such as lists of days, clock times, and simulation ticks. Furthermore, the **check inbox** action will be executed to check if a flood alert or warning has been received from the EA or if any new messages have been received from other agents (i.e. suppliers and/or customers). If no alert or warning has been received, manufacturing SMEs will execute the **production** action whereas retail SMEs will execute the **service** action. However, if an alert or warning has been received, both manufacturing and retail SMEs will execute the **emergency** action. The **production** and **service** actions include a range of actions, such as the employee **allocation strategy** and **duration**. For SME-related organisations, each organisation/business executes a different range of actions. For example, suppliers and customers execute the **check inbox**, **dispatch**, **suspension**, and **resumption** actions whereas insurance companies execute the **pay compensation** and **contact cleaning service provider** actions. For more details, please see Section C.3 of Appendix C.

In relation to the design concept (see Section C.4, Appendix C), eleven elements are presented to describe the ABMS framework's design. These elements include basic principles, emergence, adaption, objectives, learning, prediction, sensing, interactions, stochasticity, collectives, and observation. The developed framework is described in terms of each of these elements to provide a more detailed description of its design.

For the initialization element (see Section C.5, Appendix C), the developed framework consists of several agents that represent different types of organisation; all agents are created at the beginning of the simulation at the point when agent variables are also assigned. Most variables are set uniformly for each manufacturing or retail SME agent; however, some are randomly assigned within a specified range, such as number of employees and behaviour durations.

In terms of the input element (see Section C.6, Appendix C), the framework uses input data from the Ordnance Survey MasterMap© (*Topography layer, AddressBased Plus layer and Integrated Transport Network layer*) as external sources. In addition, the developed framework uses inundation data provided by flood modelling and simulation.

In relation to the sub-models (see Section C.7, Appendix C), a more detailed overview of the implemented actions within the agents modelled is presented. In addition, a set of algorithms featured to provide further detail on the manufacturing and retail SME agents' design and implementation.

By providing this detailed overview of the ODD protocol (which is presented in Appendix C and summarised in this section), it is hoped that readers will be able to better understand the developed ABMS framework's purpose and design structure. Additionally, these details will enable other researchers to develop similar models.

7.4 SUMMARY

Manufacturing and retail SMEs are modelled as autonomous agents with a set of static and dynamic attributes, behaviours, and pre-defined precautionary measures. SMEs' behaviours can be carried out pre- and post-flood whereas SMEs' precautionary measures are implemented by SMEs prior to a flood event taking place to prevent or reduce the amount of floodwater entering a premises; or to remove the need for, or reduce the duration of, some pre- and post-flood behaviours. The behaviours and precautionary measures along with their associated information were collected from various sources (i) transcripts of semi-structured interviews with SMEs having experience of flooding or being at risk of flooding, and (ii) EA guidance, and (iii) academic literature. Additionally, SMEs are modelled with a set of static and dynamic attributes, in which the latter contribute directly to SMEs' performance, i.e. production level (*PL*) and service capability (*SC*) for manufacturing and retail SMEs, respectively. SME-related organisations were also modelled as agents to ensure SME's operation and short-term recovery from flood events, in which SME-related organisations provide assistance, such as raw materials or stock delivery; or a service, such as electrical repairs. In terms of the interaction strategy, SMEs interact with these organisations via messages.

Chapter 8

Case Studies and Simulation Experiments

This chapter presents the case studies considered in this research and sets out a number of simulation experiments for manufacturing and retail SMEs. Each experiment is distinct in that they each employ different combinations of precautionary measures to investigate how SMEs' behaviours and precautionary measures, and combinations of them, impact pre-flood immediate response and post-flood short-term recovery.

Section 8.1 outlines the two UK case studies considered, namely the Lower Don Valley region of Sheffield, and Tewkesbury. Following this, Section 8.2 presents the methods of SMEs' analysis (operational disruption and statistical analysis) used in this research to determine which combination of precautionary measures most influence the immediate response and short-term recovery of manufacturing and retail SMEs. Next, Section 8.3 presents the specific questions related to the precautionary measures which the simulation experiments aim to investigate. Finally, Section 8.4 summarises and concludes the chapter.

8.1 CASE STUDIES

The two case studies considered in this research are related to the 2007 UK flood events in (a) the Lower Don Valley of Sheffield and (b) Tewkesbury. The former was selected due to its high concentration of SMEs, some of which have experienced flooding and/or are prone to flooding. The latter was selected due to the historic high water levels during flooding that has significantly impacted homes and businesses (Pitt, 2008; Tewkesbury Borough Council, 2019).

The map of the UK shown in Figure 8.1 indicates the location of Sheffield and Tewkesbury. Sheffield is the UK's fifth most populated city and has a high concentration of SMEs from a wide range of sectors especially manufacturing (Winkler, 2017). Figure 8.1 (a) presents the MGE representation of the Lower Don Valley of Sheffield used to identify flood-affected and non-flood-affected SMEs. Figure 8.1 (b) provides the MGE representation of the Tewkesbury area used to identify flood-affected and non-flood-affected SMEs. In relation to Tewkesbury, it has around 3,900 businesses; the manufacturing sector accounts for the largest proportion of total employment at 23% (Gloucestershire County Council, 2015).

The MGE of the two case studies (the Lower Don Valley of Sheffield and Tewkesbury shown in Figure 8.1 (a) and (b) respectively) was constructed using Ordnance Survey (OS) MasterMap© data from the *Topography*, *ITN*, and *AddressBase Plus* layers. Sheffield's geographical area was defined using the eastings and northings 434720.0 and 386937.5 (lower left) and 440210.0, 390837.5 (upper right), whereas Tewkesbury's geographical area was defined using the eastings and northings 387923, 232011 (lower left) and 391603,234011 (upper right).

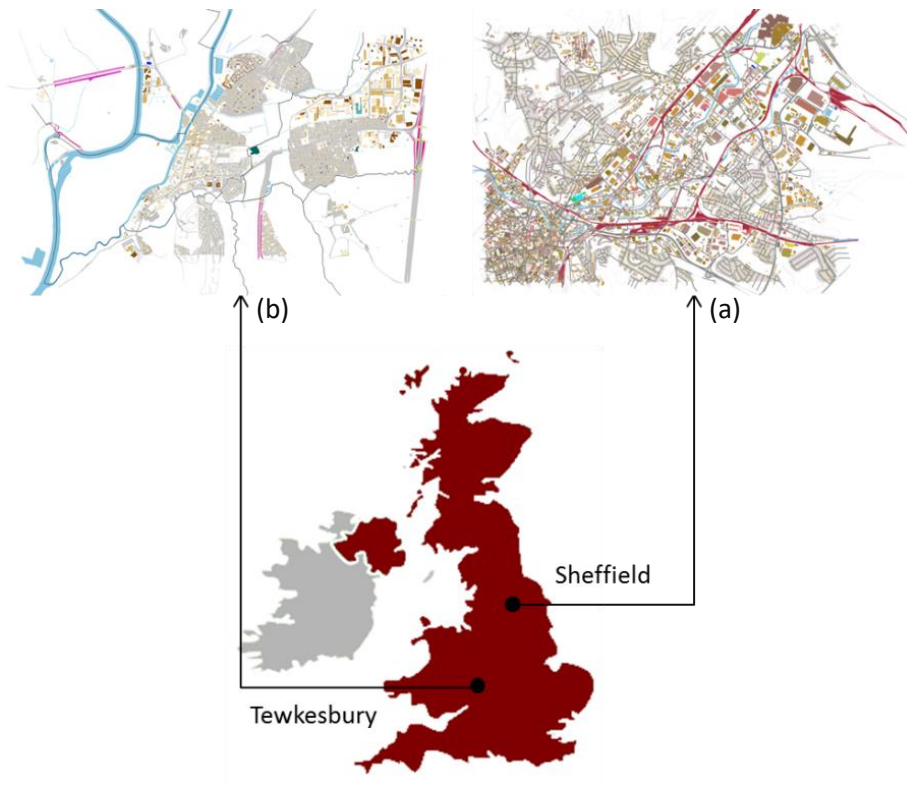


Figure 8.1: (a) modelled geographical environment of the Lower Don Valley of Sheffield and (b) modelled geographical environment of Tewkesbury.

8.1.1 Lower Don Valley, Sheffield

Coupling inundation data of the 2007 summer flood event with the MGE's three OS MasterMap® layers forms a visual representation of a series of floodwater footprints of Sheffield's Lower Don Valley as shown in Figure 8.2. Recall, inundation data of the 2007 summer flood event (i.e. the depth of floodwater at locations in the geographical area modelled) varies dynamically. In Figure 8.2, inundation data are coupled with the OS MasterMap® layers at a series of time intervals. This is, at the time the flood commenced ($t = 0$ hours), and then at 5, 14, and 23 hours after the flood commenced. Note that these time intervals ($t = 0$, $t = 5$, $t = 14$, and $t = 23$) have been selected to highlight different flood stages in the Lower Don Valley of Sheffield.

Figure 8.2 uses three colours to represent SMEs' premises, signifying the level of flooding experienced at any time during the flood event (i.e. in the condition that no precautionary measures were implemented). For example, severely flooded SMEs' premises shown in 'red' experienced a flood level greater than or equal to 0.9m. Similarly, moderately flooded SMEs' premises shown in 'amber' experienced flood levels less than or equal to 0.9m but greater than or equal to 0.3m; for lightly flooded SMEs' premises in 'green', flood levels reached no more than 0.3m.

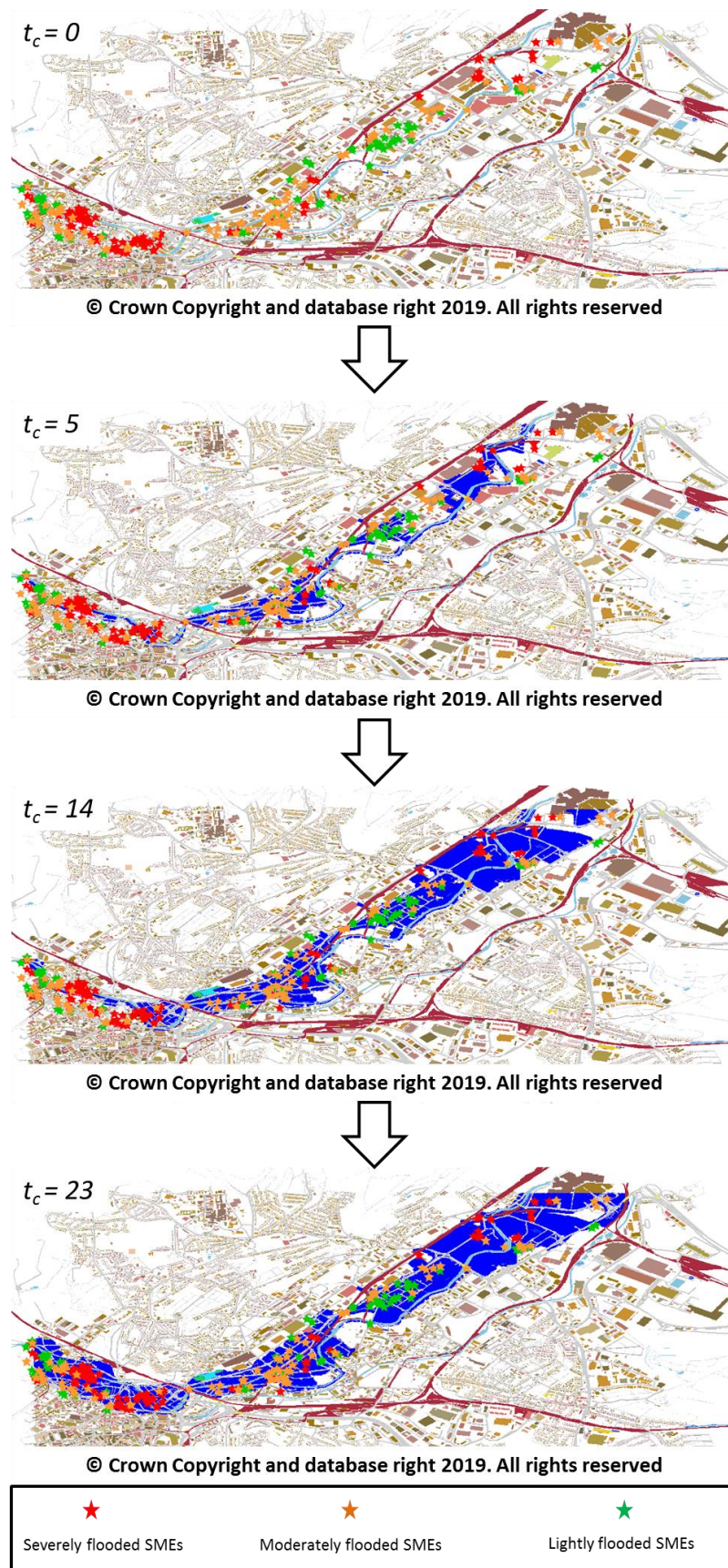


Figure 8.2: Flood footprints based on inundation data, Lower Don Valley of Sheffield geographical area

In the Lower Don Valley of Sheffield, based on the *AddressBase Plus* layer used to construct the MGE coupled with the inundation data, a total of 6224 organizations were identified where 906 had been flooded at some point during the 45.5-hour flood event modelled (i.e. the duration of the actual 2007 flood event). Table 8.1 presents a breakdown of these organizations according to the International Standard Industrial Classification of all Economic Activities (ISIC) (United Nations, 2008). Recall, the ISIC is a more recognisable sector categorisation.

ISIC	Organisations		
	Flooded	Not flooded	Total
Administrative services	116	802	918
Accommodation services	41	406	447
Agriculture/forestry/fishing	2	1	3
Arts and entertainment	13	75	88
Education	2	76	78
Electricity/gas/steam	0	7	7
Finance	3	68	71
Households as employers	1	36	37
Human health / social work	1	127	128
Information/communication	2	17	19
Manufacturing	256	1207	1463
Mining and quarrying	0	10	10
Other service activities	4	25	29
Professional services	47	234	281
Public administration	7	78	85
Real estate activities	56	769	825
Retail	13	253	266
Transportation and storage	337	1071	1408
Water	5	56	61
Total	906	5318	6224

Table 8.1: A breakdown of SMEs in the Lower Don Valley of Sheffield modelled geographical environment area

This simulation focuses on modelling manufacturing and retail SMEs as agents based on their size (i.e. micro, small or medium), which, as referred to in Chapter 7, is associated with their total number of employees. According to the statistical data on UK businesses, 99.9% of all UK businesses are SMEs: micro SMEs 96%, small SMEs 3.3%, and medium-sized SMEs 0.6% (White, 2016). Thus, as indicated in Table 8.1, the 1463 manufacturing (including the non-flooded manufacturing SMEs to be modelled as mutual aid partners) and the 13 retail SMEs (only those affected by flooding) have been modelled in these proportions. This was before they being randomly allocated a particular number of employees corresponding to their respective sizes, as indicated in Figure 8.3. For example, 246 of the 256 flood-affected

manufacturing SMEs (i.e. 96%) are modelled as micro-businesses with between 1 and 9 employees (inclusive).

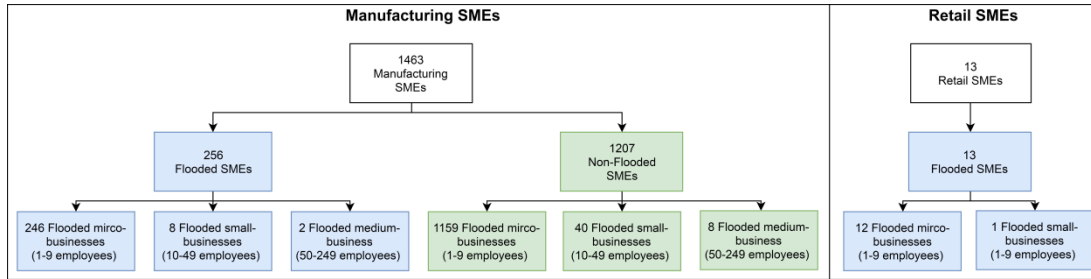


Figure 8.3: Manufacturing and retail SMEs modelled as agents in Lower Don Valley of Sheffield modelled geographical environment area

As indicated in Figure 8.4, the duration of a typical simulation period, which includes 45.5 hours flood simulation event, is 37 days. This duration was selected as it captures the time frame from the beginning of the flood event through to the point where all the manufacturing and retail SMEs were able to resume full production and service capability, respectively. The 37-day period has been divided into three main stages: *pre-flood*, *flood (non-operation)*, and *post-flood*. In a typical simulation, as indicated in Figure 8.4, the *pre-flood stage* starts at $t_c=8:00$ on day 1 until the flood event occurs at $t_c=13:00$ on day 3. The flood commencement time in the Sheffield area was determined according to the interview transcript data available. However, the time at which the floodwater reaches a particular SME's premises will vary slightly depending on the actual geographical location of the property in the flood-affected area. The *flood (non-operation) stage* begins at $t_c=13:00$ on day 3 until the floodwater recedes at $t_c=10:30$ on day 5 given the event modelled has a duration of 45.5 hours. Again, the time at which the floodwater recedes from a particular SME's premises will vary depending on its exact location. Finally, the *post-flood stage* begins from the time the water recedes from an SME's premises until $t_c=18:00$ on day 37.

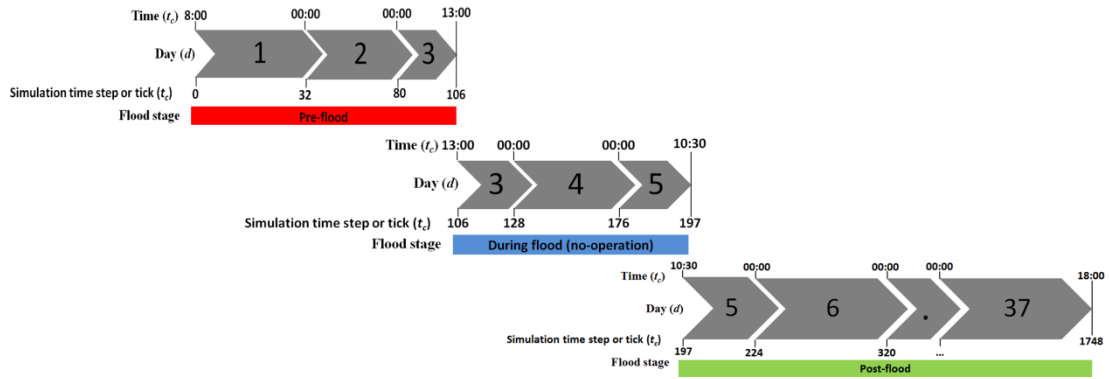


Figure 8.4: Typical simulation duration

8.1.2 Tewkesbury

The second case study presented in this research is based on the severe flood event in 2007 in Tewkesbury, UK. According to Tewkesbury Borough Council, more than 1800 houses and 300 businesses were flooded (Tewkesbury Borough Council, 2018). The flood event simulation generated inundation data representing water depths throughout the selected area modelled at 30-minute intervals over 13 days and 6.5 hours (i.e. the 318.5-hour period of the duration of the actual 2007 flood event). The duration of a typical simulation period, which includes 318.5-hour flood simulation event, is 45 days. This duration was selected as it captures the time frame from the beginning of the flood event through to the point where all the manufacturing and retail SMEs were able to resume full production and service capability. The flood commences at $t_c=17:30$ on day 1. This was determined according to the interview transcript data available.

Figure 8.5 shows the inundation data, coupled with the OS MasterMap® layer data, at a series of time intervals. That is, at the time the flood commenced ($t = 0$ hours), then at 5, 47, and 100 hours after the flood commenced. Again, these time intervals ($t = 0$, $t = 5$, $t = 47$, and $t = 100$) have been selected for illustrative purposes to signify different flood stages over the Tewkesbury geographical area. As indicated in Figure 8.5, SMEs were modelled in three different colours: ‘red’, ‘amber’ and ‘green’ each one denoting the level of floodwater reached in the respective premises (i.e. severely, moderately, or lightly flooded SMEs).

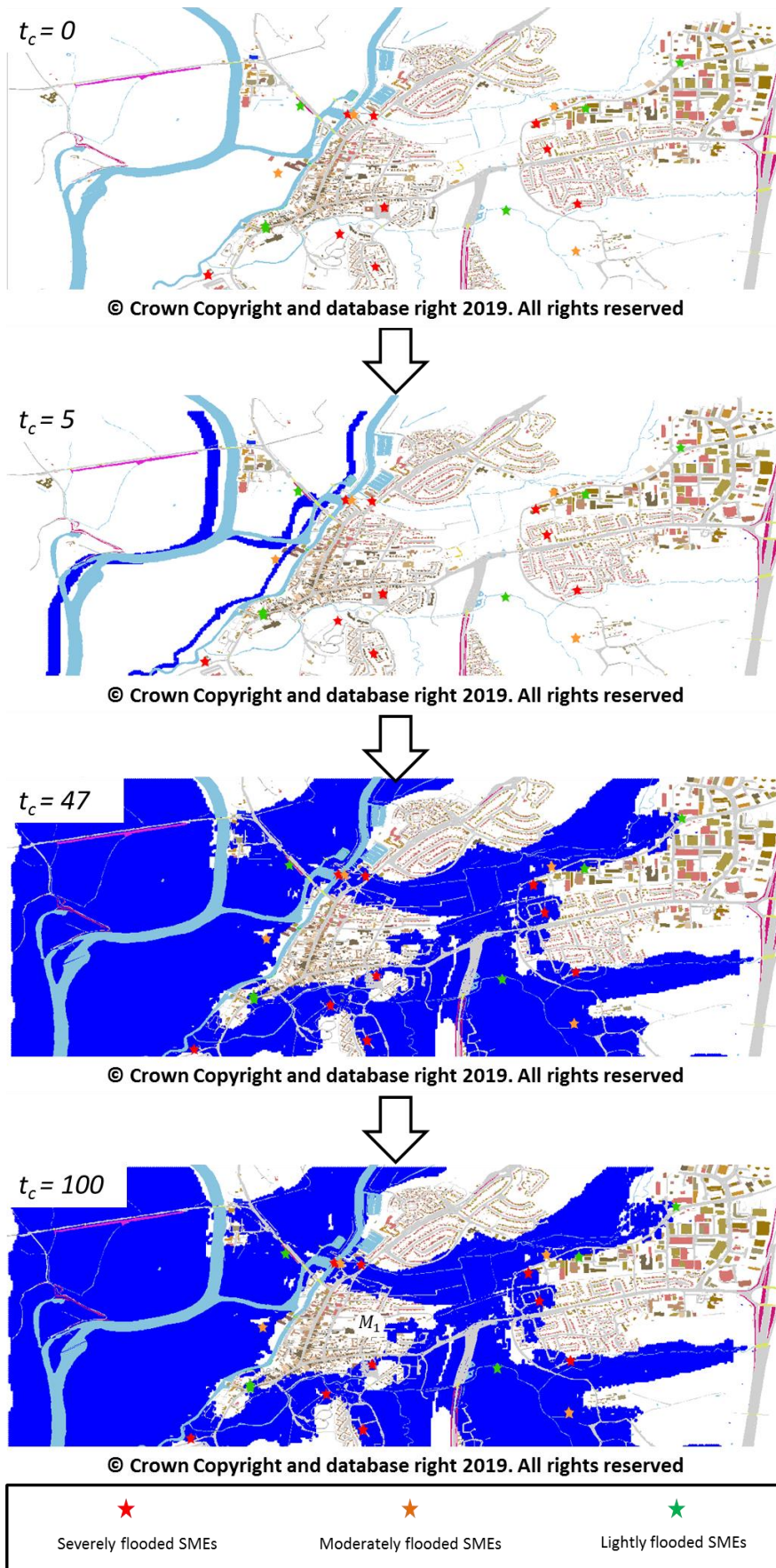


Figure 8.5: Flood footprints based on inundation data, Tewkesbury geographical area

After coupling the OS MasterMap® data, including the *AddressBase Plus* layer and the inundation data, a total of 920 organisations were identified in the area modelled of which 207 were flooded at some point during the 318.5 hours simulated. The disparity between the EA’s indication (300 businesses were flooded) and the 207 businesses identified as flooded in this research may be accounted for by the ten year difference between the actual flood event in 2007 and the OS’s *AddressBase Plus* layer dataset from 2017. Table 8.2 presents a breakdown of these organisations according to the International Standard Industrial Classification of all Economic Activities (ISIC) (United Nations, 2008).

ISIC	Organisations		
	Flooded	Not flooded	Total
Administrative services	10	39	49
Accommodation services	8	30	38
Agriculture/forestry/fishing	1	2	3
Arts and entertainment	5	11	16
Education	0	5	5
Electricity/gas/steam	1	2	3
Finance	0	6	6
Construction	1	3	4
Human health / social work	7	100	107
Information/communication	0	8	8
Manufacturing	16	107	123
Mining and quarrying	0	3	3
Other service activities	4	29	33
Professional services	0	3	3
Public administration	8	16	24
Retail	4	222	226
Transportation and storage	92	118	210
Water	50	9	59
Total	207	713	920

Table 8.2: A Breakdown of SMEs in Tewkesbury geographical area

As indicated in Table 8.2, a total of 123 manufacturing SMEs were identified of which 16 manufacturing SMEs had been flooded at some point during the 318.5-hour flood event modelled. Similarly, a total of 226 retail SMEs were identified of which 4 were identified as flooded. As in the Sheffield case study, 96%, 3.3%, and 0.6% of the manufacturing and retail SMEs identified are modelled as micro-, small- and medium-sized SMEs, respectively (see Figure 8.6). To recap, micro-sized businesses have 1 to 9 employees, small businesses have 10 to 49, and medium-sized businesses have 50 to 249 (White, 2016).

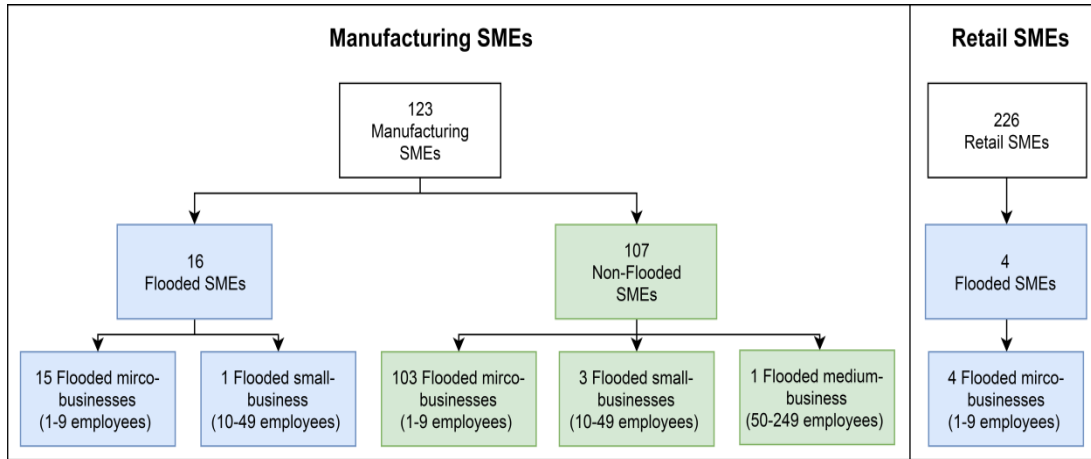


Figure 8.6: Manufacturing and retail SMEs modelled as agents in Tewkesbury’s geographical area.

8.2 METHOD OF SMES’ ANALYSIS

Two methods of analysis are used to investigate the SME’s immediate response to and short-term recovery from flooding, namely operational disruption analysis and statistical analysis. The operational disruption analysis aims to analyse the manufacturing or retail SME’s production-level loss or service-capability loss, respectively, over three stages, namely pre-flood, flood (non-operation), and post-flood. However, the statistical analysis aims to determine the difference between the two experiments using statistical methods.

8.2.1 Operational Disruption Analysis

For each flood-affected manufacturing and retail SME, production level and service capability values were computed at each simulation tick during the course of a simulation and then represented graphically as in Figure 8.7. This representation of production level and service capability values for manufacturing and retail SMEs respectively, is similar to disaster resilience visualizations presented in other research (Bruneau et al., 2003; Zobel, 2010, 2011a, 2011b). It is recognized that the *actual* profile (i.e. the graphical representation of production level or service capability) of flood-affected manufacturing or retail SMEs will be similar to, rather than the same as, those given in Figure 8.7. This figure (Figure 8.7) provides a general explanation of how pre-flood, during flood (non-operation), and post-flood operational disruption (OD_{pre} , OD_{none} , and OD_{post}) can be determined from such representations. For an

SME affected by a flood event, the production level (*PL*) or service capability (*SC*), signified by the red line in Figure 8.7, varies throughout the time period simulated, i.e. from t_0 to t_5 . The normal operation takes place at t_0 in which case the production level (*PL*) and the service capability (*SC*) are 100% until either t_1 at which an SME receives and acts on a flood alert or warning from the EA or t_2 at which the flood event (i.e. non-operation) enters premises. In Figure 8.7, the time line is divided into three stages:

- (a) In the *pre-flood stage* (from t_1 to t_2), if at t_1 , an SME receives and acts on a flood alert/warning from the EA, then production level or service capability may fall rapidly to zero or fluctuate between 0% and 100% as employees are allocated to different pre-flood behaviours, prior to the onset of the flood at t_2 . This potential drop in production and/or service capability between t_1 and t_2 would likely be non-linear given that this is dependent on the pre-flood behaviours enacted by a manufacturing or retail SME. However, if a flood alert/warning is received but *not* acted on, or even *not* received at all, then the production level or service capability may drop instantly from 100% to 0% at t_2 ($t_1 = t_2$), signifying that production and/or service capability halts immediately at the point the water reached an SME's premises.
- (b) During the flood event (i.e. the non-operational) stage (from t_2 to t_3), *PL* or *SC* remains at zero before being resumed at t_3 . However, this stage may overlap with the post-flood stage and this only occurs once the production level or the service capability is 0% and it cannot be resumed immediately after the flood receded from an SME's premises.
- (c) During the *post-flood stage* (from t_3 to t_4), as shown in Figure 8.7, this potential increase in production and/or service capability between t_3 (i.e. *PL* or *SC*=0%) and t_4 (i.e. *PL* or *SC*=100%) would likely be non-linear as it is reliant on the post-flood behaviours a manufacturing or retail SME enacts, as described in Chapter 7 Section 7.1.2.

Subsequently, from t_4 , *PL* and *SC* remain at 100% until t_5 , which corresponds with the end of the simulation.

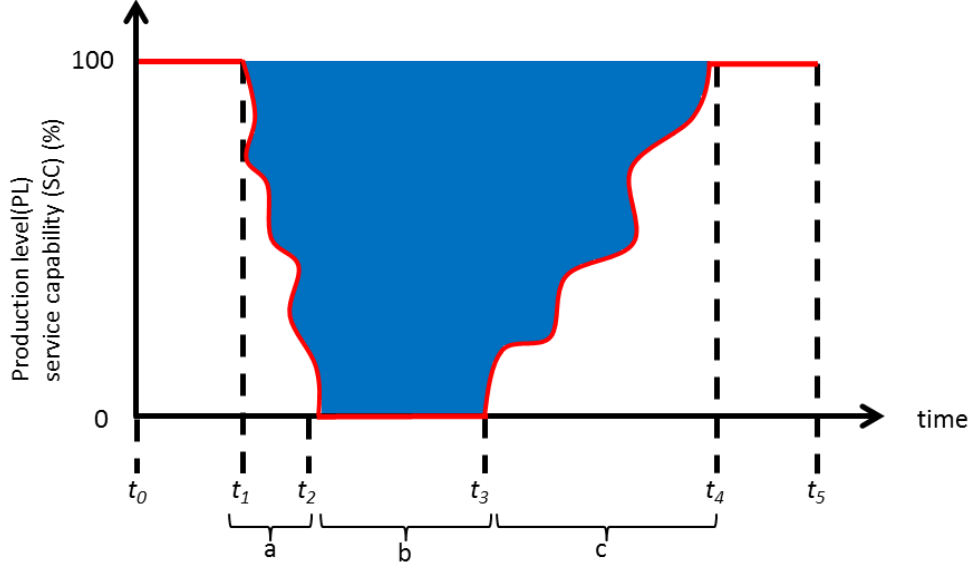


Figure 8.7: Manufacturing and retail SMEs operational disruption

As shown in Figure 8.7, the area highlighted in blue represents *operational disruption*, which has resulted due to the drop in a manufacturing SME's production or a retail SME's service. *Operational disruption* is divided into three stages: (a) pre-flood operational disruption (OD_{pre}), which is represented by the blue area highlighted from t_1 to t_2 ; (b) non-operational disruption (OD_{none}), which is represented by the blue area highlighted from t_2 to t_3 ; and (c) post-flood operational disruption (OD_{post}), which is represented by the blue area highlighted from t_3 to t_4 . Thus, there is a need to investigate specific precautionary measures that have the potential to reduce the overall operational disruption ($OD_{overall}$), (i.e. the blue area highlighted from t_1 to t_4) (see Figure 8.7). This is achieved by reducing the OD_{pre} (from t_1 to t_2), the OD_{none} (from t_2 to t_3), and the OD_{post} (from t_3 to t_4). In terms of a flood-affected manufacturing or retail SMEs, OD_{pre} , OD_{none} , and OD_{post} can be determined by equation (8.1), (8.2), and (8.3), respectively, as follows:

$$OD_{pre} = \int_{t_1}^{t_2} PL(t) dt \quad (8.1)$$

$$OD_{none} = 100 (t_3 - t_2) \quad (8.2)$$

$$OD_{post} = \int_{t_3}^{t_4} PL(t) dt \quad (8.3)$$

As mentioned earlier, the *PL* or *SC* (from t_1 to t_2) and (from t_3 to t_4), are unlikely to be linear, and thus, both OD_{pre} , and OD_{post} can be determined using the trapezoidal rule. The trapezoidal rule represents a numerical method used to approximate a definite integral (area under the curve) once the antiderivative for the integrand is difficult or impossible to determine (Kreider et al., 2005) as follows:

$$T_n \approx \int_a^b f(t)dt \quad (8.4)$$

where a and b are the boundaries of the area under the curve and $f(t)$ is the production level or service capability for manufacturing or retail SMEs. The trapezoidal rule of the definite integral, which is presented in equation 8.4)), can be computed as:

$$T_n = \frac{\Delta t}{2} [f(T_0) + 2f(T_1) + 2f(T_3) + \dots + 2f(T_{n-1}) + f(T_N)] \quad (8.5)$$

Equation (8.5) can be simplified as:

$$T_n = \frac{\Delta t}{2} \left(f(T_0) + f(T_N) + 2 \sum_{k=1}^{N-1} f(T_k) \right) \quad (8.6)$$

where T_N is the simulation tick and $f(T_N)$ is the corresponding production level or service capability for manufacturing or retail SMEs. Equation (8.5), which employs the trapezoidal rule (Kreider et al., 2005; Smyth, 2014; Trefethen & Weideman, 2014), subdivides the given interval $[a, b]$ into n subintervals of equal width, $\Delta t = \frac{b-a}{n}$, and $T_0 = a, T_N = b$. In this research, $\Delta t = 1$ since $n = b - a$.

In relation to the *pre-flood* trapezoidal rule (T_{n1}), it can be determined as follows:

$$T_{n1} = \frac{\Delta t}{2} \left(f(t_1) + f(t_2) + 2 \sum_{k=t_1+1}^{t_2-1} f(T_k) \right) \quad (8.7)$$

Thus, the *pre-flood operational disruption* (OD_{pre}) can be determined using the *pre-flood* trapezoidal rules as follows:

$$OD_{pre} = 100(t_2 - t_1) - T_{n1} \quad (8.8)$$

In equation (8.8) the trapezoidal rule subdivides the given interval $[t_1, t_2]$ (i.e. which refers to the time period pre-flood at which point the production level or service capability fall below 100% (t_1) and the time at which production or service reached 0% (t_2) as presented in Figure 8.7) into $(t_2 - t_1)$ intervals.

In relation to the *post-flood* trapezoidal rule (T_{n2}), it can be determined as follows:

$$T_{n2} = \frac{\Delta t}{2} \left(f(t_3) + f(t_4) + 2 \sum_{k=t_3+1}^{t_4-1} f(T_k) \right) \quad (8.9)$$

Thus, the OD_{post} can be determined using the *post-flood* trapezoidal rules as follows:

$$OD_{post} = 100(t_4 - t_3) - T_{n2} \quad (8.10)$$

where the trapezoidal rule partitions the given interval $[t_3, t_4]$ (i.e. which denotes the time period post-flood at which production or service is resumed (t_3), and the time at which production or service is restored to 100% (t_4) as indicated in Figure 8.7) into $(t_4 - t_3)$ intervals.

In terms of *overall operational disruption* ($OD_{overall}$), this is the total of the pre-flood, during-flood (non-operational), and post-flood operational disruption (OD_{pre} , OD_{none} , and OD_{post}) values as follows:

$$OD_{overall} = OD_{pre} + OD_{none} + OD_{post} \quad (8.11)$$

For example, referring to equation (8.2), (8.8) and (8.10) and Figure 8.7, with a simulation period from $t_0 = 0$ to $t_5 = 13$. As presented in Table 8.3, for a manufacturing SME (denoted as 'A'), which has received and acted on an EA alert or warning at $t_1 = 1$ before the flood commenced at $t_2 = 5$, and with a consequent period of non-production lasting until $t_3 = 7$ from the time production rose non-linearly until being restored to a level of 100% at $t_4 = 12$.

t	t_0	t_1				t_2		t_3					t_4	t_5
T	0	1	2	3	4	5	6	7	8	9	10	11	12	13
$f(T)$	100	100	40	20	10	0	0	0	50	20	30	60	100	100

Table 8.3: Manufacturing SME ‘A’ production level

In order to find the OD_{pre} value, which is presented in equation (8.8), the T_{n1} value (area under the curve) had to be initially computed, using equation (8.7) and the values presented in Table 8.3, as follows:

$$T_{n1} = \frac{1}{2} (100 + 0 + 2(40 + 20 + 10))$$

$$T_{n1} = \frac{1}{2} (100 + 2(70))$$

$$T_{n1} = \frac{1}{2} (240)$$

$$T_{n1} = 120 \text{ units}$$

Thus, the OD_{pre} value can be computed by substituting the T_{n1} value, which was found from equation (8.7), along with $f(t_1)$ and $f(t_2)$ values, which are presented in Table 8.3, in equation (8.8) as follows:

$$OD_{pre} = 100 (5 - 1) - 120$$

$$OD_{pre} = 100 \times 4 - 120$$

$$OD_{pre} = 280 \text{ units}$$

In relation to the OD_{none} value, this value was computed by substituting $f(t_2)$ and $f(t_3)$ values, which are presented in Table 8.3, in equation (8.2) as follows:

$$OD_{none} = 100 (7 - 5)$$

$$OD_{none} = 200 \text{ units}$$

Finally, in order to find the OD_{post} value, which is presented in equation (8.10), the T_{n2} value (area under the curve) had to be computed, using equation (8.9) and the values presented in Table 8.3, as follows:

$$T_{n2} = \frac{1}{2} (0 + 100 + 2(50 + 20 + 30 + 60))$$

$$T_{n2} = \frac{1}{2}(100 + 2(160))$$

$$T_{n2} = \frac{1}{2}(420)$$

$$T_{n2} = 210 \text{ units}$$

Thus, the OD_{post} value can be computed by substituting the T_{n2} value, which was found using equation (8.9) along with $f(t_1)$ and $f(t_2)$ values, which are presented in Table 8.3, in equation (8.10) as follows:

$$OD_{post} = 100 (12 - 7) - 210$$

$$OD_{post} = 100 (5) - 210$$

$$OD_{post} = 290 \text{ units}$$

In contrast, looking at the same simulation period for a different manufacturing SME (denoted as ‘B’), located in the same geographical area. This SME has received and acted on an EA alert/warning at $t_1 = 1$, although here, $t_2 = 5$ in which some pre-flood behaviours were enacted enabling production to be resumed at $t_3 = 6$ and reaching a level of 100% at $t_4 = 10$, consequently $OD_{pre} = 120$, $OD_{none} = 100$, and $OD_{post} = 210$ units (see Table 8.4).

t	t_0	t_1				t_2	t_3				t_4			t_5
T	0	1	2	3	4	5	6	7	8	9	10	11	12	13
$f(T)$	100	100	80	80	70	0	0	50	50	40	100	100	100	100

Table 8.4: Manufacturing SME ‘B’ production level

To allow a more consistent comparison between the OD_{pre} , OD_{none} , and OD_{post} values of the simulated SMEs, these values are linked to the manufacturing or retail SME’s production level or service capability over the same time period within the agent-based simulation had the company been unaffected by the flood event, i.e. 100 ($t_5 - t_0$), such that:

$$OD_{ABS}^{pre} = \left(\frac{OD_{pre}}{100(t_5 - t_0)} \right) \times 100 \quad (8.12)$$

$$OD_{ABS}^{none} = \left(\frac{OD_{none}}{100(t_5 - t_0)} \right) \times 100 \quad (8.13)$$

$$OD_{ABS}^{post} = \left(\frac{OD_{post}}{100(t_5 - t_0)} \right) \times 100 \quad (8.14)$$

Therefore, in the simple examples provided, over the simulation period (from $t_0 = 0$ to $t_5 = 11$), the manufacturing SME ‘A’ would experience an *absolute operational disruption* of $OD_{ABS}^{pre} = 21.5\%$, $OD_{ABS}^{none} = 15.4\%$, and $OD_{ABS}^{post} = 22.3\%$ respectively. Similarly, the manufacturing SME ‘B’ would experience an *absolute pre-, non-operation, and post-flood operational disruption* of $OD_{ABS}^{pre} = 9.2\%$, $OD_{ABS}^{none} = 7.7\%$, and $OD_{ABS}^{post} = 16.1\%$ respectively. In terms of the *overall absolute operational disruption* ($OD_{ABS}^{overall}$), it can be determined as follows:

$$OD_{ABS}^{overall} = OD_{ABS}^{pre} + OD_{ABS}^{none} + OD_{ABS}^{post} \quad (8.15)$$

Thus, the $OD_{ABS}^{overall}$ for both manufacturing SMEs ‘A’ and ‘B’ are 59.2% and 33%. It can be seen that SME ‘A’ presents a greater $OD_{ABS}^{overall}$ value than SME ‘B’, i.e. 26.2% greater than SME ‘B’.

8.2.2 Statistical Analysis

The SPSS software, which is comprised of a large number of libraries for machine-learning algorithms and text analysis to provide advanced statistical analysis, was used to conduct two statistical tests, namely the Shapiro Wilk and Mann-Whitney U.

The Shapiro Wilk test was used to test the normal distribution of a sample selected from a group of data (Hanusz et al., 2016; Razali & Wah, 2011). The normally distributed data has a small range of values and tends to be centred about its mean (Gordon, 2006). In terms of the Shapiro Wilk test, it tests two hypotheses: (a) the null hypothesis (H_0), which indicates that the data is selected from a normally distributed population, and (b) the alternative hypothesis (H_1), which demonstrates that the data is selected from a population that is not normally distributed (Hanusz et al., 2016). The Shapiro Wilk test compares the significance value (p-value) to the threshold ($\alpha = 0.05$) (Kim, 2015; McCrum-Gardner, 2008). Therefore, if the p-value is less than the threshold ($p\text{-value} < \alpha$), the null hypothesis (H_0) is rejected, which means that the population is not normally distributed. However, if the p-value is greater than the threshold ($p\text{-value} > \alpha$), the null hypothesis is not rejected, which indicates that the

data is normally distributed. This test is mainly used to determine the appropriate statistical test (i.e. the t-test if the data is normally distributed or the Mann-Whitney U test if the data is not normally distributed) (Ruxton, 2006).

In relation to the Mann-Whitney U test, it is a non-parametric test that tests the null hypothesis (H_0), which indicates that the two independent samples were selected from the same population (McKnight & Najab, 2010; Nachar, 2008). Thus, if the p-value is less than the threshold ($p\text{-value} < \alpha$), then the differences between the two groups of data tested are statistically significant (Nachar, 2008). However, if the p-value is greater than the threshold ($p\text{-value} > \alpha$), this indicates that there is no statistical significance between the two groups of data tested.

8.3 SIMULATION EXPERIMENTS

Implementing property-level and business continuity/risk management precautionary measures has the potential to reduce SMEs' vulnerability to flood risks, which in turn, reduces the overall operational disruption. For the property-level measures, several questions have been raised, which include both resistance and resilience precautionary measures. These questions aim to investigate an SME's immediate response to and short-term recovery from flooding while implementing (i) a combination of some resistance or resilience precautionary measures, or (ii) a combination of all the resistance or resilience precautionary measures without alternatives. In terms of the latter, the term 'without alternatives' refers to an SME that has implemented all of the possible precautionary measures from a specific classification (e.g. resistance or resilience precautionary measures) and ignored those precautionary measures that cannot be implemented concurrently with the implemented ones. For example, an SME can implement a combination of all the resistance precautionary measures without alternatives when building bund wall (PM_1), installing flood-proof windows (PM_5), installing anti-backflow valves (PM_6), painting brickwork with waterproofing treatments (PM_7), and installing 'below-ground' water-proof materials (PM_8). In this example, it can be seen that an SME has implemented all the resistance precautionary measures without alternatives once it chose to build a bund wall (PM_1) rather than the other alternatives, such as keeping sandbags on site (PM_2), installing flood-proof doors (PM_3), and installing flood barriers in doorways (PM_4), which cannot be implemented concurrently with the bund

wall precautionary measures. Alternatively, an SME could use another combination of all the resistance precautionary measures when it implements PM₂ (rather than PM₁, PM₃, PM₄) along with other resistance precautionary measures (PM₅, PM₆, PM₇, and PM₈). This is because some resistance precautionary measures are alternatives each of which will protect the premises to a different degree.

1. What is the effect of implementing *none* of resistance and resilience precautionary measures and *only* 'set-up and maintain an emergency financial reserve' as a business continuity/risk management precautionary measure on SMEs' short-term recovery from flooding?
2. What is the effect of implementing different combinations of *all* the resistance precautionary measures without alternatives on SMEs' short-term recovery from flooding?
3. What is the effect of implementing a combination of *some* resistance precautionary measures on SMEs' short-term recovery from flooding?
4. What is the effect of implementing a combination of *all* the resilience precautionary measures without alternatives on SMEs' short-term recovery from flooding?
5. What is the effect of implementing different combinations of *some* resilience precautionary measures on SMEs' short-term recovery from flooding?
6. What is the effect of implementing different combinations of *all* the resistance precautionary measures without alternatives along with a combination of all the resilience precautionary measures without alternatives on SMEs' short-term recovery from flooding?

In terms of business continuity/risk management precautionary measures, the British Institute of Facilities Management indicates that implementing flood-specific measures into business continuity arrangements can lead to organisations saving up to 90% of their potential flood-related losses (Flood Risk Management Guidance, 2015). Due to the importance of business continuity/risk management precautionary measures, the following questions have been raised about these measures:

7. What is the effect of implementing a combination of *all* the business continuity/risk management precautionary measures without alternatives on SMEs' short-term recovery from flooding?

8. What is the effect of implementing a combination of *some* business continuity/risk management precautionary measures on SMEs' short-term recovery from flooding?
9. What is the effect of implementing a combination of *all* the resistance precautionary measures without alternatives along with a combination of *all* the business continuity/risk management precautionary measures without alternatives on SMEs' short-term recovery from flooding?
10. What is the effect of implementing a combination of *all* the resilience precautionary measures without alternatives along with a combination of *all* the business continuity/risk management precautionary measures without alternatives on SMEs' short-term recovery from flooding?
11. What is the effect of implementing a combination of *all* the resistance and resilience precautionary measures without alternatives along with a combination of *all* the business continuity/risk management precautionary measures without alternatives on SMEs' short-term recovery from flooding?

Businesses and SMEs in particular, are able to implement any of the three types of precautionary measures to improve their premises' resistance and resilience to flooding along with safeguarding their businesses continuity. However, implementing *all* the possible resistance, resilience and business continuity/risk management precautionary measures may be costly for SMEs due to their limited financial resources. Confirming this, Finch (2004) indicates that SMEs are vulnerable to extreme weather events in general, and flooding in particular, because of their limited financial resources. Subsequently, Thurston et al. (2008) mention that households and small businesses are less likely to implement all the possible precautionary measures due to a wide range of factors including cost and property-appearance considerations. Thus, SME's lack of financial resources means they are unlikely to implement all the possible precautionary measures proposed to achieve effective flood protection. However, deciding which precautionary measures *should* be implemented is a difficult decision, and thus, this research provides a range of simulation experiments to investigate the possible effects of implementing all, some, or none of these precautionary measures. Specifically, the simulation experiments will focus on answering questions 1 to 11 to investigate the effect of implementing different combinations of precautionary measures in terms of their categories (e.g. property-

level resistance, property-level resilience, and business continuity/risk management precautionary measures). These combinations of experiments are summarised in Table 8.5.

Question No.	Simulation Experiments	Property-level precautionary measures					
		Resistance		Resilience		Business continuity/risk management	
		All*	Some	All*	Some	All*	Some
1	E1						
2	E2 (A)	✓					
	E2 (B)						
	E2 (C)						
	E2 (D)						
3	E3		✓				
4	E4			✓			
5	E5 (A)				✓		
	E5 (B)						
6	E6 (A)	✓		✓			
	E6 (B)						
7	E7					✓	
8	E8						✓
9	E9	✓				✓	
10	E10			✓		✓	
11	E11	✓		✓		✓	
* all without alternatives							

Table 8.5: Mapping of simulation experiment questions

The eleven questions will be investigated in several simulation experiments presented in Section 8.3.1.

8.3.1 SME Simulation Experiments

This section presents a set of simulation experiments to address questions 1 to 11. In relation to simulation experiment (E1), which addresses Question 1, as indicated in Table 8.6, this simulation experiment represents the worst-case scenario among the implemented simulation experiments in which an SME has *only* set-up and maintained an emergency financial reserve (PM_{23}) as a business continuity/risk management precautionary measure to ensure that the SME will not go out of business.

For Question 2, simulation experiment E2 aims to investigate the effect of implementing different combinations of *all* the resistance precautionary measures without alternatives across four associated simulation experiments. This is because some of these precautionary measures represent alternatives (i.e. they need not be implemented simultaneously). The four associated simulation experiments involve

different defence strategies: E2 (A) a bund-wall (PM_1) protected SME (1.5m); E2 (B) a flood-proof-door (PM_3) protected SME (0.9m); E2 (C) a flood-barrier (PM_4) protected SME (0.5) at doorways; and E2 (D) a sandbag (PM_2) protected SME (placed at doorways when an EA alert or warning is received) (0.3m). Simulation experiment E2 (A) represents the best-case scenario in the experiment as it provides the highest level of protection (1.5m). However, E2 (D) represents the worst-case scenario as it provides the lowest level of protection (0.3m) among the associated simulation experiments E2 involved.

In terms of Question 3, simulation experiment E3 aims to investigate the effect of implementing a combination of some resistance precautionary measures on SMEs' immediate response to and short-term recovery from flooding. Specifically, E3 aims to investigate the effect of implementing flood-proof windows (PM_5), anti-backflow valves (PM_6), and brickwork painted with waterproofing treatments (PM_7) without any doorway defence strategies, such as bund-walls (PM_1), flood-proof doors (PM_3), flood barriers (PM_4), and sandbags (PM_2) being implemented.

Simulation experiment E4 includes *all* the possible resilience precautionary measures (i.e. (PM_9 , PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , PM_{17} , PM_{18}) for manufacturing and (PM_9 , PM_{10} , PM_{11} , PM_{12} , PM_{14} , PM_{18}) for retail SMEs) to investigate their effect on SMEs' immediate response to and short-term recovery from flooding. In contrast to E4, simulation experiment E5 provides a selected range of these precautionary measures divided into two simulation experiments (e.g. E5 (A) and E5 (B)) to investigate the effect of each combination of resilience precautionary measures. In E5 (A), this associated simulation experiment considers resilience precautionary measures (i.e. (PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , PM_{17}) for manufacturing and (PM_{10} , PM_{11} , PM_{12} , PM_{14}) retail SMEs) to investigate how these combinations may reduce SME's vulnerability to flood damage. However, E5 (B) considers two resilience precautionary measures (i) installing flood-resilient flooring (PM_9), and (ii) installing and using a sump pump system (PM_{18}) to investigate how these precautionary measures may accelerate the SMEs' short-term recovery.

For Question 6, simulation experiment E6 aims to investigate the effect of implementing a combination of *all* the resistance and resilience precautionary measures without alternatives. This simulation experiment consists of two associated

simulation experiments: E6 (A) and E6 (B). The former involves a combination of all the resistance precautionary measures without alternatives (PM_1 , PM_5 , PM_6 , PM_7 , PM_8), which includes a bund-wall (PM_1) that provides the highest level of protection (i.e. as in E2 (A)), together with a combination of all the possible resilience precautionary measures (i.e. (PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , PM_{17}) for manufacturing SMEs and (PM_{10} , PM_{11} , PM_{12} , PM_{14} , PM_{18}) for retail SMEs) as those represented in E4. In terms of E6 (B), this combines E1 (C), which involves (PM_4 , PM_5 , PM_6 , PM_7 , PM_8) that provide the lowest level of protection, along with *all* the possible resilience precautionary measures represented in E4. It is acknowledged that the ‘maintain sandbags on site’ precautionary measure offers the lowest level of protection (0.3m), but it is not be enacted because EA alerts and warnings will not be received in E6 (B).

In relation to the business continuity/risk management precautionary measures, simulation experiment E7 represents an SME with a combination of *all* the business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}) in place (except mutual aid partners, which will be investigated individually). In contrast to E7, simulation experiment E8 only features *some* of these precautionary measures. Specifically, it aims to investigate the effect of not receiving EA alerts (PM_9) and warnings (PM_{10}) on SMEs’ immediate response to, and short-term recovery from, flooding. It is indicated that an early warning alert is an essential measure affecting a company’s emergency response to a flood event (Kreibich et al., 2007).

In relation to Question 9, simulation experiment E9 aims to investigate the effect of an SME implementing a combination of *all* the resistance precautionary measures without alternatives represented in E2 (D) along with a combination of *all* the business continuity/risk management precautionary measures without alternatives represented in E7. This is to investigate how sandbags could be placed at doorways when EA alerts and warnings are received.

Simulation experiment E10, which aims to answer Question 10, includes a combination of *all* the possible resilience precautionary measures represented in E4, along with a combination of *all* the business continuity/risk management precautionary measures without alternatives that E7 includes. However, simulation

experiments E11, implements a combination of *all* the resistance and resilience precautionary measures without alternatives that represented in E2 (A) and E4, respectively, along with a combination of *all* the business continuity/risk management precautionary measures without alternatives represented in E7. This is to investigate the effect(s) that may occur on an SME that has implemented this combination. It is assumed that simulation experiment E11 will provide the best level of protection compared to the others because it includes the most measures.

While simulating SMEs in any of the aforementioned simulation experiments, it is assumed that all SMEs (i) have sufficient funds available and (ii) choose to allocate employees to clean up rather than employing a cleaning service provider. This is to ensure that the results of investigating precautionary measures are not influenced by these scenarios. However, these scenarios (i.e. SMEs' financial status and cleaning-up decisions) will not be ignored; they will be investigated individually after investigating the precautionary measures.

Code	Classification	Precautionary measure	Simulation Experiments															
			E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
				A	B	C	D			A	B	A	B					
PM ₁	Property level precautionary measures	Flood resistance precautionary measures	Build bund wall	✓								✓						✓
PM ₂			Maintain sandbags on site				✓									✓		
PM ₃			Install flood-proof doors		✓													
PM ₄			Install flood barriers at doorways			✓							✓					
PM ₅			Install flood-proof windows	✓	✓	✓	✓	✓				✓	✓			✓		✓
PM ₆			Install anti-backflow valves	✓	✓	✓	✓	✓				✓	✓			✓		✓
PM ₇			Paint brickwork with waterproofing treatments	✓	✓	✓	✓	✓				✓	✓			✓		✓
PM ₈			Install 'below-ground' water-proof materials	✓	✓	✓	✓	✓				✓	✓			✓		✓
PM ₉	Property level precautionary measures	Flood resilience precautionary measures	Install flood-resilient flooring						✓		✓	✓	✓				✓	✓
PM ₁₀			Raise consumer boards						✓	✓		✓	✓				✓	✓
PM ₁₁			Raise electrical sockets						✓	✓		✓	✓				✓	✓
PM ₁₂			Raise the location at which documents are stored						✓	✓		✓	✓				✓	✓
PM ₁₃			Raise the location at which raw material can be stored						✓	✓		✓	✓				✓	✓
PM ₁₄			Raise the location at which stocks can be stored						✓	✓		✓	✓				✓	✓
PM ₁₅			Raise the location at which production machines are placed						✓	✓		✓	✓				✓	✓
PM ₁₆			Raise the location at which IT equipment is placed						✓	✓		✓	✓				✓	✓
PM ₁₇			Raise the location at which products are stored						✓	✓		✓	✓				✓	✓
PM ₁₈			Install and use a sump pump system						✓		✓	✓	✓				✓	✓
PM ₁₉	Business continuity / risk management precautionary measures		Register for EA alerts											✓		✓	✓	✓
PM ₂₀			Register for EA warnings											✓		✓	✓	✓
PM ₂₁			Obtain basic insurance															
PM ₂₂			Obtain comprehensive insurance															
PM ₂₃			Set-up and maintain an emergency financial reserve	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
PM ₂₄			Has pre-existing mutual aid partner															
PM ₂₅			Identify a mutual aid partner															
PM ₂₆			Request a mutual aid partner															
PM ₂₇			Maintain an electricity generator on site											✓	✓	✓	✓	✓
PM ₂₈			Backup IT data											✓	✓	✓	✓	✓
PM ₂₉			Maintain an emergency flood plan											✓	✓	✓	✓	✓
PM ₃₀			Display an emergency flood plan											✓	✓	✓	✓	✓
PM ₃₁			Perform emergency flood exercise											✓	✓	✓	✓	✓

Table 8.6: Simulation experiments

8.3.2 SME-Related Organisation Simulation Experiments

SME related-organizations provide SMEs with assistance or a service (such as cleaning service providers) to maintain SME's operation and support their short-term recovery. However, SMEs may return to their normal operation level without interacting with some of these related organisations. For example, manufacturing and retail SMEs may choose to allocate employees to clean-up rather than employing a cleaning service company. For manufacturing SMEs, they may restore their production to 100% without having a mutual aid partner. Similarly, retail SMEs may allocate their employees to carry out premises refurbishment (rather than contracting a refurbishment company to attend their flood-affected premises). Therefore, a set of simulation experiments has been defined to investigate the influence of employing a selection of these organisations as indicated in Table 8.7. Note that simulation experiments S1 (A), S1 (B), S1 (C), S2 (A), and S2 (B) are implemented with manufacturing SMEs located in the Sheffield geographical area, which includes more SMEs than Tewkesbury geographical area. However, simulation experiments S3 (A) and S3 (B) relate to retail SMEs located in the Sheffield geographical area.

	Options	Simulation Experiment						
		Manufacturing SMEs					Retail SMEs	
		S1			S2		S3	
		(A)	(B)	(C)	(A)	(B)	(A)	(B)
Insurance company	Basic	✓						
	Comprehensive		✓	✓				
Funds	Yes		✓	✓				
	No	✓						
Clean-up provider	Employees	✓	✓					
	Service provider			✓				
Mutual aid partner	Yes				✓			
	No					✓		
Refurbishment by	Employees						✓	
	Refurbishment company							✓

Table 8.7: SME-related organisations simulation experiments

Table 8.7 defines seven simulation experiments. Firstly, simulation experiment S1 aims to investigate the influence of different types of insurance coverage and financial status on the immediate response and short-term recovery of manufacturing SMEs exposed to different levels of flooding. S1 (A) represents manufacturing SMEs with basic insurance but without funds available. Following this, S1 (B) signifies manufacturing SMEs with comprehensive insurance and funds available that allocate

their own employees to clean-up the premises rather than waiting for the cleaning service provided by the insurance company. Next, S1 (C) represents manufacturing SMEs with comprehensive insurance and funds available that choose to wait for the insurance company provided cleaning service to clean-up the premises.

In relation to simulation experiment S2, two simulation experiments are defined: (i) simulation experiment S2 (A) in which manufacturing SMEs have a pre-defined mutual aid partner, and (ii) simulation experiment S2 (B) in which manufacturing SMEs do not have a mutual aid partnership.

In terms of retail SMEs, this research aims to investigate retail SMEs' immediate response to and short-term recovery from flooding by simulating both *with* and *without* a refurbishment company being called to attend the flood-affected premises. Thus, simulation experiment S3 (A) represents retail SMEs contracted companies specializing in refurbishing premises whereas simulation experiment S3 (B) denotes retail SMEs that use their own employees to refurbish their flood-affected premises.

In terms of the remainder of the SME-related organisations (e.g. suppliers, customers, electricians, and plumbers), they provide fewer options to enable them to be investigated individually, such as insurance companies or cleaning service providers.

8.4 SUMMARY

This chapter presents the two case studies considered in this research, namely (a) the Lower Don Valley in Sheffield and (b) Tewkesbury. The former was selected due to its high concentration of SMEs whereas the latter was selected due to the historic high water levels during the 2007 flood event. In the Lower Don Valley of Sheffield, a total of 6224 organizations were identified in which 906 had been flooded at some point during the 45.5-hour flood event modelled. For Tewkesbury, a total of 920 organisations were identified in Tewkesbury geographical area in which 207 had been flooded at some point during the 318.5 hours simulated.

In terms of the analysis, the pre-flood, during-flood (non-operational), and post-flood absolute operational disruption values are used to quantify the disruption that occurs to manufacturing and retail SMEs. Furthermore, 16 simulation experiments

(including the associated simulation experiments) are defined, each of which consists of different combinations of precautionary measures. In terms of SME-related organisations, six simulation experiments are defined to investigate (i) the influence of different types of insurance coverage and financial status had on SME's immediate response to and short-term recovery from flooding for SMEs exposed to a range of different levels of flooding, (ii) the interactions between manufacturing SMEs and mutual aid partners, and (iii) the interactions between retail SMEs and companies specializing in post-flood refurbishment.

Chapter 9

Results and Discussion

This chapter presents the results of modelling and simulating the flooded manufacturing SMEs identified in (a) the Lower Don Valley region of Sheffield and (b) Tewkesbury in terms of the range of precautionary measures and pre- and post-flood behaviours. Manufacturing SMEs are simulated over three stages, namely pre-flood, flood (non-operational), and post-flood. The simulation outputs of retail SMEs and SME-related organisations are presented and discussed in Appendix D.

Section 9.1 presents an overview of the chapter. Next, Section 9.2 presents the simulation outputs of modelling and simulating the lightly, moderately, and severely flooded manufacturing SMEs located in the Lower Don Valley region of Sheffield over the 16 simulation experiments defined in Chapter 8. Section 9.3 presents a brief investigation of the severely flooded manufacturing SMEs located in the Tewkesbury area. Next, Section 9.4 presents a set of recommendations based on the application of the developed ABMS framework to the previous two UK-based case studies. Finally, Section 9.4 summarises and concludes the chapter.

9.1 OVERVIEW

The modelled manufacturing SMEs were simulated over approximately 37 days (i.e. 1748 ticks) for SMEs located in the Sheffield geographical area and approximately 45 days (i.e. 2132 tick) for those located in Tewkesbury. As mentioned in Chapter 8, these durations (1748 ticks and 2132 ticks) were selected as they encapsulate the time frame from the beginning of the flood event through to the point where all the manufacturing SMEs return to normal operation, $PL=100\%$.

Throughout a simulation and at each tick, the production level of manufacturing SMEs was computed based on a range of inputs (production machines (M), employees (E), raw materials (RM), and power (P) (see Chapter 7, Section 7.1.5)). Following this, in every simulation run, the average of production level of the lightly, moderately, and severely flooded manufacturing SMEs was computed. Subsequently, the cumulative average (i.e. the average of 10 simulation runs) was computed of the lightly, moderately, and severely flooded manufacturing SMEs. This number of simulation runs was determined based on other research (Fredrick et al., 2013; Sabzian et al., 2019). When it was applied to manufacturing SMEs, it can be seen that the difference between the $OD_{ABS}^{overall}$ values associated with experiments E1 and E2 (D) (in which SMEs had the same level of damage and enacted the same set of post-flood behaviours) is only 0.1% for the lightly and moderately flooded manufacturing SMEs (see Table 9.2 and Table 9.4) and only 0.2% for the severely flooded manufacturing SMEs (see Table 9.6).

The cumulative average of manufacturing SMEs was used to compute the *operational disruption* as well as the *absolute operational disruption* values (see Chapter 8 Section 8.2.1) for every stage of the simulation period, i.e. pre-flood, during flood (non-operation), and post-flood. As an example, Figure 9.1 illustrates the process by which the cumulative average for the moderately flooded manufacturing SMEs located in the Sheffield geographical area ($n=115$) was computed. As presented in Figure 9.1, the cumulative average is the average of 10 simulation runs of the production level for 115 moderately flooded manufacturing SMEs (i.e. $115 \times 10 = 1150$).

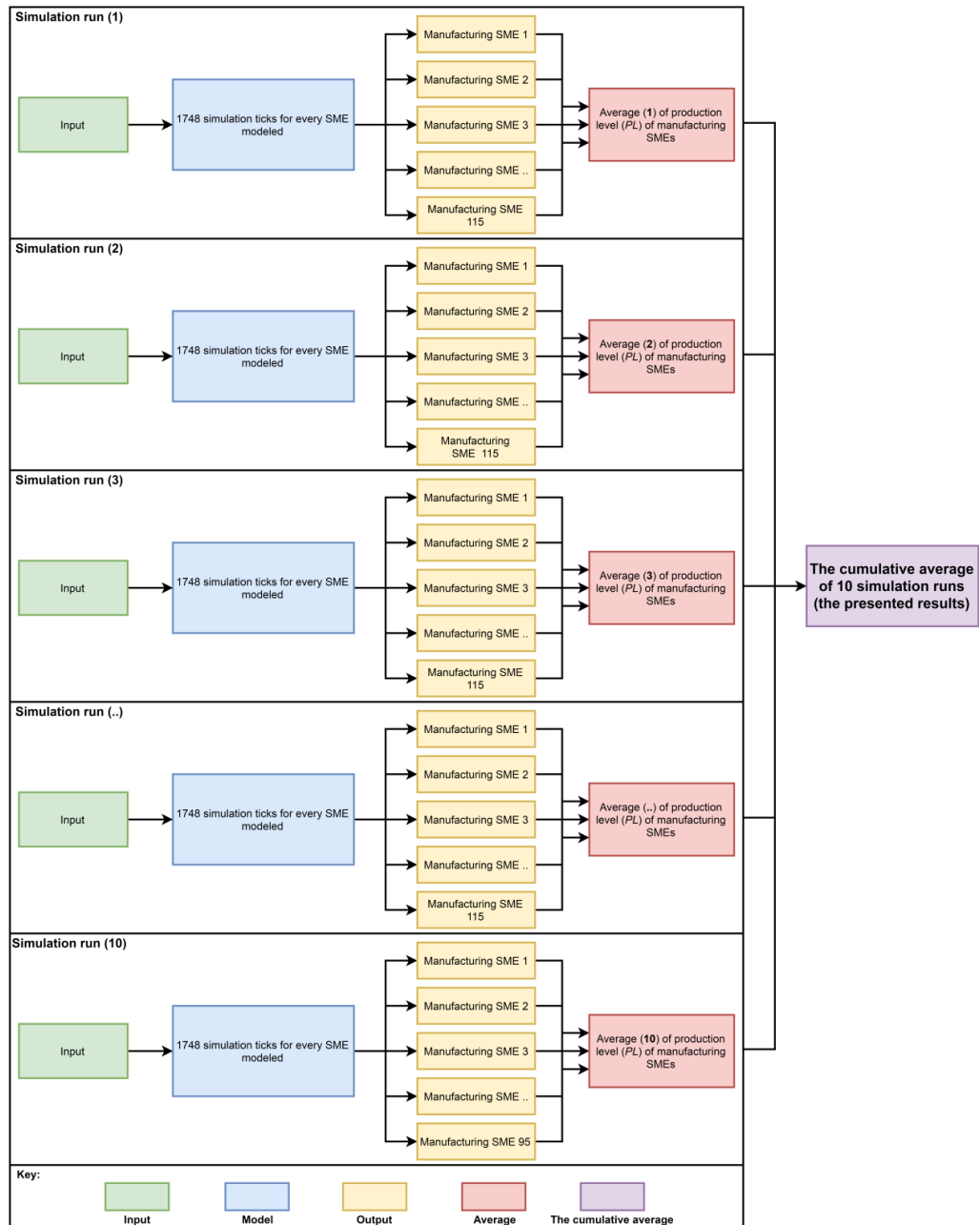


Figure 9.1: The process undertaken to compute the cumulative average of the moderately flooded manufacturing SMEs in the Sheffield geographical area

The process illustrated in Figure 9.1 was also applied to the lightly and severely flooded manufacturing SMEs. Also, it is applied to the lightly, moderately, and severely flooded retail SMEs, which are presented and discussed in Section D.1 of Appendix D. Please note that all the clock times (t_c) as well as the simulation times (t_s) stated in this chapter represent the average times of the simulated SMEs. Also, please refer to Table 8.6 for all the precautionary measures codes mentioned in this chapter.

9.2 SMES LOCATED IN THE LOWER DON VALLEY, SHEFFIELD

Manufacturing SMEs located in the Lower Don Valley of Sheffield were categorised in accordance with the floodwater levels reached in their respective premises, in the case that no precautionary measures were implemented. According to the EA (Environment Agency, 2019b), floodwater level is classified as: (i) lightly flooded if the floodwater level is less than 0.3m, (ii) moderately flooded if the floodwater is greater than or equal to 0.3m but less than or equal to 0.9m, and (iii) severely flooded if the floodwater is greater than 0.9m. Table 9.1 indicates the number of manufacturing and retail SMEs belonging to each of the three categories.

Categories Sectors	Flooded SMEs Category			Total
	Lightly ($W_d < 0.3\text{m}$)	Moderately ($0.3 \leq W_d \leq 0.9\text{m}$)	Severely ($W_d > 0.9\text{m}$)	
Manufacturing	68	115	73	256
Retail	6	5	2	13

Table 9.1: Manufacturing and retail SMEs located in the Lower Don Valley of Sheffield categorised on the basis of the floodwater level reached in their premises

The simulation experiments include all 256 flooded manufacturing SMEs identified in the Lower Don Valley of Sheffield along with the inundation data associated with each of them. Specifically, for all 16 experiments defined in Chapter 8, the figures (E.1 – E.16) illustrating the cumulative average of production levels for lightly, moderately, and severely flooded manufacturing SMEs are provided in Section E.1 of Appendix E. These figures represent the production level of the lightly, moderately, and severely flooded manufacturing SMEs to illustrate the SMEs' performance throughout the course of a simulation when implementing different combinations of precautionary measures. It is important to note that these figures do not correspond explicitly to a particular SME, rather they represent the cumulative average production level resulting from 10 simulation runs of 68 lightly, 115 moderately, and 73 severely flooded manufacturing SMEs.

The data (cumulative average of production level) associated with each of the figures, which are presented in Section E.1 of Appendix E, were used to quantify the production loss, which is represented in the *operational disruption* as well as the *absolute operational disruption* values, for every stage of the simulation period, i.e. pre-flood, during flood (non-operation), and post-flood.

Figure 9.2 presents the cumulative average of production level of the lightly, moderately, and severely flooded manufacturing SMEs in simulation experiment E1 (indicated in Chapter 8), which corresponds to the scenario in which SMEs *only* set-up and maintain an emergency financial reserve (see Figure E.1 Appendix E), and simulation experiment E11, which corresponds to the scenario in which *most* the precautionary measures are in place (see Figure E.16 Appendix E).

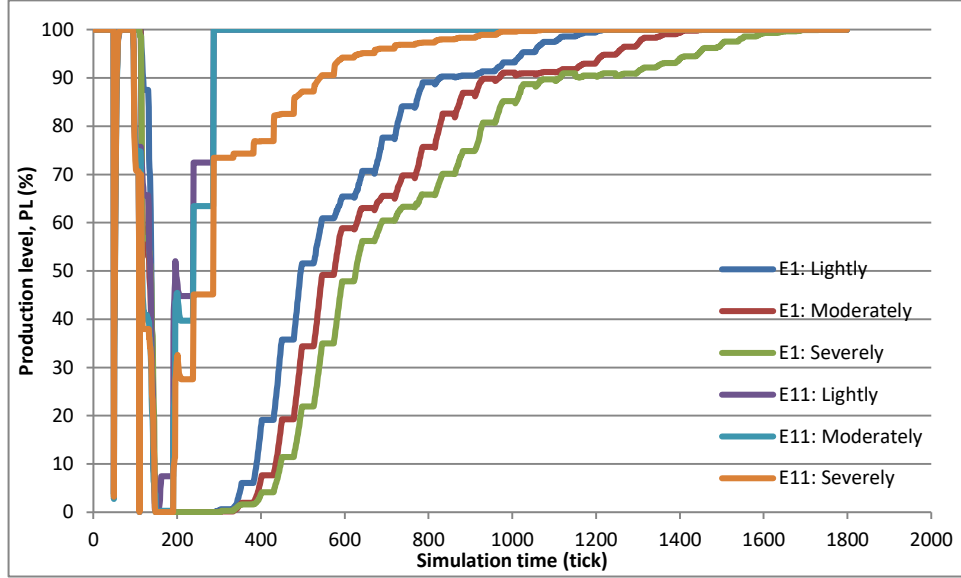


Figure 9.2: Cumulative average of production level of 256 flood-affected manufacturing SMEs located in Sheffield versus time over 10 simulation runs

The cumulative average of production level of all the 68 lightly, 115 moderately, and 73 severely flooded manufacturing SMEs was used to compute the OD_{ABS}^{pre} , OD_{ABS}^{none} , OD_{ABS}^{post} , and $OD_{ABS}^{overall}$ values for each of these categories. For the sixteen simulation experiments undertaken (E1 to E11), Figure 9.3 presents a visual representation of the $OD_{ABS}^{overall}$ values, which were calculated from the cumulative averages of the lightly, moderately, and severely flooded manufacturing SMEs production level using equation (8.15). The $OD_{ABS}^{overall}$ values of the lightly, moderately, and severely flooded manufacturing SMEs presented in Figure 9.3 are derived from Table 9.2 (see page 150), Table 9.4 (see page 167), and Table 9.6 (see page 173).

In all sixteen experiments, the simulation starts at $t_s = 0$ ($t_c = 8:00$ on day 1) and ends at $t_s = 1748$ ($t_c = 18:00$ on day 37), corresponding to an approximate

duration of 37 days. As mentioned previously, the time at which the floodwater reaches a particular SME's premises varies slightly depending on its actual geographical location in the flood-affected area. However, the simulated flood event's start and end times are $t_s = 106$ ($t_c = 13:00$ on day 3) and at $t_s = 197$ ($t_c = 10:30$ on day 5) respectively. This indicates that all 256 SMEs' premises were flooded at some point during this period (see Chapter 8 Section 8.1.1). Furthermore, for each day simulated, working hours start at clock time $t_c = 8:00$ and finish at $t_c = 18:00$, which corresponds to a duration of 20 simulation ticks, i.e. 10 hour working day.

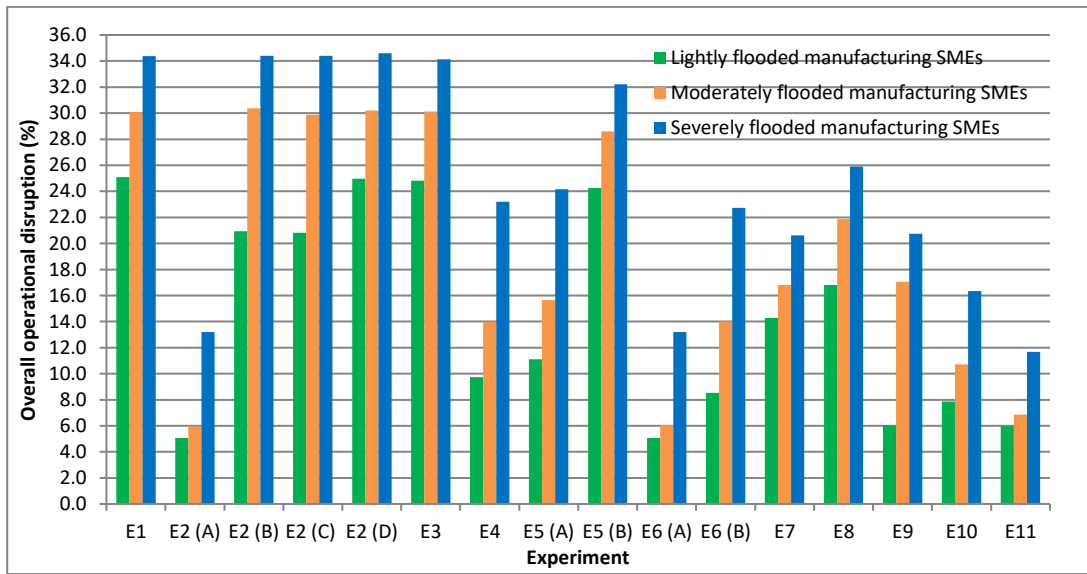


Figure 9.3: The *overall absolute operational disruption* of the lightly, moderately, and severely flooded manufacturing SMEs located in Sheffield geographical area

For the lightly flooded manufacturing SMEs, as presented in Figure 9.3, the greatest $OD_{ABS}^{overall}$ values are associated with the manufacturing SMEs simulated in E1, E2 (D), E3, and E5 (B). However, the lowest $OD_{ABS}^{overall}$ values are associated with the lightly flooded manufacturing SMEs simulated in E2 (A), E6 (A), E9, and E11.

In relation to the moderately flooded manufacturing SMEs, as shown in Figure 9.3, the greatest $OD_{ABS}^{overall}$ values are linked to the SMEs simulated in E1, E2 (B), E2 (C), E2 (D), E3, and E5 (B). In contrast, the lowest $OD_{ABS}^{overall}$ values are linked to manufacturing SMEs simulated in E2 (A), E6 (A), and E11.

The severely flood manufacturing simulated in E1, E2 (B), E2 (C), E2 (D), E3, and E5 (B) yielded the greatest $OD_{ABS}^{overall}$ values. However, the severely flooded

manufacturing SMEs simulated in E2 (A), E6 (A), and E11 yielded the lowest $OD_{ABS}^{overall}$ values.

It can be seen that the lightly, moderately, and severely flooded manufacturing SMEs yielded the lowest $OD_{ABS}^{overall}$ values when simulated in E2 (A), E6 (A), and E11. This is because those simulation experiments included a bund-wall (PM1) being erected around SMEs' premises as a flood-resistance precautionary measure, which was able to provide protection against flooding up to a level of 1.5m (see Chapter 7, Section 7.1.3.1).

Each of these categories (lightly, moderately, and severely flooded manufacturing SMEs) will be investigated individually against each of the 16 simulation experiments in Section 9.2.1.1, Section 9.2.1.2, and Section 9.2.1.3 respectively.

9.2.1 Lightly Flooded Manufacturing SMEs

The simulation of lightly flooded manufacturing SMEs is investigated over three stages, namely pre-flood (t_1 to t_2), flood (non-operational) (t_2 to t_3), and post-flood (t_3 to t_4). Table 9.2 presents information, such as OD_{ABS}^{pre} , OD_{ABS}^{none} , and OD_{ABS}^{post} for each of the three stages. It also presents overall information, such as $OD_{ABS}^{overall}$ for the lightly flooded manufacturing SMEs simulated. For definitions of t_1 , t_2 , t_3 , and t_4 see nomenclature.

Please note that the cumulative average of production level data of the 68 lightly flooded manufacturing SMEs used in equations (8.2), (8.8), (8.10), and (8.12) to (8.15) to compute the values presented in Table 9.2 is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t_1 to t_2)																	
Start (t_1)	Day (d)	3	3	3	3	3	3	3	3	3	3	3	2	3	2	2	2
	Time (t_c)	17:00	17:00	17:00	17:00	17:00	17:00	17:00	17:00	17:00	17:00	17:00	08:30	17:00	08:30	08:30	08:30
	Tick (t_s)	114	114	114	114	114	114	114	114	114	114	114	49	114	49	49	49
End (t_2)	Day (d)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Time (t_c)	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30
	Tick (t_s)	149	149	149	149	149	149	149	149	149	149	149	149	149	149	149	149
Durations (ticks)		36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	101.0	36.0	101.0	101.0	101.0
Pre-flood operational disruption (units) (OD_{pre})		1,265.5	1,265.4	1,264.6	1,265.7	1,265.2	1,265.4	1,265.2	1,264.5	1,264.5	1,264.6	1,264.8	2,784.9	1,264.6	2,859.5	2,613.9	2,665.9
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1.6	0.7	1.6	1.5	1.5
Non-operation (t_2 to t_3)																	
Start (t_2)	Day (d)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Time (t_c)	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30	10:30
	Tick (t_s)	149	149	149	149	149	149	149	149	149	149	149	149	149	149	149	149
End (t_3)	Day (d)	7	4	4	4	7	7	4	4	7	4	4	6	6	4	4	4
	Time (t_c)	09:00	11:00	11:00	11:00	10:00	10:00	11:00	11:00	14:00	11:00	11:00	07:00	07:00	11:00	11:00	11:00
	Tick (t_s)	290	150	150	150	292	292	150	150	300	150	150	238	238	150	150	150
Durations (ticks)		141.0	1.0	1.0	1.0	143.0	143.0	1.0	1.0	151.0	1.0	1.0	89.0	89.0	1.0	1.0	1.0
Non-operation operational disruption (units) (OD_{none})		14,100.0	100.0	100.0	100.0	14,300.0	14,300.0	100.0	100.0	15,100.0	100.0	100.0	8,900.0	8,900.0	100.0	100.0	100.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		8.1	0.1	0.1	0.1	8.2	8.2	0.1	0.1	8.6	0.1	0.1	5.1	5.1	0.1	0.1	0.1
Post-flood (t_3 to t_4)																	
Start (t_3)	Day (d)	7	4	4	4	7	7	4	4	7	4	4	6	6	4	4	4
	Time (t_c)	09:00	11:00	11:00	11:00	10:00	10:00	11:00	11:00	14:00	11:00	11:00	07:00	07:00	11:00	11:00	11:00
	Tick (t_s)	290	150	150	150	292	292	150	150	300	150	150	238	238	150	150	150
End (t_4)	Day (d)	26	7	26	27	27	27	13	17	26	7	19	13	18	7	9	7
	Time (t_c)	14:03	07:00	12:03	09:03	08:03	13:00	10:00	07:00	10:00	07:00	07:03	11:00	12:00	07:00	07:00	07:00
	Tick (t_s)	1,213	286	1,209	1,251	1,249	1,258	580	766	1,204	286	863	582	824	286	382	286
Durations (ticks)		923.0	136.0	1,059.0	1,101.0	957.0	966.0	430.0	616.0	904.0	136.0	713.0	344.0	586.0	136.0	232.0	136.0
Operational disruption (units) (OD_{post})		28,510.9	7,482.0	35,224.2	35,008.4	28,066.1	27,798.9	15,667.2	18,068.2	26,019.0	7,506.7	13,559.3	13,267.6	19,232.2	7,621.8	11,020.9	7,664.2
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		16.3	4.3	20.2	20.0	16.1	15.9	9.0	10.3	14.9	4.3	7.8	7.6	11.0	4.4	6.3	4.4
Overall operational disruption (units) ($OD_{overall}$)		43,876.5	8,847.3	36,588.9	36,374.1	43,631.3	43,364.3	17,032.4	19,432.7	42,383.4	8,871.4	14,924.1	24,952.5	29,396.9	10,581.2	13,734.8	10,430.1
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		25.1	5.1	20.9	20.8	25.0	24.8	9.7	11.1	24.2	5.1	8.5	14.3	16.8	6.1	7.9	6.0

Table 9.2: Lightly flooded (68) manufacturing SMEs located in Lower Don Valley of Sheffield

9.2.1.1 Simulation Experiment E1 for the Lightly Flooded Manufacturing SMEs

As expected, manufacturing SMEs simulated in E1 yield the greatest $OD_{ABS}^{overall}$ with a value of 25.1%, which is due to the failure to implement any resistance or resilience, and only set-up and maintained an emergency financial reserve as a business continuity/risk management precautionary measures. As shown in Table 9.2, in the pre-flood stage, on day 3 at clock time ($t_c=17:00$) and simulation tick ($t_s=114$), the average production level of the 68 lightly flooded manufacturing SMEs begins dropping gradually for 149 simulation ticks, which in turn result in an OD_{ABS}^{pre} value of 0.7%. Recall that the production level does not correspond explicitly to a particular company, rather, it represents the average production level of 68 lightly flooded manufacturing SMEs. During the flood (non-operation) stage, on day 4 at clock time ($t_c=10:30$) and simulation tick ($t_s=149$), none of the manufacturing SMEs simulated in E1 engaged in production at their respective premises for 141 simulation ticks, which led to a significant OD_{ABS}^{none} value of 8.1%. This is due to the damage occurred to electrical sockets, documents, production machines, raw materials, IT equipment, and products, which were not lifted-up as pre-flood behaviours or raised as precautionary measures. On day 7 at clock time ($t_c=9:00$) and simulation tick ($t_s=290$), all of the lightly flooded manufacturing SMEs began resuming their production levels gradually for 923 simulation ticks until day 26 at clock time ($t_c=14:30$) and simulation tick ($t_s=1213$) at which time all the manufacturing SMEs returned to normal operation (PL = 100%). This caused a great OD_{ABS}^{post} value of 16.3%. During the non-operation and post-flood stages, a set of the appropriate post-flood behaviours (e.g. contacting an electrician to repair power supply and damaged sockets, contacting a plumber to repair damaged pipes, allocating employees to acquire the necessary cleaning equipment in order to clean-up the premises, repairing production machines, contacting an IT specialist to repair associated equipment, reproducing/preparing documents, and contacting suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively) were enacted. These post-flood behaviours can either be enacted simultaneously or sequentially based on the number or production employees available (see Chapter 7, Section 7.1.2).

9.2.1.2 Simulation Experiments E2 (A) to E3 for the Lightly Flooded Manufacturing SMEs

This sub-section presents an analysis of the lightly flooded manufacturing SMEs simulated in five experiments E2 (A), E2 (B), E2 (C), E (D), and E3. Each of these experiments includes a different set of SMEs' resistance precautionary measures. This is to investigate which combination(s) of SMEs' flood-resistance precautionary measures most impact SMEs' immediate response to and short-term recovery from flooding.

For the lightly flooded manufacturing SMEs simulated in E2 (A), they represent the lowest $OD_{ABS}^{overall}$ value of 5.1%. This is because they erected a bund-wall (PM₁) around their premises as a flood-resistance precautionary measure, which was able to provide protection against flooding up to a level of 1.5m (see Chapter 7, Section 7.1.3.1). On day 3 at clock time ($t_c=17:00$) and simulation tick ($t_s=114$), the floodwater reached SMEs' premises (although it did not flood the SMEs' premises due to the bund-wall being erected around SMEs' premises) in which case the employees had to evacuate. This led to a gradual drop in the average production level for 36 simulation ticks, which subsequently caused OD_{ABS}^{pre} at a value of 0.7%. Unsurprisingly, this pre-flood information is exactly the same as the pre-flood information presented in E1. This is because the manufacturing SMEs simulated in both simulation experiments E1 and E2 (A) did not receive EA alerts or warnings, and thus, none of the pre-flood behaviours were enacted (in which case SMEs acted in exactly the same ways). In terms of the non-operation stage, the manufacturing SMEs simulated in E2 (A) were non-operational for only one simulation tick. This led to a very low OD_{ABS}^{none} value of approximately 0.1%. Subsequently, on day 4 at clock time ($t_c=11:00$) and simulation tick ($t_s=150$), some of the lightly flooded manufacturing SMEs simulated in E2 (A) were able to resume their production. However, on day 7 at clock time ($t_c=7:00$) and simulation tick ($t_s=286$), all manufacturing SMEs simulated in E2 (A) were able to return to their normal operation level (PL = 100%), which caused a very low level of OD_{ABS}^{post} at just 4.3%. During the post-flood stage, the lightly flooded SMEs had to contact their suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively.

In terms of simulation experiments E2 (B) and E2 (C), these present similar $OD_{ABS}^{overall}$ values of 20.9% and 20.8%, respectively. The 68 lightly flooded manufacturing SMEs simulated in E2 (B) and E2 (C) were able to secure their doorways by implementing a different combination of all the flood-resistance precautionary measures without alternatives (PM₃, PM₅, PM₆, PM₇, and PM₈) and (PM₄, PM₅, PM₆, PM₇, and PM₈), respectively. However, air-bricks were not covered because EA alerts or warnings were not received, and thus, 60 of the 68 lightly flooded manufacturing SMEs' premises (i.e. those with a floodwater level at any point greater than the location of air-bricks 0.075m (see Chapter 7, Section 7.1.1)) were lightly flooded. This caused damage to production machines, raw materials, paper documents, and IT equipment, which were not lifted-up as pre-flood behaviours or raised as precautionary measures. Thus, the pre-flood and non-operation information (e.g. OD_{ABS}^{pre} and OD_{ABS}^{none}) associated with the lightly flooded manufacturing SMEs in simulation experiments E2 (B) and E2 (C) are exactly the same as those associated with E2 (A) at 0.7% and 0.1%. For the pre-flood stage, this similarity is because the SMEs simulated in E1, E2 (A), E2 (B), and E2 (C) did not receive EA alerts and warnings, and thus, none of the pre-flood behaviours were enacted, enabling the manufacturing SMEs simulated in these simulation experiments to implement none of the pre-flood behaviours, such as covering air-brick and lifting-up IT equipment and paper documents. In terms of the non-operation stage, the similarity between E2 (A), E2 (B), and E2 (C) is due to eight of the 68 manufacturing SMEs simulated in E2 (B) and E2 (C) were not flooded (i.e. the floodwater that reached their premises lower than the location of the air-bricks ($W_d < 0.075$)), and thus, they were able to resume production immediately after the flood had receded, which in turn, affected the overall average of production level of the lightly flooded manufacturing SMEs. On day 4 at clock time ($t_c=11:00$) and simulation tick ($t_s=150$), the post-flood stage began and this lasted for 1059 and 1101 simulation ticks for E2 (B) and E2 (C), respectively. During this stage, the 60 flood-affected manufacturing SMEs simulated in E2 (B) and E2 (C) allocated production employees to contact electricians, plumbers, IT specialists, suppliers, and customers (see Chapter 7, Section 7.1.2). Also, a proportion of production employees were allocated to acquire the necessary cleaning equipment to clean up their respective premises before repairing the affected production machines. However, the eight non-flooded manufacturing SMEs only contacted their suppliers

and customers to inform them of the resumption of raw material dispatch and product delivery, respectively. On day 26 at clock time ($t_c=12:30$) and simulation tick ($t_s=1209$), all manufacturing SMEs simulated in E2 (B) were able to return to their normal operation level, $PL = 100\%$, yielding a OD_{ABS}^{post} value of 20.2%. However, all manufacturing SMEs simulated in E2 (C) returned to normal operation on day 27 at clock time ($t_c=9:30$) and simulation tick ($t_s=1251$), i.e. a total of 1101 simulation ticks, representing a OD_{ABS}^{post} value of 20%.

For simulation experiments E2 (D) and E3, all manufacturing SMEs simulated in these experiments were flooded due to implementing insufficient flood-resistance, resilience, and business continuity/risk management precautionary measures. As presented in Table 9.2, the $OD_{ABS}^{overall}$ values associated with E2 (D) and E3 are 25% and 24.8%, respectively. The manufacturing SMEs simulated in experiment E2 (D), which includes a combination of all the resistance precautionary measures without alternatives (PM₂, PM₅, PM₆, PM₇, and PM₈), did not place sandbags (PM₂) at doorways although sandbags were available. This is because the EA alerts and warnings were not received, and thus, production was carried out up until the moment the flood commenced, which led to a lower level of OD_{ABS}^{pre} at a value of 0.7% (see Table 9.2). The manufacturing SMEs simulated in experiment E3, which involves a combination of some of the resistance precautionary measures (PM₅, PM₆, PM₇, and PM₈), were unable to prevent water ingress at their premises due to not securing the doorways of their premises. As shown in Table 9.2, the SMEs simulated in E1, E2 (D), and E3 present similar pre-flood, non-operation, and post-flood values for OD_{ABS}^{pre} , OD_{ABS}^{none} , and OD_{ABS}^{post} . This is due to all the 68 manufacturing SMEs simulated in these three experiments being flooded with the same level of floodwater in their premises. They were flooded due to implementing inadequate flood-resistance precautionary measures, which would have protected SMEs' premises from floodwater ingress (see Chapter 7, Section 7.1.3.1), or resilience and business continuity/risk management precautionary measures, which would have reduced the flood impacts and speeded up the post-flood recovery processes, respectively.

It is noteworthy that the lightly flooded manufacturing SMEs simulated in E2 (A), which included a bund-wall being erected around SMEs' premises, achieved the lowest $OD_{ABS}^{overall}$ value (5.1%). However, the bund-wall precautionary measure is

structurally and financially costly. Also, an SME's premises must be detached in order to have a bund-wall erected around its premises. Next, the lightly flooded manufacturing SMEs simulated in E2 (B) and E2 (C) yielded lower $OD_{ABS}^{overall}$ values than E3 (i.e. a difference of 3.9% and 4%, respectively). This is because the lightly flooded manufacturing SMEs simulated E2 (B) and E2 (C) were able to secure all the floodwater entry points (with the exception of air-bricks which are only covered when the EA alerts or warnings were received) by implementing different combinations of all the resistance precautionary measures without alternatives, which included flood-proof doors (for SMEs simulated in E2 (B)) and flood barriers (for the same SMEs simulated in E2 (C)) being installed at SME's premises. These two sets of resistance precautionary measures implemented in E2 (B) and E2 (C) were effective at protecting only eight of the 68 manufacturing SMEs, i.e. those with a floodwater level at any point not greater than the location of air-bricks (0.075m above ground level). Therefore, it can be concluded that covering air-bricks is an essential measure to protect SMEs' premises from floodwater ingress, especially, if all other floodwater entry points have been secured. For experiments E2 (D) and E3, SMEs had implemented inadequate combinations of resistance precautionary measures that were unable to prevent floodwater ingress into their premises, and thus all the 68 manufacturing SMEs became lightly flooded. Also, in these experiments, the SMEs did not implement any resilience or business continuity/risk management precautionary measures, which could have reduced the flood damage they incurred.

9.2.1.3 Simulation Experiments E4 to E6 (B) for the Lightly Flooded Manufacturing SMEs

This sub-section presents an analysis of the lightly flooded manufacturing SMEs simulated in five experiments E4, E5 (A), E5 (B), E6 (A), and E6 (B). Each of these experiments (E4, E5 (A), and E5 (B)) included a different set of SME flood-resilience precautionary measures. However, experiments E6 (A) and E6 (B) tested different combinations of the flood-resistance and resilience precautionary measures. This was to investigate which combination of flood precautionary measures implemented by these experiments (E4, E5 (A), E5 (B), E6 (A), and E6 (B)) can be employed to improve manufacturing SMEs' immediate response to and short-term recovery from flood events.

The lightly flooded manufacturing SMEs simulated in E4 implemented all the manufacturing-related resilience precautionary measures (PM_9 , PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , PM_{17} , and PM_{18}) along with PM_{23} as a business continuity/risk management precautionary measure. As shown in Table 9.2, the $OD_{ABS}^{overall}$ values associated with the manufacturing SMEs simulated in E4 is 9.7%, i.e. 15.4% lower than E1, which represents the worst-case scenario among the implemented simulation experiments in which an SME has only set-up and maintained an emergency financial reserve. In terms of the pre-flood stage, the OD_{ABS}^{pre} value associated with E4 is exactly the same as those being associated with E1, E2 (A), E2 (B), E2 (C), E2 (D), and E3. This is because SMEs simulated in these experiments did not register for EA alerts and warnings and thus they did not receive EA alerts or warnings in the pre-flood stage. Subsequently, none of the pre-flood behaviours was enacted. For the non-operation stage, on day 4 at clock time ($t_c=10:30$) and simulation tick ($t_s=149$), none of the manufacturing SMEs simulated in E4 were engaged in production at their respective premises for only one simulation tick. This is because they raised the height of their electrical sockets (PM_{11}), paper documents (PM_{12}), raw materials (PM_{13}), production machines (PM_{15}), IT equipment (PM_{16}), and products (PM_{17}) above the level of the flood reached at these SMEs' premises. Thus, implementing this combination of resilience precautionary measures (PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , and PM_{17}) enabled the lightly flooded manufacturing SMEs simulated in E4 to resume their production 140 simulation ticks earlier than the manufacturing SMEs simulated in E1 and 142 simulation ticks earlier than those simulated in E2 (D) and E3, although they all (E1, E2 (D), E3, and E4) were flooded. In terms of the post-flood stage, production was resumed on the same day (day 4) at clock time ($t_c=11:00$) and simulation tick ($t_s=150$), and subsequently, the SMEs simulated in E4 had to contact electricians and plumbers to carry out the necessary repairs, restore power, and allocate production employees to acquire the necessary cleaning equipment to clean-up their respective premises. Also, these SMEs allocated a proportion of their employees to contact suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively. On day 13 at clock time ($t_c=10:00$) and simulation tick ($t_s=580$), all the manufacturing SMEs simulated in E4 were able to return to the normal operation ($PL=100\%$), yielding a OD_{ABS}^{post} value of 9%.

For simulation experiments E5 (A) and E5 (B), the manufacturing SMEs simulated in these experiments implemented a different combination of some of the resilience precautionary measure (PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , and PM_{17}) and (PM_9 , and PM_{18}) respectively. As shown in Table 9.2, the $OD_{ABS}^{overall}$ values associated with the manufacturing SMEs simulated in E5 (A) and E5 (B) are 11.1% and 24.2% respectively. In terms of the pre-flood stage, the manufacturing SMEs simulated E5 (A) and E5 (B) started being flooded on day 3 at clock time ($t_c=17:00$) and simulation tick ($t_s=114$), causing lower OD_{ABS}^{pre} value of 0.7%. For the non-operation stage, the manufacturing SMEs simulated in E5 (A) were able to maintain a very low $OD_{ABS}^{overall}$ value of 0.1%. This is because SMEs simulated in E5 (A) implemented all the manufacturing-related resilience precautionary measures (e.g. raising consumer boards (PM_{10}), electrical sockets (PM_{11}), documents (PM_{12}), raw materials (PM_{13}), production machines (PM_{15}), IT equipment (PM_{16}), and products (PM_{17}) above the level of the flood reached at SMEs' premises) as in E4. In contrast to E5 (A), simulation experiment E5 (B) presents a greater OD_{ABS}^{none} value of 8.6%. This is due to the damage to electrical sockets, documents, production machines, raw materials, IT equipment, and products, which were not raised. In terms of the post-flood stage, the SMEs simulated in E5 (A) and E5 (B) had to allocate employees to acquire cleaning equipment to allocate a proportion of employees to clean-up their respective premises and contact suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively. However, the manufacturing SMEs simulated in E5 (B) had to enact additional post-flood behaviours, such as contacting an electrician to repair damaged sockets, contacting a plumber to repair damaged pipes, repairing production machines, contacting an IT specialist to repair associated equipment, and reproducing/preparing documents. On day 17 at clock time ($t_c=7:00$) and simulation tick ($t_s=766$), the manufacturing SMEs simulated in E5 (A) regained their normal operation level ($PL=100\%$), with a OD_{ABS}^{post} value of 10.3%, whereas the manufacturing SMEs simulated in E5 (B) returned to normal operation on day 26 at clock time ($t_c=10:00$) and simulation tick ($t_s=1204$) (i.e. 438 simulation ticks later than the manufacturing SMEs simulated in E5 (A)) with a OD_{ABS}^{post} value of 14.9%.

In relation to simulation experiments E6 (A) and E6 (B), the lightly flooded manufacturing SMEs simulated implemented different combinations of all the

resistance and manufacturing-related resilience precautionary measures without alternatives. Specifically, the manufacturing SMEs simulated in E6 (A) erected a bund-wall (PM_1) around their premises whereas the manufacturing SMEs simulated in E6 (B) deployed flood barriers (PM_4) at their doorways as resistant precautionary measures. As shown in Table 9.2, the $OD_{ABS}^{overall}$ values associated with E6 (A) and E6 (B) are 5.1% and 8.5%, respectively. In terms of E6 (A), the manufacturing SMEs achieved the same pre-flood, non-operation, and post-flood values as those simulated in E2 (A). This is due to the erection of a bund-wall around manufacturing SME's premises simulated in E2 and E6 (A), which was able to prevent SMEs' premises from the ingress of floodwater (see Chapter 7, Section 7.1.3.1). For E6 (B), the manufacturing SMEs deployed flood barriers at doorways, but did not cover their air-bricks because the EA alerts or warnings were not received, and thus, 60 of the 68 manufacturing SMEs' premises (i.e. those with a floodwater level at any point greater than the location of the air-bricks 0.075m (see Chapter 7, Section 7.1.1)) were flooded. However, because eight of the 68 manufacturing SMEs simulated in E6 (B) were not flooded, the non-operation stage for the manufacturing SMEs simulated in E6 (B) is minimal, at just 0.1%. In terms of the post-flood stage, the manufacturing SMEs simulated in E6 (B) had to contact electricians and plumbers to carry out the necessary repairs, restore power, acquire the necessary cleaning tools, allocate employees to clean-up SMEs' premises, and contact suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively. The post-flood behaviours enacted by the manufacturing SMEs simulated in E6 (B) are similar to the post-flood behaviours enacted by SMEs simulated in E4. However, all the 68 SMEs simulated in E4 were flooded because they did not secure their doorways, which was not the case in the manufacturing SMEs simulated in E6 (B). Subsequently, the OD_{ABS}^{post} value of the SMEs simulated in E6 (B) is 7.8%, i.e. 1.2% lower than the same SMEs simulated in E4.

It is noteworthy that the lightly flooded manufacturing SMEs simulated in E4 yielded a lower $OD_{ABS}^{overall}$ value of 9.7% (i.e. $11.1 - 9.7 = 1.4\%$ lower than the same SMEs simulated in E5 (A) and $24.2 - 9.7 = 14.5\%$ lower than E5 (B)). This is because the manufacturing SMEs simulated in E4 implemented all the manufacturing flood-resilience precautionary measures, which included raising the location of production machines (PM_{14}) and raw materials (PM_{12}) to the height of 0.5m and 1.5m,

respectively (see Chapter 7, Section 7.1.3.1.2). Thus, these SMEs were able to resume production immediately after cleaning-up floodwater from their premises. However, the same SMEs simulated in E5 (A) and E5 (B) implemented only some of the manufacturing flood-resilience precautionary measures; these were insufficient to allow them to resume their production as early as the same SMEs simulated in E4.

In terms of E6 (A), the manufacturing SMEs simulated achieved a lower $OD_{ABS}^{overall}$ value than the same SMEs simulated in E4, (i.e. $9.7 - 5.1 = 4.6\%$). This is because the SMEs simulated in E6 (A) had erected a bund-wall (PM1) around their premises as a flood-resistance precautionary measure; this provided protection against flooding up to a level of 1.5m (see Chapter 7, Section 7.1.3.1). However, as mentioned previously, the bund-wall precautionary measure is restricted to SMEs with detached premises and it is also a structurally and financial costly option.

The SMEs simulated in E6 (B) achieved a higher $OD_{ABS}^{overall}$ value than the same SMEs simulated in E6 (A) (i.e. $8.5 - 5.1 = 3.4\%$ greater than E6 (A)). This is because the combination of the flood-resistance and resilience precautionary measures implemented in E6 (B) were inadequate to protect SMEs' premises from floodwater ingress although these measures included flood barriers being installed at SMEs' doorways. However, air-bricks were not covered because EA alerts and warnings were not received, and thus, 60 of the 68 lightly flooded manufacturing SMEs' premises (i.e. those with a floodwater level at any point greater than the location of air-bricks 0.075m) became flooded. The combination of precautionary measures implemented in E6 (B) enabled these SMEs to achieve lower $OD_{ABS}^{overall}$ values than the same SMEs simulated in E4 (i.e. a difference of 0.8%). This is because in E4 all the 68 manufacturing SMEs became flooded, which was not the case in E6 (B).

9.2.1.4 Simulation Experiments E7 to E11 for the Lightly Flooded Manufacturing SMEs

This sub-section investigates and discusses five simulation experiments E7, E8, E9, E10, and E11. Each of these experiments implemented different combinations of precautionary measures. This is to investigate which combination of flood precautionary measures can be employed to improve manufacturing SMEs' immediate response to and short-term recovery from flood events.

For the manufacturing SMEs simulated in E7 and E8, they implemented a different combination of the business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}) and (PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}), respectively. As indicated in Table 9.2, the $OD_{ABS}^{overall}$ values associated with E7 and E8 are 14.3% and 16.8% respectively. For simulation experiment E7, on day 2 at clock time ($t_c=8:30$) and simulation tick ($t_s=49$), the manufacturing SMEs received and acted on EA alerts and warnings, which, in turn, enabled them to allocate production employees to lift-up raw materials, products, documents, and IT equipment. However, production machines were not lifted-up due to their weight, and these machines were consequently damaged by floodwater (see Chapter 7, Section 7.1.1). Subsequently, enacting these pre-flood behaviours, which halted the production, led SMEs to achieve greater OD_{ABS}^{pre} value of 1.6% (i.e. 0.9% greater than E1). On day 4 at clock time ($t_c=10:30$) and simulation tick ($t_s=149$), the SMEs simulated in E7 were not able to engage in production for 89 simulation ticks until day 6 at clock time ($t_c=7:00$) and simulation tick ($t_s=238$). This is due to the damage to their production machines, which were not lifted-up in the pre-flood stage due to their heavy weight. However, because of the availability of an electricity generator, the SMEs simulated in E7 were able to allocate production employees to repair the damaged machines earlier than the manufacturing SMEs simulated in E1, which had to restore the power in order to carry out machine repairs (see Chapter 7, Section 7.1.2). Before returning to the normal operation, the SMEs simulated in E7 had to clean-up their premises and return the paper documents, products, and IT equipment that had been lifted-up (to protect them from damage) to their normal locations. These post-flood behaviours were enacted during the non-operation and post-flood stages while the production level was 0% and was not resumed yet. Recall that the non-operation stage may overlap with the post-flood stage and this only occurs once the production level is 0% and it cannot be resumed immediately after the flood receded from an SME's premises. This led to greater OD_{ABS}^{none} and OD_{ABS}^{post} values of 5.1% and 7.6%, respectively.

For simulation experiment E8, Table 9.2 shows that the manufacturing SMEs simulated in E8 present the same pre-flood information as those in E1 to E6 (B) where OD_{ABS}^{pre} value is 0.7%. This is because SMEs simulated in these simulation experiments did not register for EA alerts and warnings and thus they did not receive them in the

pre-flood stage. Subsequently, none of the pre-flood behaviours was enacted. In relation to the non-operation stage, on day 4 at clock time ($t_c=10:30$) and simulation tick ($t_s=149$), none of the manufacturing SMEs simulated in E8 engaged in production at their respective premises for 89 simulation ticks, which led to a great OD_{ABS}^{none} value of 5.1%. This is due to the damage to electrical sockets, documents, production machines, raw materials, IT equipment, and products, which were not lifted-up as pre-flood behaviours or raised as precautionary measures. However, SMEs simulated in E8 were able to resume their production quicker than E1, which had the same level of damage. This is because SMEs simulated in E8 maintained and used electricity generators (PM_{27}), which enabled them to enact post-flood behaviours quicker than those without electricity (see Chapter 7, Section 7.1.2). In terms of the post-flood stage, the SMEs simulated in E8 had to contact electricians and plumbers to carry out the necessary repairs, clean-up their premises, reproduce documents, contact IT specialists, supervise IT repairs, setting-up IT equipment, and restore IT data (see Chapter 7, Section 7.1.2). This is because the manufacturing SMEs simulated in E8 did not receive EA alerts or warnings, and thus, they did not lift-up documents, IT equipment, raw materials, which were consequently flooded. However, the SMEs simulated in E8 had an electricity generator (PM_{27}) available at their premises, which enabled them to restore the post-flood behaviours 26 hours before the same SMEs simulated in E1. They also had their IT data backed-up (PM_{28}) as a business continuity/risk management precautionary measure. In addition to these, they maintained and displayed an emergency flood plan (PM_{29} and PM_{30}), which enabled them to enact some of the pre- and post-flood behaviours in shorter times (see Chapter 7, Section 7.1.3.2). These precautionary measures (PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}) enabled the SMEs simulated in E8 to achieve a $OD_{ABS}^{overall}$ value of 16.8% (i.e. 9% lower than the same SMEs simulated in E1). On day 18 at clock time ($t_c=12:00$) and simulation tick ($t_s=824$), the SMEs simulated in E8 returned to normal operation ($PL=100\%$), yielding a OD_{ABS}^{post} value of 11%.

Simulation experiment E9 involved a combination of all (i) the flood-resistance precautionary measures without alternatives (PM_2 , PM_5 , PM_6 , PM_7 , and PM_8) and (ii) business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}). On day 2 at clock time ($t_c=8:30$) and simulation tick ($t_s=49$), the manufacturing SMEs simulated in E9

received and acted on EA alerts, which enabled them to allocate production employees to: (i) place sandbags at doorways (provided that sandbags are available at SMEs premises), and (ii) contact suppliers and customers to inform them of the suspension of raw material dispatch and product delivery, respectively. The manufacturing SMEs simulated in E9 achieved a relatively greater $OD_{ABS}^{overall}$ value of 6.1% because they enacted the pre-flood behaviours detailed above.

Simulation experiment E10 involves *all* the manufacturing-related resilience precautionary measures ($PM_9, PM_{10}, PM_{11}, PM_{12}, PM_{13}, PM_{15}, PM_{16}, PM_{17}$, and PM_{18}) with a combination of *all* the business continuity/risk management precautionary measures without alternatives ($PM_{19}, PM_{20}, PM_{23}, PM_{27}, PM_{28}, PM_{29}, PM_{30}$, and PM_{31}) to provide flood protection to manufacturing SMEs. As shown in Table 9.2, the $OD_{ABS}^{overall}$ value associated with the manufacturing SMEs simulated in E10 is 7.9%. Similarly to E7 and E9, on day 2 at clock time ($t_c=8:30$) and simulation tick ($t_s=49$), the manufacturing SMEs simulated in E10 received and acted on EA alerts which enabled them to allocate production employees to cut-off electricity, and contact suppliers and customers to inform them of the suspension of raw material dispatch and product delivery, respectively. In contrast to E7, the manufacturing SMEs simulated in E10 did not need to lift-up raw materials, products, documents, and IT equipment because they had already been raised as precautionary measures. Also, the manufacturing SMEs simulated in E10 did not need to place sandbags at doorways because sandbags were not available on these SMEs' premises as a precautionary measure. Therefore, due to enacting these pre-flood behaviours (cut-off electricity, contact suppliers and customers), the manufacturing SMEs simulated in E10 yielded a OD_{ABS}^{pre} value of 1.5% (i.e. 0.1% less than E7 and E9, which also received EA alerts, but they, additionally, had to lift-up raw materials, products, documents, and IT equipment on desks, which was not the case in the same SMEs simulated in E10 (see Chapter 7, Section 7.1.1)). On day 4 at clock time ($t_c=10:30$) and simulation tick ($t_s=149$), the manufacturing SMEs simulated in E10 were unable to engage in production for only one simulation tick. This is because SMEs' documents, IT equipment, production machines, raw materials, and products were raised as precautionary measures and thus they were not flooded. Subsequently, on the same day (day 4) at clock time ($t_c=11:00$) and simulation tick ($t_s=150$), the manufacturing SMEs simulated in E10 allocated production employees to acquire the necessary

cleaning equipment in order to clean-up their respective premises. Furthermore, production employees were allocated to contact their suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively. On day 9 at clock time ($t_c=7:00$) and simulation tick ($t_s=382$), the manufacturing SMEs simulated in E10 returned to the normal operation ($PL=100\%$), yielding a OD_{ABS}^{post} value of 6.3%.

In terms of simulation experiment E11, these SMEs implemented a combination of *all* (i) the resistance precautionary measures without alternatives (PM_1 , PM_5 , PM_6 , PM_7 , and PM_8), (ii) resilience precautionary measures (PM_9 , PM_{10} , PM_{11} , PM_{12} , PM_{13} , PM_{15} , PM_{16} , PM_{17} , and PM_{18}), and (iii) business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}). As shown in Table 9.2, the $OD_{ABS}^{overall}$ value associated with the manufacturing SMEs simulated in E11 is 6% (i.e. 0.9% greater than SMEs simulated E2 (A) and E6 (A), which also had bund-wall erected around SMEs' premises). This is because SMEs simulated in E11 had received EA alerts and warnings, which enabled them to enact more pre-flood behaviours, such as contacting suppliers and customers to inform them of the suspension of raw material dispatch and product delivery, respectively, which was not the case in E2 (A) and E6 (A).

It is noteworthy that the $OD_{ABS}^{overall}$ value achieved by the manufacturing SMEs simulated in E7 is lower than the $OD_{ABS}^{overall}$ value associated with the same SMEs simulated in E8 (i.e. $16.8 - 14.3 = 2.5\%$). This is because SMEs simulated in E7 received and acted on EA alerts and warnings, which, in turn, enabled them to allocate production employees to lift-up raw materials, products, documents, and IT equipment. This demonstrates that receiving EA alerts or warnings improved manufacturing SMEs' production level by 2.5%.

9.2.1.5 Statistical Analysis for the Lightly Flooded Manufacturing SMEs

Two statistical analysis tests (Shapiro-Wilk and Mann-Whitney U tests) were used (see Chapter 8, Section 8.2.2). First, the Shapiro-Wilk test determined whether the simulation experiment's output data (production level of the 68 lightly flooded manufacturing in which each of them underwent 10 simulation runs) selected are normally distributed. Following this, the Mann-Whitney U test was used to compare

the differences between every two simulation experiments to determine whether they differed significantly from one another. The two statistical analysis tests (Shapiro-Wilk and Mann–Whitney U tests) were performed at one simulation tick during the agent-based simulation for each experiment, namely in the short-term recovery stage at $t_s = 389$ ticks. This simulation tick was selected where the production level values of most the experiments were inconstant. However, according to the experiment's output data, it is impossible that all the experiments (E1 – E11) had inconstant production level values at any given simulation tick. This is because simulation experiments E2, E6 (A), E9, E10, and E11 always return to a state of normal operation (PL=100%) while simulation experiments E1, E2 (C), E2 (D), E3, E5 (B) are remain in the non-operational stage (PL = 0%). Please note that the simulation experiment's (E1 – E11) output data (production levels) for all the 68 lightly flooded manufacturing SMEs, which each had 10 simulation runs, is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

In relation to the Shapiro-Wilk test, the results show that the production level sample selected from each simulation experiment (E1 – E11) is not normally distributed. Thus, the Mann–Whitney U test (see Chapter 8, Section 8.2.2) was applied to the same sample of production level selected from each simulation experiment (E1 – E11). This is to test the differences between each pair of experiments and determine whether they are significantly different or not. As indicated in Table 9.3, the p-values of the insignificant pair of experiments are highlighted in red.

	E2 (A)	E2 (B)	E2 (C)	E2 (D)	E3	E4	E5 (A)	E5 (B)	E6 (A)	E6 (B)	E7	E8	E9	E10	E11
E1	<0.0003	<0.0001	<0.0009	0.9046	0.1790	<0.0001	<0.0003	0.0660	<0.0003	<0.000	<0.0002	<0.0001	<0.0003	<0.0003	<0.0003
E2 (A)		<0.0009	<0.0001	<0.0001	<0.0001	<0.0006	<0.0003	<0.0006	1	<0.0001	<0.0006	<0.0002	1	1	1
E2 (B)			0.8114	<0.0001	<0.0003	<0.0004	<0.0001	<0.0005	<0.0009	<0.0001	<0.0003	<0.0001	<0.0009	<0.0009	<0.0009
E2 (C)				<0.0001	<0.0003	<0.0004	<0.0002	<0.0007	<0.0001	<0.0001	<0.0003	<0.0009	<0.0001	<0.0001	<0.0001
E2 (D)					0.2163	<0.0004	<0.0004	0.0902	<0.0001	<0.0001	<0.0002	<0.0004	<0.0001	<0.0001	<0.0001
E3						<0.0003	<0.0002	0.6573	<0.0001	<0.0001	<0.0009	<0.0003	<0.0001	<0.0001	<0.0001
E4							<0.0002	<0.0004	<0.0006	0.0043	<0.0001	<0.0001	<0.0006	<0.0006	<0.0006
E5 (A)								<0.0003	<0.0003	<0.0002	0.0021	<0.0001	<0.0003	<0.0003	<0.0003
E5 (B)									<0.0006	<0.0006	<0.0002	<0.0002	<0.0006	<0.0006	<0.0006
E6 (A)										<0.0001	<0.0006	<0.000	1	1	1
E6 (B)											<0.0003	<0.0002	<0.0001	<0.0001	<0.0001
E7												<0.0001	<0.0006	<0.0006	<0.0006
E8													<0.0002	<0.0002	<0.0008
E9														1	1
E10															1

Table 9.3: The results of Mann–Whitney U test applied to the lightly flooded (68) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11

At the simulation tick considered in the short-term recovery stage for the lightly flooded manufacturing SMEs ($t_s = 389$ ticks), the Mann–Whitney U test shows that the production level samples tested are not significantly different between experiments E1 and E2 (D) (p-value 0.9046), E1 and E3 (p-value 0.1790), E1 and E5 (B) (p-value 0.0660). Similarly, at this point in the short-term recovery stage, this is also the case when comparing experiments E2 (D) and E3 (p-value 0.2163), E2 (D) and E5 (B) (p-value 0.0902), and E3 and E5 (B) (p-value 0.6573). This is because the combinations of the precautionary measures implemented in these experiments (E1, E2 (D), E3, and E5 (B)) were unable to prevent the floodwater ingress at SMEs premises and thus all SMEs' premises were inundated by floodwater. Subsequently, these SMEs' documents, production machines, products, and raw materials became damaged by floodwater.

For simulation experiments E2 (B) and E2 (C), they are not significantly different (p-value 0.8114). This is because the precautionary measures implemented in both experiments were able to protect only eight SMEs' premises (those with a floodwater level at any point not greater than the above-ground height of air-bricks 0.075m) of the 68 lightly flooded manufacturing SMEs' premises. However, the remainder (the 60 manufacturing SMEs) were lightly flooded and thus all their documents, production machines, products, and raw materials became flood damaged.

In relation to simulation experiments E2 (A), E6 (B), E9, E10, and E11, the production-level samples, which were selected from each of them, are not significantly different between experiments E2 (A) and E6 (B) (p-value 1), E2 (A) and E9 (p-value 1), E2 (A) and E10 (p-value 1), and E2 (A) and E11 (p-value 1). This is also the case when comparing experiments E6 (B) and E9 (p-value 1), E6 (B) and E10 (p-value 1), E6 (B) and E11 (p-value 1), E9 and E10 (p-value 1), E9 and E11 (p-value 1), and E10 and E11 (p-value 1). It can be seen that the p-value associated with each pair of these experiments is one (1). This is because all the manufacturing SMEs simulated in these experiments returned to normal operation (PL=100%) before the selected simulation tick ($t_s = 389$ ticks). However, all these simulation experiments (with the exception of E10) implemented sufficient combinations of flood-resistance precautionary measures, which in turn, enabled them to protect SMEs' premises from floodwater. For simulation experiment E10, although the manufacturing SMEs simulated in this experiment were flooded, no damage occurred. This is because they had raised their

IT equipment, documents, production machines, raw materials, products, consumer boards, and sockets above the flood level as resilience precautionary measures. They also had electricity generators, which enabled them to resume production immediately after cleaning-up their premises (see Chapter 7, Section 7.1.2).

9.2.2 Moderately Flooded Manufacturing SMEs

The moderately flooded manufacturing SMEs experienced a level of floodwater greater than or equal to 0.3m but less than or equal to 0.9m. This height of floodwater causes greater damage to the manufacturing SMEs' production machines, IT equipment, and paper documents than the lightly flooded manufacturing SMEs (see Chapter 7, Section 7.1.2). Also, it prolongs the time required to clean-up SMEs' premises. Therefore, as shown in Figure 9.2, the moderately flooded manufacturing SMEs always present greater $OD_{ABS}^{overall}$ values than the lightly flooded manufacturing SMEs. For more details, Table 9.4 presents the pre-flood, flood (non-operation), and post-flood information, which includes OD_{ABS}^{pre} , OD_{ABS}^{none} , and OD_{ABS}^{post} as well as the duration of each stage.

Please note that the cumulative average of production-level data of the 115 moderately flooded manufacturing SMEs used in equations (8.2), (8.8), (8.10), and (8.12) to (8.15) to compute the values presented in Table 9.4 is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
		A	B	C	D				A	B	A	B					
Pre-flood (t_1 to t_2)																	
Start (t_1)	Day (d)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0
	Time (t_c)	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	08:30	16:30	08:30	08:30	08:30
	Tick (t_s)	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0	49.0	113.0	49.0	49.0	49.0
End (t_2)	Day (d)	4.0	4.0	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00
	Tick (t_s)	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0
Durations (ticks)		36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	100.0	36.0	100.0	100.0	100.0
Pre-flood operational disruption (units) (OD_{pre})		1,893.9	1,893.8	1,895.0	1,894.3	1,894.1	1,894.7	1,893.7	1,894.6	1,894.5	1,894.1	1,894.3	3,258.6	1,895.0	3,300.4	3,123.9	3,152.3
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.9	1.1	1.9	1.8	1.8
non-operation (t_2 to t_3)																	
Start (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00	10:00
	Tick (t_s)	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0
End (t_3)	Day (d)	7.0	4.0	7.0	7.0	7.0	7.0	4.0	4.0	7.0	4.0	4.0	6.0	6.0	6.0	4.0	4.0
	Time (t_c)	11:00	16:00	08:00	11:30	07:00	13:00	16:00	16:00	11:30	16:00	16:00	07:00	07:00	07:00	16:00	16:00
	Tick (t_s)	294.0	160.0	288.0	295.0	286.0	298.0	160.0	160.0	295.0	160.0	160.0	238.0	238.0	238.0	160.0	160.0
Durations (ticks)		146.0	12.0	140.0	147.0	138.0	150.0	12.0	12.0	147.0	12.0	12.0	90.0	90.0	90.0	12.0	12.0
Non-operation operational disruption (units) (OD_{none})		14,600.0	1,200.0	14,000.0	14,700.0	13,800.0	15,000.0	1,200.0	1,200.0	14,700.0	1,200.0	1,200.0	9,000.0	9,000.0	9,000.0	1,200.0	1,200.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		8.4	0.7	8.0	8.4	7.9	8.6	0.7	0.7	8.4	0.7	0.7	5.1	5.1	5.1	0.7	0.7
Post-flood (t_3 to t_4)																	
Start (t_3)	Day (d)	7.0	4.0	7.0	7.0	7.0	7.0	4.0	4.0	7.0	4.0	4.0	6.0	6.0	6.0	4.0	4.0
	Time (t_c)	11:00	16:00	08:00	11:30	07:00	13:00	16:00	16:00	11:30	16:00	16:00	07:00	07:00	07:00	16:00	16:00
	Tick (t_s)	294.0	160.0	288.0	295.0	286.0	298.0	160.0	160.0	295.0	160.0	160.0	238.0	238.0	238.0	160.0	160.0
End (t_4)	Day (d)	31.0	7.0	32.0	31.0	32.0	32.0	16.0	18.0	30.0	7.0	19.0	17.0	22.0	18.0	18.0	7.0
	Time (t_c)	14:00	07:00	09:30	16:30	10:00	07:00	14:30	10:30	13:30	07:00	07:30	12:00	15:30	07:30	07:30	07:00
	Tick (t_s)	1,452.0	286.0	1,491.0	1,457.0	1,492.0	1,486.0	733.0	821.0	1,403.0	286.0	863.0	776.0	1,023.0	815.0	815.0	286.0
Durations (ticks)		1,158.0	126.0	1,203.0	1,162.0	1,206.0	1,188.0	573.0	661.0	1,108.0	126.0	703.0	538.0	785.0	577.0	655.0	126.0
Operational disruption (units) (OD_{post})		36,086.9	7,316.6	37,194.7	35,643.8	37,085.7	35,753.2	21,344.3	24,259.7	33,417.4	7,474.0	21,399.6	17,144.2	27,352.8	17,533.2	14,396.5	7,633.9
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		20.6	4.2	21.3	20.4	21.2	20.5	12.2	13.9	19.1	4.3	12.2	9.8	15.6	10.0	8.2	4.4
Overall operational disruption (units) ($OD_{overall}$)		52,580.8	10,410.5	53,089.6	52,238.2	52,779.8	52,647.9	24,437.9	27,354.3	50,011.9	10,568.1	24,493.9	29,402.8	38,247.8	29,833.5	18,720.5	11,986.3
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		30.1	6.0	30.4	29.9	30.2	30.1	14.0	15.6	28.6	6.0	14.0	16.8	21.9	17.1	10.7	6.9

Table 9.4: Simulation data for the moderately flooded (115) manufacturing SMEs located in Lower Don Valley of Sheffield

The moderately flooded manufacturing SMEs simulated in E1 achieved a greater $OD_{ABS}^{overall}$ value of 30.1%, i.e. 5% greater than the lightly flooded manufacturing SMEs simulated in the same experiment (see Table 9.4). This is because the level of floodwater reached in the moderately flooded manufacturing SMEs' premises caused greater damage to production machines, IT equipment, and paper documents (see Chapter 7, Section 7.1.2). This higher level of floodwater also prolongs the time required to clean-up these SMEs' premises. This sub-section focuses on investigating the moderately flooded SMEs that achieved $OD_{ABS}^{overall}$ values greater than 5% for the corresponding lightly flooded manufacturing SMEs as in E2 (B), E2 (C), E6 (B), and E9.

In relation to simulation experiments E2 (B), E2 (C), and E6 (B), all the 115 moderately flooded manufacturing SMEs simulated in these experiments were flooded whereas 60 of the 68 lightly flooded manufacturing SMEs simulated in the same simulation experiments were flooded. This is because the floodwater level associated with all these 115 moderately flooded manufacturing SMEs exceeded the location of the airbricks, which was not the case in the lightly flooded manufacturing SMEs. Recall that airbricks taken as being at least 0.075m above ground level (see Chapter 7, Section 7.1.1). Thus, the moderately flooded manufacturing SMEs simulated in E2 (B), E2 (C), and E6 (B) achieved greater $OD_{ABS}^{overall}$ values of 30.4%, 29.9%, and 14%, respectively (i.e. 9.5%, 9.1%, and 5.5% greater than the lightly flooded manufacturing SMEs simulated in the same experiment respectively). Therefore, it can be concluded that covering air-bricks is an essential measure to protect SMEs' premises from floodwater ingress (i.e. only if all other floodwater entry points have been secured).

In relation to simulation experiment E9, the moderately flooded manufacturing SMEs simulated achieved a greater $OD_{ABS}^{overall}$ value of 17.1% (i.e. 11% greater than the corresponding lightly flooded manufacturing SMEs). This is because the floodwater level associated with the moderately flooded manufacturing SMEs exceeded the height of the sandbags placed at doorways (0.3m, see Chapter 7, Section 7.1.2), which caused damage to the lifted-up raw materials, products, paper documents, and IT equipment at only 19 of the 115 moderately flooded manufacturing SMEs (i.e. those with a floodwater level at any point greater than the height of the lifted-up resources (0.72m, see Chapter 7, Section 7.1.1)). However, this was not the

case for the lightly flooded manufacturing SMEs: all of them experienced a floodwater level less than 0.3m (i.e. lower than the location of the lifted-up raw materials, products, paper documents, and IT equipment). Therefore, it can be concluded that any flood-resistance precautionary measure, such as sandbags or flood-barriers, which provide a protection level of less than 0.9m is not effective for *all* the moderately flooded manufacturing SMEs.

As presented in Table 9.4, the moderately flooded manufacturing SMEs that implemented a combination of *all* the flood-resistance precautionary measures by erecting bund-walls around their premises were able to achieve the lowest $OD_{ABS}^{overall}$ values of 6% as in E2 (A) and E6 (A) and 6.9% as in E11. In contrast with the lightly flooded manufacturing SMEs, the moderately flooded manufacturing SMEs that implemented a combination of *all* the manufacturing-related resilience precautionary measures along with a combination of *all* the business continuity/risk management precautionary measures were able to achieve lower $OD_{ABS}^{overall}$ values of 10.7% as in E10.

In relation to the statistical analysis tests, in order to determine if the simulation experiments output data (production levels of 115 manufacturing SMEs each had 10 simulation runs) are normally distributed or not, the Shapiro-Wilk test was carried out at one simulation tick during the agent-based simulation for each experiment, namely in the short-term recovery stage at $t_s = 466$ ticks (see Chapter 8, Section 8.2.2). This simulation tick was selected where the production level values of most the experiments were inconstant. Please note that the simulation experiments (E1 – E11) output data (production levels) for the 115 moderately flooded manufacturing SMEs, which each had 10 simulation runs, is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

The Shapiro-Wilk test result shows that the production level samples selected from each simulation experiment (E1-E11) are not normally distributed. Subsequently, the Mann–Whitney U test (see Chapter 8, Section 8.2.2) was applied to the same samples of production levels selected from each simulation experiment. This is to test the differences between each pair of experiments and determine whether they are significantly different. As indicated in Table 9.5, the p-values of the insignificant pair of experiments are highlighted in red.

	E2 (A)	E2 (B)	E2 (C)	E2 (D)	E3	E4	E5 (A)	E5 (B)	E6 (A)	E6 (B)	E7	E8	E9	E10	E11
E1	<0.0007	0.3938	0.3005	0.1931	0.6504	<0.0002	<0.0002	<0.0001	0.0000	<0.0004	<0.0004	<0.0001	<0.0002	<0.0004	<0.0005
E2 (A)		<0.0006	<0.0006	<0.0005	<0.0002	<0.0001	<0.0001	<0.0008	1	<0.0001	<0.0003	<0.0007	<0.0001	<0.0006	1
E2 (B)			0.0619	0.0315	0.1959	<0.0002	<0.0007	<0.0002	<0.0002	<0.0003	<0.0001	<0.0002	<0.0004	<0.0001	<0.0003
E2 (C)				0.7978	0.5482	<0.0004	<0.0004	<0.0001	<0.0005	<0.0003	<0.0007	<0.0001	<0.0003	<0.0003	<0.0008
E2 (D)					0.3996	<0.0001	<0.0002	<0.0002	<0.0008	<0.0002	<0.0001	<0.0001	<0.0008	<0.0002	<0.0002
E3						<0.0006	<0.0005	<0.0002	<0.0008	<0.0001	<0.0004	<0.0009	<0.0002	<0.0002	<0.0003
E4							<0.0002	<0.0001	0.0000	0.7144	<0.0001	<0.0002	<0.0001	<0.0003	<0.0001
E5 (A)								<0.0004	0.0000	<0.0001	0.6689	<0.0002	0.6027	<0.0004	<0.0001
E5 (B)									<0.0002	<0.0006	<0.0001	<0.0002	<0.0003	<0.0004	<0.0007
E6 (A)										<0.000	<0.0003	<0.0008	<0.0001	<0.0006	1
E6 (B)											<0.0002	<0.0001	<0.0003	<0.0001	<0.0001
E7												<0.0009	0.3326	<0.0003	<0.0004
E8													<0.0001	<0.0003	<0.0001
E9														<0.0003	<0.0001
E10															<0.0006

Table 9.5: The results of Mann–Whitney U test applied to the moderately flooded (115) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11

In contrast to the lightly flooded manufacturing SMEs, as indicated in Table 9.5, the Mann–Whitney U test shows that the production level samples are not significantly different between experiments E1 and E2 (B) (p-value 0.3938), E1 and E2 (C) (p-value 0.3005), and E2 (B) and E2 (C) (p-value 0.0619). This is because all the 115 manufacturing SMEs simulated in E2 (B) and E2 (C) experienced a floodwater level greater than or equal to 0.3m but less than or equal to 0.9m, which was greater than the above-ground height of the air-bricks, and thus, all the 115 manufacturing SMEs became moderately flooded. However, this was not the case in the 68 lightly flooded manufacturing SMEs: eight of them were not flooded because they experienced a floodwater level lower than the above-ground height of the air-bricks ($w_d < 0.075 \text{ m}$).

For the moderately flooded manufacturing SMEs, experiments E4 and E6 (B) do not show statistically significant differences (p-value 0.7144). The manufacturing SMEs simulated in these experiments implemented all the flood-resistance precautionary measures. However, their premises were inundated due to not covering air-bricks. It is acknowledged that the manufacturing SMEs simulated in E6 (B) implemented all the resistance precautionary measures without alternatives, which included flood barriers being installed at doorways to protect SMEs' premises from floodwater ingress. However, this combination of precautionary measures was ineffective while the air-bricks were not covered.

In contrast to the lightly flooded manufacturing SMEs, there are significant differences between experiments E5 (A) and E7 (p-value 0.6689), E5 (A) and E9 (p-value 0.6027), and E7 and E9 (p-value 0.3326). This is because all the 115 manufacturing SMEs simulated in E5 (A) implemented all the manufacturing resilience precautionary measures (raising consumer boards, raising electrical sockets, raising the height at which documents are stored, raising the location at which raw materials are stored, raising the location at which production machines are placed, raising the location at which IT equipment is placed, and raising the location at which products are stored) whereas the same manufacturing SMEs simulated in E7 and E9 received and acted on EA alerts and warnings, which, in turn, enabled them to allocate production employees to lift-up raw materials, products, documents, and IT equipment. However, while production machines, sockets, and consumer boards were not raised in the manufacturing SMEs simulated in E7 and E9, it is realised that raising them did not make a significant difference to the flood damage caused. It is acknowledged that the manufacturing SMEs simulated in E9 had covered air-bricks and placed sandbags at doorways to protect their premises from floodwater ingress. However, the level of floodwater reached in their premises exceeded the protection level of sandbags (0.3m) and thus all the 115 manufacturing SMEs' premises became moderately flooded.

9.2.3 Severely Flooded Manufacturing SMEs

The severely flooded manufacturing SMEs have experienced a level of floodwater greater than 0.9m. This height of floodwater causes greater damage to SMEs' production machines, IT equipment, and paper documents than the lightly and moderately flooded manufacturing SMEs (see Chapter 7, Section 7.1.2). Also, it extends the time required to clean-up SMEs' premises. Therefore, the severely flooded manufacturing SMEs always present greater $OD_{ABS}^{overall}$ values than the lightly and moderately flooded manufacturing SMEs due to this higher level of floodwater inundating their premises (e.g. $W_d > 0.9$ m). For example, the severely flooded SMEs simulated in E4 yielded a $OD_{ABS}^{overall}$ value of 23.2%, (i.e. 13.5% and 9.2% greater than the lightly and moderately flooded SMEs simulated in the same experiment, respectively (see Table 9.6)). This sub-section investigates the severely flooded SMEs

that achieved $OD_{ABS}^{overall}$ values greater than 13% for the corresponding lightly flooded manufacturing SMEs as E4, E5 (A), E6 (B), and E10.

Please note that the cumulative average of production level data of the 73 severely flooded manufacturing SMEs used in equation (8.2), (8.8), (8.10), and (8.12) to (8.15) to compute the values presented in Table 9.6 is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t_1 to t_2)																	
Start (t_1)	Day (d)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0
	Time (t_c)	15:30	15:30	15:30	15:30	15:30	15:30	15:30	15:30	15:30	15:30	15:30	08:30	15:30	08:30	08:30	08:30
	Tick (t_s)	111.0	111.0	111.0	111.0	111.0	111.0	111.0	111.0	111.0	111.0	111.0	49.0	111.0	49.0	49.0	49.0
End (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30
	Tick (t_s)	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0
Durations (ticks)		37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	99.0	37.0	99.0	99.0	99.0
Pre-flood operational disruption (units) (OD_{pre})		1,654.5	1,654.3	1,655.0	1,654.2	1,654.5	1,653.9	1,654.3	1,654.7	1,654.2	1,654.1	1,654.9	3,043.2	1,655.0	3,118.7	2,916.5	3,125.8
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.7	0.9	1.8	1.7	1.8
Non-operation (t_2 to t_3)																	
Start (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30	09:30
	Tick (t_s)	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0	147.0
End (t_3)	Day (d)	7.0	5.0	7.0	8.0	7.0	7.0	7.0	6.0	7.0	5.0	6.0	7.0	7.0	6.0	5.0	5.0
	Time (t_c)	14:30	07:00	07:00	07:00	15:00	09:30	07:00	15:30	12:00	07:00	13:00	07:00	07:00	07:00	07:30	07:00
	Tick (t_s)	301.0	190.0	286.0	334.0	302.0	291.0	286.0	255.0	296.0	190.0	250.0	286.0	286.0	238.0	191.0	190.0
Durations (ticks)		154.0	43.0	139.0	187.0	155.0	144.0	139.0	108.0	149.0	43.0	103.0	139.0	139.0	91.0	44.0	43.0
Non-operation operational disruption (units) (OD_{none})		15,400.0	4,300.0	13,900.0	18,700.0	15,500.0	14,400.0	13,900.0	10,800.0	14,900.0	4,300.0	10,300.0	13,900.0	13,900.0	9,100.0	4,400.0	4,300.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		8.8	2.5	8.0	10.7	8.9	8.2	8.0	6.2	8.5	2.5	5.9	8.0	8.0	5.2	2.5	2.5
Post-flood (t_3 to t_4)																	
Start (t_3)	Day (d)	7.0	5.0	7.0	8.0	7.0	7.0	7.0	6.0	7.0	5.0	6.0	7.0	7.0	6.0	5.0	5.0
	Time (t_c)	14:30	07:00	07:00	07:00	15:00	09:30	07:00	15:30	12:00	07:00	13:00	07:00	07:00	07:00	07:30	07:00
	Tick (t_s)	301.0	190.0	286.0	334.0	302.0	291.0	286.0	255.0	296.0	190.0	250.0	286.0	286.0	238.0	191.0	190.0
End (t_4)	Day (d)	37.0	37.0	37.0	36.0	36.0	36.0	35.0	37.0	35.0	35.0	34.0	26.0	26.0	26.0	24.0	23.0
	Time (t_c)	09:03	15:00	12:00	09:00	10:00	13:00	07:30	11:00	08:30	07:30	09:00	12:30	10:00	10:30	09:00	15:00
	Tick (t_s)	1,731.0	1,742.0	1,736.0	1,682.0	1,684.0	1,690.0	1,631.0	1,734.0	1,633.0	1,631.0	1,586.0	1,209.0	1,204.0	1,205.0	1,106.0	1,070.0
Durations (ticks)		1,430.0	1,552.0	1,450.0	1,348.0	1,382.0	1,399.0	1,345.0	1,479.0	1,337.0	1,441.0	1,336.0	923.0	918.0	967.0	915.0	880.0
Operational disruption (units) (OD_{post})		43,050.1	17,125.3	44,579.7	39,783.9	43,332.2	43,604.4	25,002.1	29,769.7	39,749.5	17,120.2	27,789.2	19,098.3	29,716.8	24,028.5	21,255.8	12,968.3
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		24.6	9.8	25.5	22.8	24.8	24.9	14.3	17.0	22.7	9.8	15.9	10.9	17.0	13.7	12.2	7.4
Overall operational disruption (units) ($OD_{overall}$)		60,104.6	23,079.6	60,134.7	60,138.1	60,486.6	59,658.3	40,556.4	42,224.5	56,303.7	23,074.2	39,744.0	36,041.4	45,271.8	36,247.2	28,572.4	20,394.2
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		34.4	13.2	34.4	34.4	34.6	34.1	23.2	24.2	32.2	13.2	22.7	20.6	25.9	20.7	16.3	11.7

Table 9.6: Simulation data for the severely flooded (73) manufacturing SMEs located in Lower Don Valley of Sheffield

In simulation experiments E4, E5 (A), E6 (B), and E10, the severely flooded manufacturing SMEs simulated in these experiments achieved greater $OD_{ABS}^{overall}$ values of 23.2%, 24.2%, 22.7%, and 16.3% (i.e. 13.5%, 13.1%, 14.2%, and 14.8 greater than the corresponding lightly flooded manufacturing SMEs), respectively. This is due to the floodwater reached in 20 of the 73 severely flooded manufacturing SMEs premises (those with a floodwater level at any point greater than 1.5m (see Chapter 7, Section 7.1.1)), which exceeded the location of the raised production machines, IT equipment, documents, raw materials, products, consumer boards, and sockets and thus damaged to them. However, the height of the floodwater reached in the remainder 53 severely flooded manufacturing SMEs' premises remained below the location of the raised IT equipment, documents, raw materials, products, consumer boards, and sockets and thus they were able to resume the production earlier than the 20 flooded SMEs. In comparison to the lightly and moderately flooded manufacturing SMEs, the height of floodwater reached in the lightly and moderately flooded SMEs' premises was always less than or equal to 0.9m (lower than the location of the raised IT equipment, documents, raw materials, products, consumer boards, and sockets) and thus no damage occurred to them, which enabled them to resume the production immediately after restoring power and cleaning-up their premises. It is acknowledged that the manufacturing SMEs simulated in E6 (B) implemented a combination of all the resistant precautionary measures without alternatives, which included flood barriers being installed at doorways. However, the floodwater reached in their premises exceeded the protection level of the flood barriers (0.5m, see Chapter 7, Section 7.1.3.1.1). Therefore, it can be concluded that not any resistant precautionary measure can be effective for the severely flooded manufacturing SMEs. In this research, it can be seen that the bund-wall precautionary measure provides better protection than the other alternatives, such as flood-proof doors or flood barriers, but, as mentioned previously, the bund-wall precautionary measure is an extreme option which is restricted to some conditions.

For the manufacturing SMEs simulated in E1, E2 (B), E2 (C), and E2 (D), they yielded greater $OD_{ABS}^{overall}$ values (34.4%, 34.4%, 34.4%, 34.6%, and 34.1%, respectively) than the same manufacturing SMEs simulated in the previously discussed experiments E4, E5 (A), E6 (B), and E10 (23.2%, 24.2%, 22.7%, and 16.3%, respectively). This is because the floodwater was able to enter *all* the 73 SMEs'

premises via the unsecured doorways as in E1, E2 (D), and E3 and uncovered air-bricks as in E2 (B) and E2 (C) and damaged SMEs' IT equipment, documents, production machines, raw materials, products, consumer boards, and sockets, which were not lifted-up as pre-flood behaviours or raised as precautionary measures. This was not the case in the same SMEs simulated in E4, E5 (A), E6 (B), and E10 in which only 20 of them were affected.

The severely flooded manufacturing SMEs simulated in E11 yielded the lowest $OD_{ABS}^{overall}$ values of 11.7% due to implementing a combination of *all* (i) the resistance precautionary measures without alternatives (PM₁, PM₅, PM₆, PM₇, and PM₈), (ii) resilience precautionary measures (PM₉, PM₁₀, PM₁₁, PM₁₂, PM₁₃, PM₁₅, PM₁₆, PM₁₇, and PM₁₈), and (iii) business continuity/risk management precautionary measures without alternatives (PM₁₉, PM₂₀, PM₂₃, PM₂₇, PM₂₈, PM₂₉, PM₃₀, and PM₃₁). This contrasts with the lightly and moderately flooded manufacturing SMEs, which yielded the lowest $OD_{ABS}^{overall}$ values of 5.1% and 6% respectively, when simulated in E2 (A). Therefore, it can be concluded that implementing a combination of all the resistance precautionary measures, which includes a bund-wall being erected around SMEs' premises, along with all the resilience and business continuity/risk management precautionary measures enables severely flooded manufacturing SMEs to achieve lower $OD_{ABS}^{overall}$ values.

In relation to the statistical analysis test, the Shapiro-Wilk test was initially carried out at one simulation tick during the agent-based simulation for each experiment (E1 – E11), namely in the short-term recovery period at $t_s = 490$ ticks. This simulation tick was selected in which cases most of the experiments output data (which is the production levels of 73 severely flooded manufacturing SMEs in which each had 10 simulation runs) are inconstant values. Please note that the simulation experiments (E1 – E11) output (production level) for the 73 severely flooded manufacturing SMEs, which each had 10 simulation runs, is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

For the Shapiro-Wilk test's results, the production level sample selected from each simulation experiment are not normally distributed. Subsequently, the Mann–Whitney U test (see Table 9.7) was applied to the same samples of production level selected from each simulation experiment (E1-E11). This is to test the differences

between each pair of experiments and determine whether they are significantly different. As indicated in Table 9.7, the p-values of the insignificant pair of experiments are highlighted in red.

	E2 (A)	E2 (B)	E2 (C)	E2 (D)	E3	E4	E5 (A)	E5 (B)	E6 (A)	E6 (B)	E7	E8	E9	E10	E11
E1	<0.0002	0.5644	0.5791	0.5689	0.3911	<0.006	<0.0002	<0.0002	0.0000	<0.0006	<0.0001	<0.0002	<0.0004	<0.0006	<0.0004
E2 (A)		<0.0007	<0.0008	<0.0002	<0.0001	<0.0001	<0.0001	<0.0006	0.7415	<0.0001	<0.0006	<0.0003	<0.0004	<0.0002	0.0500
E2 (B)			0.9837	0.9815	0.1517	<0.0004	<0.0004	<0.0005	<0.0001	<0.0001	<0.0003	<0.0003	<0.0001	<0.0004	<0.0001
E2 (C)				0.9942	0.1573	<0.0001	<0.0002	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0002	<0.0004	<0.0005
E2 (D)					0.1443	<0.0008	<0.0002	<0.0001	<0.0009	<0.0005	<0.0007	<0.0005	<0.0004	<0.0009	<0.0001
E3						<0.0007	<0.0004	<0.0002	<0.0004	<0.0008	<0.0005	<0.0005	<0.0002	<0.0001	<0.0001
E4							0.3063	<0.0003	<0.0004	0.3419	<0.0004	<0.0001	<0.0001	<0.0001	<0.0003
E5 (A)								<0.0002	<0.0007	0.0654	<0.0001	<0.0007	<0.0003	<0.0004	<0.0003
E5 (B)									<0.0008	<0.0007	<0.0001	<0.0004	<0.0001	<0.0002	<0.000
E6 (A)										<0.0008	<0.0002	<0.0006	<0.0001	<0.0002	0.0747
E6 (B)											<0.0001	<0.0007	<0.0004	<0.0008	<0.0005
E7												<0.0002	0.7334	<0.0001	<0.0001
E8													<0.0003	<0.0004	<0.0002
E9														<0.0002	<0.0004
E10															<0.0001

Table 9.7: The results of Mann–Whitney U test applied to the severely flooded (73) manufacturing SMEs located in the Lower Don Valley of Sheffield and simulated in E1 - E11

In the severely flooded manufacturing SMEs, experiments E4 and E5 (A) (p-value 0.3063), and E4 and E6 (B) (p-value 0.3419) are not significantly different, although this was not the case in the lightly and moderately flooded manufacturing SMEs. This is because 20 of the 73 severely flooded manufacturing SMEs' documents, IT equipment, raw materials, and products suffered flood damage (a fate that the moderately and lightly flooded SMEs did not suffer). The 20 flood-affected SMEs had to enact the same post-flood behaviours, such as contacting IT specialists and supervising IT repairs (see Chapter 7, Section 7.1.2). Similarly, the remainder 53 manufacturing SMEs enacted the same post-flood behaviours, such as restoring power and cleaning-up premises.

9.3 SMES LOCATED IN TEWKESBURY

An indicated in Table 9.8, there are fewer manufacturing ($n = 16$) and retail ($n = 4$) SMEs located in the Tewkesbury geographical area compared to the number of manufacturing and retail SMEs located in the Sheffield geographical area. However, as mentioned in Chapter 8, the SMEs located in the Tewkesbury area have historically experienced high floodwater levels and longer flood durations, which have significantly impacted homes and businesses (Tewkesbury Borough Council, 2018).

For manufacturing and retail SMEs located in Tewkesbury, they were categorised in accordance with the floodwater levels reached in their respective premises, in the case that no precautionary measures were implemented. Table 9.8 indicates the number of manufacturing and retail SMEs belong to each of the three categories, i.e. lightly, moderately, and severely.

Categories Sectors	Flooded SMEs Category			Total
	Lightly ($W_d < 0.3\text{m}$)	Moderately ($0.3 \leq W_d \leq 0.9\text{m}$)	Severely ($W_d > 0.9\text{m}$)	
Manufacturing	3	7	6	16
Retail	3	0	1	4

Table 9.8: Manufacturing and retail SMEs located in Tewkesbury categorised on the basis of the floodwater level reached in their premises

Similar to the SMEs located in the Sheffield area, the cumulative average of 10 simulation runs of the 16 manufacturing SMEs located in the Tewkesbury area were simulated over three stages, namely, pre-flood, during-flood (non-operation), and post-flood. For all 16 experiments defined in Chapter 8, the figures (E.40 – E.55) illustrating the cumulative average of production levels for lightly, moderately, and severely flooded manufacturing SMEs are provided in Section E.4 of Appendix E. These figures represent the production level indicating the SMEs' performance throughout the course of a simulation for the lightly, moderately, and severely flooded manufacturing SMEs, respectively, when implementing different combinations of precautionary measures. It is important to note that these figures do not correspond explicitly to a particular SME, rather they represent the cumulative average production level resulting from 10 simulation runs of three lightly, seven moderately, and six severely flooded manufacturing SMEs.

As an example, Figure 9.4 presents the cumulative average of production level of the lightly, moderately, and severely flooded manufacturing SMEs in simulation experiment E1 (indicated in Chapter 8), which corresponds to the scenario in which SMEs *only* set-up and maintain an emergency financial reserve (see Figure E.40, Appendix E), and simulation experiment E11, which corresponds to the scenario in which *most* the precautionary measures are in place (see Figure E.55, Appendix E).

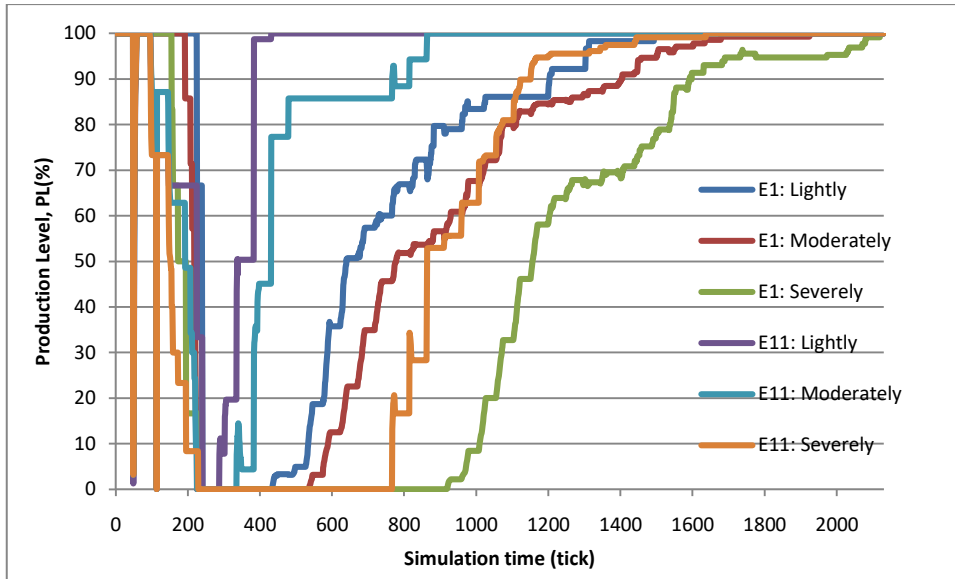


Figure 9.4: Cumulative average of production level of 16 flood-affected manufacturing SMEs located in Tewkesbury over time located

This section will discuss the severely flooded manufacturing SMEs located in the Tewkesbury geographical area. This is to represent the difference between this proportion of SMEs (which experienced high floodwater levels and longer flood durations, which was not in the lightly and moderately flooded manufacturing SMEs) and the corresponding SMEs located in the Sheffield geographical area.

For the severely flooded manufacturing SMEs located in Tewkesbury, Table 9.9 presents information, such as OD_{ABS}^{pre} , OD_{ABS}^{none} , and OD_{ABS}^{post} for each of the three stages, namely pre-flood (t_1 to t_2), flood (non-operational) (t_2 to t_3), and post-flood (t_3 to t_4). It also presents overall information, such as $OD_{ABS}^{overall}$ for the severely flooded manufacturing SMEs simulated.

Please note that the cumulative average of production level data of the six severely flooded manufacturing SMEs used in equations (8.2), (8.8), (8.10), and (8.12) to (8.15) to compute the values presented in Table 9.9 is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t ₁ - t ₂)																	
Start (t ₁)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.0	4.0	2.0	2.0	2.0
	Time (t _c)	13:30	13:30	13:30	13:30	13:30	13:30	13:30	13:30	13:30	13:30	13:30	08:00	13:30	08:00	08:00	08:00
	Tick (t _s)	155.0	155.0	155.0	155.0	155.0	155.0	155.0	155.0	155.0	155.0	155.0	48.0	155.0	48.0	48.0	48.0
End (t ₂)	Day (d)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
	Time (t _c)	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00
	Tick (t _s)	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0
Durations (ticks)		74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	74.0	181.0	74.0	181.0	181.0	181.0
Pre-flood operational disruption (units) (OD _{pre})		4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	4,441.7	8,971.4	4,441.7	7,991.5	7,706.7	8,140.7
Pre-flood absolute operational disruption (%) (OD ^{pre} _{ABS})		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	4.2	2.1	3.8	3.6	3.8
Non-operation (t ₂ - t ₃)																	
Start (t ₂)	Day (d)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
	Time (t _c)	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00	02:00
	Tick (t _s)	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0	228.0
End (t ₃)	Day (d)	20.0	17.0	20.0	21.0	19.0	19.0	19.0	19.0	19.0	17.0	19.0	19.0	19.0	19.0	17.0	17.0
	Time (t _c)	10:30	07:00	11:30	07:30	10:30	12:00	08:00	11:30	16:30	07:00	07:00	07:00	07:00	07:00	07:30	07:00
	Tick (t _s)	917.0	766.0	919.0	959.0	869.0	872.0	864.0	871.0	881.0	766.0	862.0	862.0	862.0	862.0	767.0	766.0
Durations (ticks)		689.0	538.0	691.0	731.0	641.0	644.0	636.0	643.0	653.0	538.0	634.0	634.0	634.0	634.0	539.0	538.0
Non-operation operational disruption (units) (OD _{none})		68,900.0	53,800.0	69,100.0	73,100.0	64,100.0	64,400.0	63,600.0	64,300.0	65,300.0	53,800.0	63,400.0	63,400.0	63,400.0	63,400.0	53,900.0	53,800.0
Non-operation absolute operational disruption (%) (OD ^{none} _{ABS})		32.3	25.3	32.4	34.3	30.1	30.2	29.9	30.2	30.7	25.3	29.8	29.8	29.8	29.8	25.3	25.3
Post-flood (t ₃ - t ₄)																	
Start (t ₃)	Day (d)	20.0	17.0	20.0	21.0	19.0	19.0	19.0	19.0	19.0	17.0	19.0	19.0	19.0	19.0	17.0	17.0
	Time (t _c)	10:30	07:00	11:30	07:30	10:30	12:00	08:00	11:30	16:30	07:00	07:00	07:00	07:00	07:00	07:30	07:00
	Tick (t _s)	917.0	766.0	919.0	959.0	869.0	872.0	864.0	871.0	881.0	766.0	862.0	862.0	862.0	862.0	767.0	766.0
End (t ₄)	Day (d)	45.0	44.0	45.0	45.0	45.0	44.0	43.0	45.0	45.0	44.0	45.0	37.0	37.0	35.0	34.0	35.0
	Time (t _c)	11:30	16:00	16:00	12:30	09:30	14:30	14:00	15:00	12:30	14:00	11:30	10:30	13:00	10:00	09:00	10:00
	Tick (t _s)	2,119.0	2,080.0	2,128.0	2,121.0	2,115.0	2,077.0	2,028.0	2,126.0	2,121.0	2,076.0	2,119.0	1,733.0	1,738.0	1,636.0	1,586.0	1,636.0
Durations (ticks)		1,202.0	1,314.0	1,209.0	1,162.0	1,246.0	1,205.0	1,164.0	1,255.0	1,240.0	1,310.0	1,257.0	871.0	876.0	774.0	819.0	870.0
Operational disruption (units) (OD _{post})		34,119.5	23,868.0	34,425.8	28,405.0	41,374.7	36,734.7	28,557.9	31,942.3	37,260.2	24,809.7	29,823.0	21,287.3	27,640.2	21,423.8	23,367.0	17,658.6
Post-flood absolute operational disruption (%) (OD ^{post} _{ABS})		16.0	11.2	16.2	13.3	19.4	17.2	13.4	15.0	17.5	11.6	14.0	10.0	13.0	10.1	11.0	8.3
Overall operational disruption (units) (OD _{overall})		107,461.2	82,109.7	107,967.5	105,946.7	109,916.4	105,576.3	96,599.5	100,683.9	107,001.9	83,051.4	97,664.7	93,658.7	95,481.9	92,815.3	84,973.7	79,599.3
Overall absolute operational disruption (%) (OD ^{overall} _{ABS})		50.5	38.5	50.7	49.7	51.6	49.6	45.4	47.3	50.2	39.0	45.9	44.0	44.8	43.6	39.9	37.4

Table 9.9: Simulation data for the severely flooded (6) manufacturing SMEs located in Tewkesbury

As indicated in Table 9.9, it can be seen that the $OD_{ABS}^{overall}$ value associated with all simulation experiments is greater than 25%. This is due to the longer flood duration (318.5 hours in the actual 2007 flood event) that impacted the Tewkesbury area (see Chapter 8, Section 8.1.2). For example, the severely flooded manufacturing SMEs simulated in E1 yielded a greater $OD_{ABS}^{overall}$ value of 50.5% (i.e. 16.3% greater than the corresponding SMEs located in the Sheffield area). Also, the OD_{ABS}^{none} value associated with the same SMEs is 32.3% (i.e. 23.5% greater than the corresponding SME in the Sheffield area). Note that the severely flooded manufacturing SMEs located in Tewkesbury had the same level of damage occurred to the severely flooded manufacturing SMEs located in Sheffield. However, as indicated in Table 9.6 and Table 9.9, the Tewkesbury severely flooded manufacturing SMEs simulated in E1 experienced longer non-operational period of 344.5 hours whereas the severely flooded manufacturing SMEs located in Sheffield experienced shorter non-operational period of 70.5 hours when simulated in the same experiment. Recall that the non-operation period comprises both (i) the flood period, and (ii) the post-flood period before the production is resumed.

Similar to the severely flooded manufacturing SMEs located in Lower Don Valley of Sheffield, the Tewkesbury severely flooded manufacturing SMEs simulated in E11 achieved the lowest $OD_{ABS}^{overall}$ value of 37.4% (i.e. 1.1% less than the same SMEs simulated in E2 (A)). It is acknowledged that both experiments E2 (A) and E11 included a bund-wall precautionary measure being erected around SMEs premises, which was able to prevent the floodwater ingress into four of the seven manufacturing SME's premises (i.e. those with a floodwater level at any point not greater than the height of the erected bund-wall (1.5m, see Chapter 7, Section 7.1.3.1.1)). However, the severely flooded manufacturing SMEs simulated in E11 had additionally implemented a combination of all the business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}), which enabled them to (i) enact the post-flood behaviours more quickly than the same SMEs simulated in E2 (A), and (ii) reduced the durations of some pre- and post-flood behaviours (see Chapter 7, Section 7.1.3.2). In specific, the SMEs simulated in E11 had an electricity generator (PM_{27}) available at their premises, which enabled the three flooded SMEs to restore the post-flood behaviours 75.5 hours before the same SMEs simulated in E2 (A). They also had their IT data backed-up

(PM₂₈), which enabled them to recover 52 hours earlier than the same SMEs simulated in E2 (A). In addition to these, they maintained and displayed an emergency flood plan (PM₂₉ and PM₃₀), which enabled them to enact some of the pre- and post-flood behaviours more quickly than those simulated in E2 (A) (see Chapter 7, Section 7.1.3.2). However, implementing the business continuity/risk management precautionary measures without any resistance precautionary measures was insufficient as applied in experiment E7, which achieved a $OD_{ABS}^{overall}$ value of 44% (i.e. 6.6% greater than E11).

For the statistical analysis, the Shapiro-Wilk test was carried out at one simulation tick during the agent-based simulation for each experiment (E1 – E11), namely in the short-term recovery stage at $t_s = 1054$ ticks. This is to test whether the simulation experiment's output data (production levels of the six severely flooded manufacturing SMEs located in Tewkesbury in which each of them had 10 simulation runs) are normally distributed (see Chapter 8, Section 8.2.2). Note that these data are provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

The Shapiro-Wilk test shows that the production level sample selected from each experiment is not normally distributed. Thus, the Mann–Whitney U test (see Chapter 8, Section 8.2.2) was applied to the same samples of production levels selected from each experiment to test the differences between each pair of experiments and determine whether they are significantly different. As presented in Table 9.10, the p-values of the insignificant pair of experiments are highlighted in red.

	E2 (A)	E2 (B)	E2 (C)	E2 (D)	E3	E4	E5 (A)	E5 (B)	E6 (A)	E6 (B)	E7	E8	E9	E10	E11
E1	<0.0002	0.6000	0.7740	0.0910	0.4900	0.0010	0.0040	0.6430	<0.0007	<0.0002	0.0010	0.0360	0.0050	<0.0001	<0.0002
E2 (A)		<0.0004	<0.0003	<0.0002	<0.0004	0.0010	0.0010	<0.0004	0.8540	0.0050	0.0010	<0.0007	<0.0008	0.7060	0.3620
E2 (B)			0.8110	0.0310	0.8230	0.0030	0.0190	0.9840	<0.0004	<0.0002	0.0020	0.0890	0.0170	<0.0002	<0.0004
E2 (C)				0.0350	0.6440	0.0010	0.0040	0.8230	<0.0002	<0.0002	0.0010	0.0400	0.0060	<0.0007	<0.0007
E2 (D)					0.0130	<0.0004	<0.0004	0.0250	<0.0001	<0.0001	<0.0004	0.0010	<0.0001	<0.0009	<0.0004
E3						0.0030	0.0130	0.8310	<0.0004	<0.0007	0.0030	0.0900	0.0190	<0.0008	<0.0004
E4							0.7370	0.0030	0.0010	0.1370	0.2130	0.7190	0.6630	<0.0002	<0.0002
E5 (A)								0.0120	0.0010	0.0800	0.1110	0.9480	0.4250	<0.0002	<0.0003
E5 (B)									<0.0002	<0.0002	0.0020	0.0740	0.0150	<0.0004	<0.0006
E6 (A)										0.0050	0.0010	<0.0001	<0.0009	0.6880	0.3470
E6 (B)											0.7910	0.1530	0.5310	<0.0002	<0.0002
E7												0.1190	0.4050	0.0010	<0.0001
E8													0.4600	<0.0008	<0.0007
E9														<0.0003	<0.0003
E10															0.1470

Table 9.10: The results of Mann–Whitney U test applied to the severely flooded (6) manufacturing SMEs located Tewkesbury and simulated in E1 – E11

As presented in Table 9.10, the Mann–Whitney U test shows that the production level samples tested are insignificantly different between experiments E1 and E2 (B) (p-value 0.6000), E1 and E2 (C) (p-value 0.7740), E1 and E2 (D) (p-value 0.0910), E1 and E3 (p-value 0.4900), and E1 and E5 (B) (p-value 0.6430). This is because the precautionary measures implemented in these experiments were inadequate to protect SMEs' premises from floodwater ingress. Also, they were insufficient to protect SMEs' production machines, IT equipment, documents, raw materials, products, consumer boards, and sockets from damage. This is also the case when comparing experiments E2 (B) and E2 (C) (p-value 0.8110), E2 (B) and E3 (p-value 0.8230), E2 (B) and E5 (B) (p-value 0.9840), E2 (C) and E3 (p-value 0.6440), E2 (C) and E5 (B) (p-value 0.8230), and E3 and E5 (B) (p-value 0.8310).

In contrast to the severely flooded manufacturing SMEs located in Lower Don Valley of Sheffield, the Mann–Whitney U test shows that there is no significant difference between experiments E2 (A) and E6 (A) (p-value 0.8540), E2 (A) and E10 (p-value 0.7060), E2 (A) and E11 (p-value 0.3620), E6 (A) and E10 (p-value 0.6880), E6 (A) and E11 (p-value 0.3470), and E10 and E11 (p-value 0.1470). All the manufacturing SMEs simulated in E2 (A), E6 (A), and E11 (with the exception of E10) had bund-walls being erected around their premises. However, the floodwater exceeded the bund-walls of three of the seven severely flooded manufacturing SMEs and damaged the raised documents, production machines, raw materials, products, sockets, and consumer boards. The remaining four manufacturing SMEs simulated in E2 (A), E6 (A), and E11 were not flooded and thus they were able to resume their production immediately. For SMEs simulated in E10, the floodwater has damaged the raised documents, production machines, raw materials, products, sockets, and consumer boards of three of them. However, the remaining four manufacturing SMEs simulated in E10 were less affected because the floodwater did not reach the raised documents, IT equipment, raw materials, products, consumer boards, and sockets, which raised at a level of 1.5 m (see Chapter 7, Section 7.1.3.1.2). They also maintained electricity generators, which enabled them to enact the post-flood behaviours, such as repairing production machines, cleaning-up premises, and contacting IT specialists to carry out repairs, before the power supply was restored (see Chapter 7, Section 7.1.3.2).

9.4 RECOMMENDATIONS FOR MANUFACTURING SMES

The research reported in this thesis presents a specific set of recommendations tailored for manufacturing SMEs that have experienced flooding and/or are prone to flooding. These recommendations are based on the application of the developed ABMS framework to the two UK-based case studies: (a) the Lower Don Valley region of Sheffield in South Yorkshire and (b) Tewkesbury in Gloucestershire. These recommendations are presented based on the level of floodwater experienced by SMEs, i.e. lightly flooded, moderately flooded, or severely flooded.

9.4.1 Recommendations for the Lightly Flooded Manufacturing SMEs

Based on the investigation of the lightly flooded manufacturing SMEs presented in Section 9.2.1, this group of SMEs are recommended to implement the following resistance precautionary measures along with registering for EA alerts and warnings services. These precautionary measures are grouped into *Recommendation 1* as follows:

- Manufacturing SMEs located in areas prone to light flooding are recommended to secure all the floodwater entry points including doorways. In particular, they are advised to install flood-proof windows, install anti-backflow valves, paint brickwork with waterproofing treatments, and install below-ground waterproof materials. To protect doorways, these SMEs are advised to build a bund-wall around their premises, maintain sandbags on site, install flood-proof doors or install flood barriers. However, as discussed previously, the bund-wall precautionary measure is a financially and structurally costly option and is only suitable for detached SMEs. In addition to these precautionary measures, SMEs are also recommended to register for EA alerts and warnings services to receive them at the pre-flood stage. This will enable SMEs in lightly flooded areas to place sandbags at doorways (if needed) and cover air-bricks to prevent floodwater ingress (see Experiment E9, Section 9.2.1.4).

It is recognised that the precautionary measures presented in *Recommendation 1* are sufficient for this proportion of SMEs due to the lower level of floodwater potential (see Experiments E2 (A), E6 (A), E9, and E11, Section 9.2.1). However, if manufacturing SMEs located in a lightly flooded area are not able to secure all the

floodwater entry points and so risk becoming flooded, then they are recommended to implement the resilience and business continuity/risk management precautionary measures grouped in *Recommendation 2* as follows:

- SMEs are recommended to raise consumer boards and electrical sockets above the likely floodwater level. Additionally, they are recommended to raise the storage height of their documents, raw materials, production machines, IT equipment, and products above the likely floodwater level. In terms of the business continuity/risk management precautionary measures, SMEs are recommended to obtain comprehensive insurance to receive assistance from a cleaning service provider and receive financial compensation for flood damage. This financial assistance will enable SMEs to quickly acquire the required services (electrician, plumbers, and IT specialists) (see Appendix D, Section D.3.1). In terms of cleaning service providers, SMEs are recommended to allocate their own employees, if possible, to clean-up their premises rather than waiting for the cleaning service provided by their insurance company (see Appendix D, Section D.3.1). Furthermore, SMEs are recommended to seek a pre-defined mutual aid partner to enable them to restore their production immediately and maintain production during a period in which they would otherwise remain non-operational (see Appendix D, Section D.3.2). They are also recommended to maintain electricity generators. This will enable them to use this alternative power supply until the main power is restored, and thus, SMEs can start their short-term recovery process before the power supply is restored (see Experiment E7, Section 9.2.1.4). In addition to these precautionary measures, SMEs are advised to back-up their IT data which will enable them to restore their data rather than recovering the damaged IT data, which will delay the short-term recovery process (see Experiment E8, Section 9.2.1.3). Finally, SMEs are recommended to maintain and display an emergency flood plan, which will enable them to enact pre- and post-flood behaviours more quickly than those without an emergency flood plan in place (see Experiment E8, Section 9.2.1.3).

9.4.2 Recommendations for the Moderately Flooded Manufacturing SMEs

This group of SMEs is recommended to implement all of the precautionary measures of *Recommendation 1*, which was prepared for the manufacturing SMEs located in a lightly flooded area. However, in terms of protecting doorways, manufacturing SMEs located in a moderately flooded area are recommended to implement any precautionary measure(s) that protects their premises up to an above-ground height of 0.9m, such as erecting a bund-wall around their premises or installing flood-proof doors (see Experiments E2 (A), E6 (A), and E11, Section 9.2.2). Similarly, if manufacturing SMEs located in a moderately flooded area are not able to secure all the floodwater entry points (in which case they will be flooded), then they are recommended to implement the resilience and business continuity/risk management precautionary measures, which was presented in *Recommendation 2* for manufacturing SMEs located in lightly flooded areas.

9.4.3 Recommendations for the Severely Flooded Manufacturing SMEs

For manufacturing SMEs located in a severely flooded area, it is recognised that only implementing the precautionary measures presented in *Recommendation 1* will be insufficient to protect them from flooding. This is because the floodwater level that may reach these SMEs' premises is unlimited and thus it may exceed the implemented resistance precautionary measures (see Experiment E2 (A), Section 9.2.3). Recall that the severely flooded manufacturing SMEs have experienced a level of floodwater greater than 0.9m. Therefore, in addition to the precautionary measures presented in *Recommendation 1* (with the exception of the doorway-related options that protect against floodwater to a height of less than or equal to 0.9m), SMEs located in a severely flooded area are also recommended to implement the precautionary measures recommended in *Recommendation 2* concurrently. However, this proportion of SMEs are recommended to raise the height at which documents, IT equipment, raw materials, products, sockets, and consumer boards are stored to a higher level than the protection height of the implemented doorway-related precautionary measures (e.g. water-proof doors or bund-walls).

It is noteworthy that this set of recommendations is suitable for all the severely flooded manufacturing SMEs including those, which experienced high floodwater levels and longer flood durations. This was recognised following an analysis of (a) the severely flooded manufacturing SMEs located in Sheffield (see Section 9.2.3, page 171), and (b) the severely flooded manufacturing SMEs located in Tewkesbury (Section 9.3, page 176) simulated in the 16 experiments defined in Chapter 8.

9.5 SUMMARY

A matrix has been developed (see Table 9.11) to evaluate the lightly, moderately, and severely flooded manufacturing SMEs located in Lower Don Valley of Sheffield over each of the 16 simulation experiments with respect to the $OD_{ABS}^{overall}$ values. Additionally, it includes the severely flooded manufacturing SMEs located in the Tewkesbury area.

		Sheffield Geographical Area			Tewkesbury Geographical Area
		Lightly	Moderately	Severely	Severely
E1		15	12	12	14
E2	A	1	1	2	2
	B	11	14	12	15
	C	10	11	12	12
	D	14	13	13	16
E3		13	12	11	11
E4		6	5	7	8
E5	A	7	6	8	10
	B	12	10	10	13
E6	A	1	2	2	3
	B	5	5	6	9
E7		8	7	4	6
E8		9	9	9	7
E9		3	8	5	5
E10		4	4	3	4
E11		2	3	1	1

Table 9.11: The overall cumulative average of manufacturing SMEs simulated in E1 to E11

The matrix ranks the simulation experiments in terms of their associated $OD_{ABS}^{overall}$ values ascendingly, in which the simulation experiment with the lowest $OD_{ABS}^{overall}$ value is ranked as number one. However, if two simulation experiments achieved the same $OD_{ABS}^{overall}$ values, they were assigned the same rank.

In terms of the lightly flooded manufacturing SMEs located in Lower Don Valley of Sheffield, simulation experiments E2 (A), E6 (A), E9, and E11, which involved different combinations of the resistance precautionary measures, yielded the lowest $OD_{ABS}^{overall}$ values of 5.1%, 5.1%, 6.1%, and 6% respectively. The lightly flooded manufacturing SMEs simulated in these experiments secured all the floodwater entry points, such as erecting a bund-wall around their premises as simulated in E2 (A), E6 (A), and E11, and placing sandbags in doorways for the same SMEs simulated in E9. Thus, this indicates that the resistance precautionary measures are sufficient for this group of SMEs. Following these experiments, experiment E10 is ranked as the fifth experiment in terms of achieving the lowest $OD_{ABS}^{overall}$ value, although the lightly flooded manufacturing SMEs simulated in E10 became flooded. However, these SMEs raised their documents, IT equipment, production machines, raw materials, and products as precautionary measures and thus these elements were not damaged. They also had electricity generators available at their premises, which enabled them to start their short-term recovery process before the main power supply was restored. Furthermore, they had their IT data backed-up as a business continuity/risk management precautionary measure. In addition, they had maintained and displayed an emergency flood plan, which enabled them to enact some of the pre- and post-flood behaviours more quickly.

For the moderately flooded manufacturing SMEs, simulation experiments E2 (A), E6 (A), and E11, which included a combination of all the resistance precautionary measures with a bund-wall being erected around SMEs' premises, yielded the lowest $OD_{ABS}^{overall}$ values of 6%, 6%, and 6.9% respectively. However, the bund-wall precautionary measure is structurally and financially costly. Also, an SME's premises must be detached in order to erect a bund-wall around its premises. In addition to these experiments, it can be seen that experiment E10 which implemented all the possible resilience and business continuity/risk management precautionary measures without

alternatives was ranked as the fourth experiment in terms of achieving the lowest $OD_{ABS}^{overall}$ value.

For the severely flooded manufacturing SMEs located in Sheffield and Tewkesbury geographical areas, simulation experiments E2 (A), E6 (A), and E11, which involve a combination of the resistance precautionary measures with a bund-wall being erected around SMEs' premises, yielded the lowest $OD_{ABS}^{overall}$ values of 13.2%, 13.2%, and 11.7% respectively. Next, simulation experiments E10 and E9 are ranked as fourth and fifth in terms of the lowest $OD_{ABS}^{overall}$ values, respectively. It is noteworthy that the severely flooded manufacturing SMEs selected from the two UK-based case studies were considered to perform similarly when simulated in the experiments defined.

Chapter 10

Evaluation

This chapter evaluates the ABMS framework in relation to the requirements it addresses by examining its application to the two case studies presented in Chapter 9.

Section 10.1 highlights the achievements and weaknesses of the developed ABMS framework in terms of the requirements identified in Chapter 4 while Section 10.2 summarises the framework's achievements and weaknesses and closes the chapter.

10.1 ACCOMPLISHMENTS AND WEAKNESSES

This section outlines the achievements and weaknesses of the developed ABMS framework in terms of (i) modelling a geographical environment; (ii) modelling SMEs; (iii) modelling SME-related organisations; (iv) modelling interactions between SMEs and SME-related organisations; and (v) modelling performance metrics to measure manufacturing and retail SME's performance throughout the course of the simulation.

10.1.1 Modelled Geographical Environment (MGE)

The MGE has been developed in order to identify flood-affected and non-flood-affected organisations in two geographical areas, the Lower Don Valley of Sheffield, and Tewkesbury. Based on the application of the developed ABMS framework to the two UK-based case studies presented in Chapter 9, the MGE element achieved the following:

Achievements

- OS MasterMap® layers (i.e. *Topography*, *ITN*, and *AddressBase Plus* layers) have been applied and then edited in terms of their visual representation, and then combined with the flood event simulation (i.e. inundation data), which in turn enabled:
 - identification of the flooded and non-flooded organisations in the two geographical areas; and
 - the visual representation of the flooding affecting the modelled geographical areas for every simulation tick throughout the course of the simulation.

Weaknesses

- The flood-event inundation data used in the simulation are related to the 2007 UK flood events in the Lower Don Valley of Sheffield and Tewkesbury, whereas the incorporated MasterMap® AddressBase Plus layer dataset was created in 2017. Therefore, this ten-year difference creates some disparity between the EA's indication data and the businesses identified in this research.

10.1.2 Modelling and Simulating SMEs

SMEs have been modelled as autonomous agents with a set of behaviours, attributes, and pre-defined precautionary measures to investigate their immediate response to and short-term recovery from flood events.

10.1.2.1 Behaviours

Behaviours are actions that can be completed over different durations (e.g. hours) in either the pre- or post-flood stages.

Achievements

- Behaviours have been identified from (i) the academic literature, (ii) transcripts of semi-structured interviews with employees from SMEs that have experience of flooding or being at risk of flooding, and (iii) EA guidance.

- SMEs' behaviours have been classified in terms of two key flood periods: pre-flood and post-flood. The pre-flood behaviours can be enacted from the time an SME receives EA alerts or warnings until the flood event occurs, whereas the post-flood behaviours can be enacted from the time the floodwater recedes from an SME's premises until the time an SME returns to normal operation.
- The relationships among the behaviours have been modelled so that on completion of a specific behaviour, the next linked, dependent behaviour can be enacted.
- Five employees allocation strategies (*normal operation, flood is possible, immediate action, flooding, and recovery*) have been implemented. This is to provide the multiple and single employee behaviours with the appropriate number of employees required to enact them, based on SMEs' current status where is (i) no flood sign, (ii) after receiving EA alerts (iii) after receiving EA warnings, (iv) flooding, or (v) after the flood receded from SMEs' premises.
- Based on the literature and the interview transcripts, each behaviour has been allocated a specific priority-of-execution value. This is required when the number of behaviours that need to be enacted exceeds the number of employees available. In this case, behaviours with a higher priority value are assigned the relevant number of employees available so that they can be executed before other lower priority behaviours.
- Behaviours have been classified in terms of whether the SME sectors modelled require generic or specific behaviours; generic behaviours can be enacted by both manufacturing and retail SMEs, whereas specific behaviours can be enacted by *either* manufacturing SMEs *or* retail SMEs, respectively.
- Each behaviour has been associated with a specific duration range that indicates the time required to complete a particular behaviour.
- The information (behaviours' relationships, the number of employees required to enact behaviours, priority of execution, behaviours classification, duration range) used has been carefully managed to enact the pre- and post-flood behaviours. Thus, the associated information can be accessed before enacting a specific behaviour, and on the completion of each behaviour, the information

can be updated and maintained. This means the information can then be retrieved in case it is required for another behaviour.

Weaknesses

- According to the literature and the interview transcripts, there is no consensus on how SMEs' behaviour-relationship dependencies should be modelled as well as the priority of execution. Therefore, the behaviour-relationship dependencies and priority of execution that have been incorporated into the developed ABMS framework are subjective, and thus, they can be further developed according to SMEs' decision-makers' wishes.

10.1.2.2 Attributes

The attributes have been modelled to define SME's identities and performance throughout the simulation.

Achievements

- The attributes are classified as either *static* (e.g. SMEs' names and locations) or *dynamic* (e.g. employees available at SMEs premises, and power supply). The static attributes remain constant throughout the course of the simulation and are used only to define SMEs. However, the dynamic attributes are subject to change during the course of the simulation and some of them are used to determine SMEs' performance (i.e. *PL* for manufacturing SMEs or *SC* for retail SMEs).
- Because most of the SME's attributes were derived from the OS MasterMap® *AddressBase Plus* layer, each SME is modelled at its exact location along with relevant details such as its business name and sector to increase the accuracy of identifying flooded and non-flooded organisations.

Weaknesses

- The OS MasterMap® *AddressBase Plus* layer does not provide information regarding the floor level at SMEs' locations. This information can improve SMEs' immediate response to and short-term recovery from flooding as it

allows SMEs to allocate employees to lift-up stock and equipment to an upstairs location rather than on desks.

10.1.2.3 Precautionary Measures

SMEs implement precautionary measures prior to (i) receiving an EA flood alert or warnings, and (ii) a flood event occurring.

Achievements

- The precautionary measures are classified as (i) flood-resistance property-level; (ii) flood-resilience property-level, and (iii) business-continuity and risk-management precautionary measures. This classification facilitates the process to carry out several distinct simulation experiments where each one employs different combinations of precautionary measures. This enables the investigation of how behaviours and precautionary measures (and combinations of them) impact SMEs' immediate pre-flood responses and post-flood short-term recovery.
- Precautionary measures can prevent or reduce the amount of water entering an SME's premises and remove the need for (and reduce the duration required for) specific behaviours. For example, installing flood barriers in doorways at an SME's premises may prevent floodwater ingress while simultaneously removing the need to place sandbags in doorways.

Weaknesses

- The simulation experiments were designed in accordance with the precautionary measures classification outlined in the literature. However, different studies classify precautionary measures in different ways (i.e. structural and social precautionary measures or property-level and business-level precautionary measures). Thus, choosing the appropriate classification remains a subjective decision.

10.1.3 Modelling SME-Related Organisations

SME-related organisations have been modelled as agents and simulated to support SMEs in terms of their immediate response to and short-term recovery from flooding.

10.1.3.1 The Environment Agency (EA)

Achievements

- The EA has been modelled as an agent to which every SME can register for EA services (e.g. alerts and/or warnings).
- EA alerts are implemented so that every registered SME receives an EA alert 36 hours before the flood occurs, which enables an SME to enact pre-flood behaviours.
- EA warnings are implemented and thus every EA-registered SME receives an EA warning three hours before the flood occurs, which in turn, enables the SMEs to enact pre-flood behaviours.

Weaknesses

- SMEs receive EA alerts and warnings 36 hours and 3 hours prior to the expected flood commencement time, respectively. However, in reality, SMEs may receive EA alerts or warnings between 36 hours to 3 hours prior to a flood event because of the difficulties involved in accurately predicting the flood exact time (although this is not the case in this research's simulation as it depends on past data).

10.1.3.2 Suppliers and Customers

Achievements

- Suppliers:
 - Suppliers are modelled as agents to interact with manufacturing and retail SMEs in the pre- and post-flood stages to preserve SMEs'

operational continuity by providing manufacturing and retail SMEs with raw material or stock respectively.

- Supplier's delivery services have been modelled so that every supplier delivers raw materials or stock to manufacturing or retail SMEs' premises, respectively, at regular intervals. If a flood occurs, suppliers suspend delivery when (i) informed to do so by SMEs or (ii) suppliers are unable to reach SMEs' premises due to flooding. Once an SME is in a position to recommence production (for a manufacturing SME) or providing a service (for retail SMEs), its supplier is contacted to resume raw material or stock delivery.
 - Every manufacturing and retail SME can have a certain number of suppliers.
 - Every SME sector (manufacturing or retail) has its own suppliers that only interact with SMEs from the same sector.
- Customers:
 - They are modelled to interact with manufacturing SMEs (with the exception of retail SMEs) in the pre- and post-flood stages to take delivery of products from these businesses. This is because retail SMEs tend to deal with the public and thus they are less likely to have a specific known number of customers (which is not the case in the manufacturing SMEs) in order to contact them in the pre- and/or post-flood stages.
 - The dispatch service has been modelled in which every manufacturing SME dispatches products to customers at regular intervals. However, if a flood occurs, manufacturing SMEs suspend the dispatch of products and contact their customers to inform them of this suspension. However, if manufacturing SMEs are not able to contact customers before the flood occurs, then customers are contacted at the beginning of the post-flood period to inform them of the situation.

Weaknesses

- Suppliers provide manufacturing and retail SMEs with raw materials and stock at regular intervals e.g. daily, every three days, weekly, or every two weeks. However, it is recognised that these varieties of intervals do not affect SMEs' immediate responses to and short-term recovery from flooding. Similarly, customers take delivery from manufacturing SMEs at regular intervals the same as suppliers, although it is also recognised that these intervals do not affect their immediate responses to and short-term recovery from flood events.
- Suppliers and customers have been modelled with a lower level of detail with respect to their attributes and behaviours than manufacturing and retail SMEs. Specifically, they have been modelled with less accurate information, such as names and locations, which is not the case for the manufacturing and retail SMEs.

10.1.3.3 Insurance Companies

Achievements

Insurance companies have been modelled as agents that offer two types of cover, namely comprehensive and basic. In the post-flood stage, a flooded SME will contact its insurer, which will send a loss adjuster within seven days to assess the damage and produce a report followed by (i) payment being released within five working days of the visit, and, if covered sufficiently, (ii) a cleaning service to attend the flooded SME's premises.

- Comprehensive cover ensures that, post-flood, insured SMEs receive the assistance of a cleaning service and financial compensation. In this case, the interaction between insurance companies and cleaning services has been modelled to enable them to provide a cleaning service to the SME(s) they insure.
- Basic cover denotes that the insured SMEs only receive financial compensation.

Weaknesses

- SMEs, especially those with no funds available, may remain non-operational for few days due to delays in the process of (i) sending a loss adjuster and (ii) releasing payments undertaken by insurance companies. During this period, although employees are available at SMEs' premises, they cannot engage in the recovery process because of the delay in receiving payments from their insurers in order to carry out post-flood recovery, such as contacting electricians, plumbers, cleaning service providers, and IT specialists.

10.1.3.4 Cleaning Service Providers

Achievements

- Cleaning service providers have been modelled as agents such that every cleaning service provider can attend any SME's premises during the recovery period if requested directly by an SME or via the insurance company.
- The locations of the cleaning service providers have been considered. Cleaning service providers are modelled as either regional (i.e. in the same geographical area) or national. National cleaning service providers are only contacted if an SME is unable to secure the services of a regional provider (as regional providers are always limited in terms of numbers). The number of regional cleaning service providers is determined according to the UK business directory. In terms of arrival times, because regional organizations may not be able to arrive immediately, they can schedule their attendance at an SME's premises for up to 24 hours ahead (see Chapter 7, Section 7.2.4). Alternatively, SMEs will contact national cleaning service providers, which are likely to arrive later (e.g. 24-48 hours) than regional service providers although there are a greater number of them available.
- A contract service has been modelled in which the cleaning service provider can have a pre-defined contract with any insurance company. If an insurance company requests a cleaning service for an insured SME, the requested team will arrive at the SME's premises between 2 and 24 hours (see Chapter 7, Section 7.2.3).

Weaknesses

- An SME may request a service from a cleaning-service provider that has a pre-defined contract with insurance companies. However, the requested service could be interrupted, when requested by the insurance company, before arriving at an SME's premises. Subsequently, an SME may contact another cleaning-service provider that also has a contract with insurance companies, although this might also be interrupted. This interruption may cause unanticipated delays in SMEs' short-term recovery process.

10.1.3.5 Service Provider Organisations

Achievements

- Electricians, plumbers, IT specialists, and refurbishment companies have been modelled as agents and thus these services can be requested by SMEs during the recovery period.
- Similar to the cleaning service providers, these service provider organisations have been modelled as either regional or national in terms of their location.

Weaknesses

- These service provider organisations (electricians, plumbers, IT specialists, and refurbishment companies) have been modelled to provide assistance or a service to maintain SMEs' operation and support their short-term recovery from flood events. Thus, no obvious weaknesses have been identified in terms of the ABMS framework's application to the two UK-based case studies presented in Chapter 9.

10.1.3.6 Mutual Aid Partners

Achievements

- Mutual aid partners have been modelled as agents. Any manufacturing SME with more than one employee can have a mutual aid pre-defined contract. That is, during flood recovery, a proportion of production employees are allocated to work at the SME's mutual-aid partner's premises while the remainder (at least one

production employee) will be allocated to work on post-flood behaviours including production at the affected premises.

- Mutual aid partners have been modelled on the same level as manufacturing SMEs in terms of the attributes. This is due to the availability of data from the *AddressBase Plus* layer.

Weaknesses

- A manufacturing SME may return to normal operation (PL=100%) after contacting their mutual aid partner, but before working at their partner's premises. Enacting this behaviour (contacting the mutual aid partner), which was not eventually needed for an SME's short-term recovery process, is more likely to cause a delay to an SME's short-term recovery process. This is because SMEs cannot anticipate the time required to return to normal operation (PL=100%) when deciding whether to contact the mutual aid partner in advance.

10.1.4 Modelling Interactions between SMEs and SME-Related Organisations

SME agents and SME-related organisation agents communicate and exchange information via messages.

Achievements

- The interactions between SME agents and SME-related organisation agents have been modelled such that every agent can send or receive messages in accordance with the agents' rules.
- SMEs and SME-related organisation agents can exchange messages; each agent has an inbox and outbox contact list that enables it to send and receive messages to and from other agents. At every tick, each agent (including SMEs and SME-related organisations) checks its inbox before enacting any behaviour (including production for manufacturing SMEs and service for retail SMEs).

Weaknesses

- SMEs and SME-related organisation agents must have each other's unique identifier in order to interact and communicate.
- SME and SME-related organisation agents can interpret the received messages based on a set of keywords, such as *suspend* and *resume*. This may limit the level of interactions between agents.

10.1.5 Modelling Performance Metrics

Performance matrices have been established and modelled to measure SME's performance during a simulation when enacting pre- and post-flood behaviours and precautionary measures, or a combination of them.

Achievements

Two performance metrics have been modelled: (i) the manufacturing-SME performance metric, and (ii) the retail SME performance metric.

- Manufacturing SME's performance is measured in terms of the relationship between the status of the power supply, number of production employees, number of production machines, and the availability of raw materials.
- Retail SME's performance is measured in terms of the relationship between the status of the power supply, working environment conditions, sales equipment, number of employees, and stock availability.

Weaknesses

- Manufacturing and retail SMEs could return to the normal operation (PL or $SC=100\%$) before enacting all the possible post-flood behaviours. For example, a manufacturing SME could return to normal operation ($PL=100\%$) despite not yet contacting customers. This is due to the interdependencies between certain behaviours. As a solution, at each simulation tick, the developed ABMS framework checks the post-flood behaviour yet to be enacted before a manufacturing or retail SME returns to its normal operation level (PL or $SC=100\%$).

10.2 SUMMARY

This chapter has presented an evaluation of the developed ABMS framework that investigates SME's immediate response to and short-term recovery from flooding. Based on these evaluations, and in relation to the framework requirements (MGE, modelling SMEs, modelling SME-related organisations, modelling interactions between SMEs and SME-related organisations, and modelling performance metrics) identified in Chapter 4, this chapter has identified the achievements and weaknesses of the developed ABMS framework based on the application of the ABMS framework to the two case studies presented in Chapter 9 to ensure that it can meet the specified requirements.

Chapter 11

Conclusion

In this thesis, an ABMS framework has been developed to investigate SMEs' immediate response to and short-term recovery from flooding. Figure 11.1 illustrates the work presented in this thesis and shows how the chapters are linked. Furthermore, the relevant chapters and parts of the thesis are cross-referenced to each aspect of the work.

11.1 MOTIVATION FOR THE RESEARCH

Flooding is defined as one of nature's most disruptive events, and can cause damage to almost every industrial sector of the economy. The UK's 5.4 million SMEs are essential to the country's economy, as they represent 99.9% of all businesses. However, despite the economic importance of SMEs, in recent years this type of business has proven vulnerable to flooding due to their limited resources and tendency to not implement disaster mitigation plans. In particular, flooding has caused significant financial losses to UK SMEs and remains a serious threat. According to the Environment Agency (EA), losses to UK businesses due to flooding in 2007 were in the region of £740 million (Chatterton et al., 2010). In England, it is projected that the annual loss suffered by residential and business properties due to flooding exceeds £1 billion (Leinster, 2009).

11.2 KEY ELEMENTS OF ABMS FRAMEWORK

In order to identify the key elements needed to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding, a literature review of existing research in (i) ABMs and related flood events, and (ii) ABMs and SMEs, was established. Based on the literature reviewed, information was

identified in terms of key elements of developing an ABMS framework to enable the investigation of SMEs' immediate response to and short-term recovery from flooding. These elements comprised: modelling a geographic environment; modelling SMEs; modelling SME-related organisations; modelling interactions between SMEs and SME-related organisations; and modelling performance metrics.

A geographical environment was modelled to (i) identify each individual organisation flooded over the timeline of simulated flood events, and (ii) produce a visual representation of the modelled geographical area. Furthermore, SMEs were modelled with a set of behaviours, attributes, and pre-defined precautionary measures. Next, related organisations (including electricians, plumbers, IT specialists, cleaning service providers, suppliers, customers, EA, insurance companies, mutual aid partners, and refurbishment companies) were modelled to interact with SMEs to provide assistance or a service to maintain SMEs' operation and support their short-term recovery from flooding. For the performance metrics, it was implemented to assess SMEs' performance before, during, and after a flood event in terms of their production level and service capability for manufacturing and retail SMEs respectively.

As a result of the literature reviewed, it has been recognised that none of the existing research incorporate all of the identified key elements to develop an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding. Furthermore, the limitations of existing research have been identified since they do not provide knowledge with respect to: (i) how to model a geographical environment appropriately to enable the identification of the flooded and non-flooded SMEs; (ii) how to model SMEs appropriately with a set of attributes, behaviours, and pre-defined precautionary measures in a specified geographical area in relation to disruptive event, i.e. a major flood; (iii) how to model SME-related organisations so that they can provide assistance or a service to SMEs appropriately to maintain their operation and support their short-term recovery from flooding; (iv) how to model the interaction between SMEs and SME-related organisations, and (v) how to measure SMEs' performance.

11.3 REQUIREMENTS OF ABMS FRAMEWORK

The requirements of developing an ABMS framework to investigate SMEs' immediate response to and short-term recovery from flooding have been identified.

- Geographical environment
 - enable the identification of flooded and non-flooded organisations;
 - produce a visual representation of the modelled geographical areas.
This is to help the reader gain a better understanding of the modelled geographical area.
- Modelling SMEs
 - model SMEs' behaviours, including their dependency relationships, the number of employees required to undertake the tasks related to these relationships, priority of execution, classification, and duration range;
 - model a set of attributes to define SMEs' identities; and
 - model precautionary measures to improve SMEs' immediate response to and short-term recovery from flooding.
- Modelling SME-related organisations
 - EA to send flood alerts and warnings to EA-registered SMEs;
 - suppliers and customers to support SMEs' operational continuity;
 - insurance companies to support SMEs' recovery from flooding with financial compensation and the provision of a cleaning service provider, if sufficiently insured;
 - cleaning service providers to support SMEs' recovery in the flood aftermath phase where this proportion of organisations or businesses should be modelled in terms of their locations (i.e. *regional* or *national*).
 - service provider organisations (i.e. electricians, plumbers, IT service providers, and refurbishment companies) are also modelled as *regional* and *national* organisations;

- mutual aid partners that interact with manufacturing SMEs during the recovery period to support their recovery.
- Modelling interactions between SMEs and SME-related organisations
 - define the communication protocol between SMEs and SME-related organisations.
- Modelling performance metrics
 - measure SMEs' performance in order to investigate their operation over a specific timeframe to enable analysis.

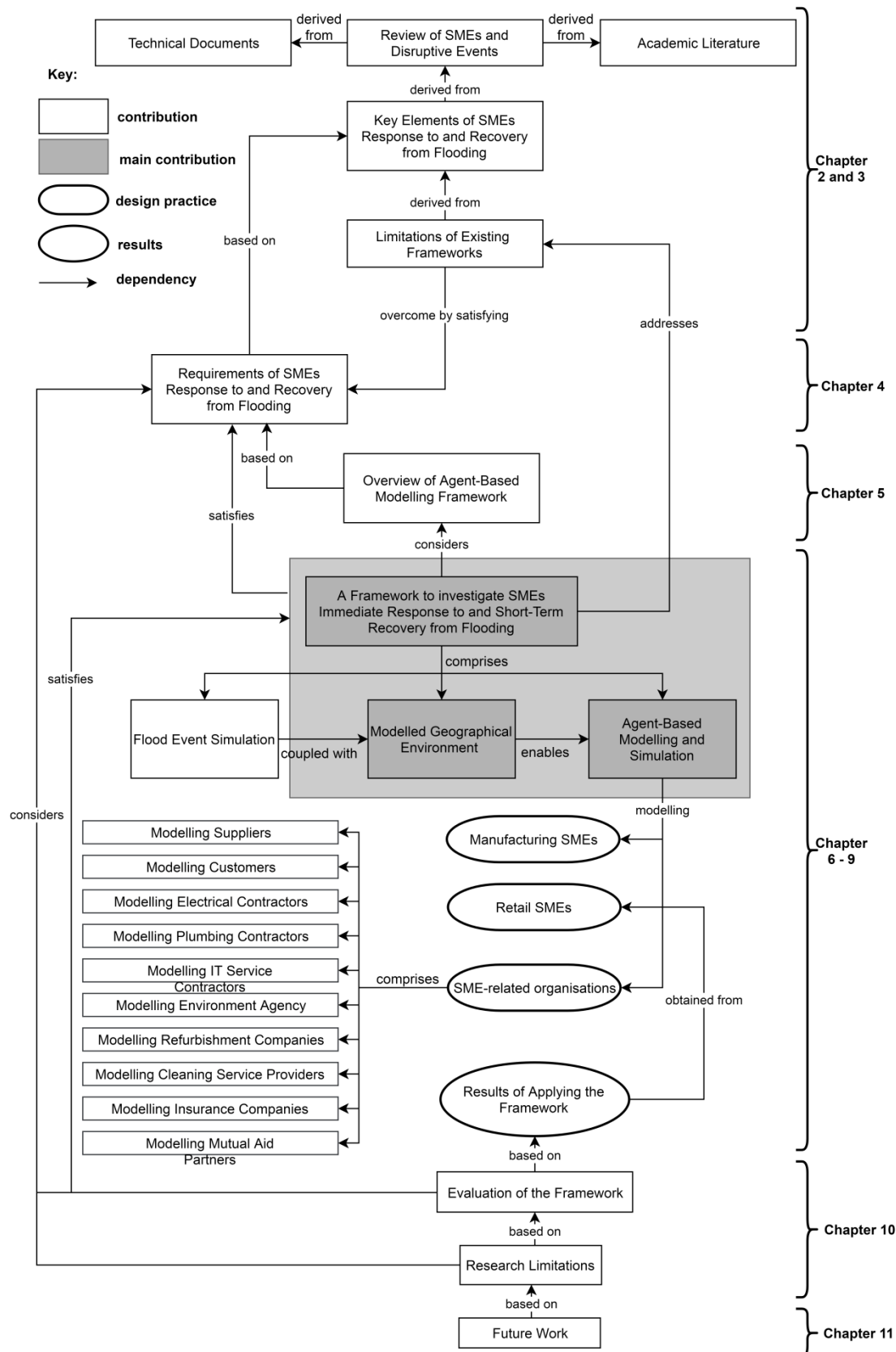


Figure 11.1: Summary of the work

11.4 ABMS FRAMEWORK

The developed ABMS framework presents an original and significant contribution to knowledge in the area of investigating SMEs' immediate response to and short-term recovery from flooding. The ABMS framework consists of three integrated components: flood event simulation; modelled geographical environment (MGE); and agent-based modelling and simulation.

- 1) Flood event simulation represents the input data (e.g. inundation data) that feeds into the MGE component. The input data is not part of the presented contribution to knowledge. This is because it was provided from colleges at the University of Leeds.
- 2) The MGE combines Ordnance Survey (OS) MasterMap® data (e.g. *Topography*, Integrated Transport Network (*ITN*), and *AddressBase Plus* layers) with the input from the flood event simulation to enable the identification of the flooded and non-flooded organisations. Consequently, the identified organisations, including flooded and non-flooded SMEs, in addition to related organisations, are modelled as autonomous agents and simulated over three timeframes: pre-flood, during flood, and post-flood.
- 3) Agent-based modelling and simulation was chosen as a suitable method due to its established efficacy in solving complex business-related problems. Agent-based models (ABMs) are computational constructs used to simulate the actions and interactions of autonomous agents in order to evaluate their impacts on a system as a whole (Axelrod, 2005). The Recursive Porous Agent Simulation Toolkit (Repast) was used to implement the ABMS due to its capability to model social interventions (and industrial analysis) based on current theories and data (Tobias & Hofmann, 2004).

11.5 CASE STUDIES AND RESULTS

The two case studies considered in this research are related to the 2007 UK flood events in (a) the Lower Don Valley of Sheffield and (b) Tewkesbury. The former was

selected due to its high concentration of SMEs, some of which have experienced flooding and/or are prone to flooding; the latter was selected due to the historic high water levels during flooding that have significantly impacted homes and businesses.

For the Lower Don Valley of Sheffield, the *AddressBase Plus* layer was used to construct the MGE coupled with the inundation data. A total of 6224 organisations were identified in the area, of which 906 were flooded at some point during the 45.5-hour flood event modelled. For Tewkesbury, after coupling the OS MasterMap® data, including the *AddressBase Plus* layer and the inundation data, a total of 920 organisations were identified in the area, of which 207 were flooded at some point during the 318.5 hours simulated.

In both geographical areas, the identified manufacturing and retail SMEs were modelled as autonomous agents and simulated in accordance with their (i) pre-flood and post-flood behaviours, (ii) static and dynamic attributes, and (iii) a set of the flood-resistance, flood-resilience, and business continuity/risk management precautionary measures. A total of 16 different simulation experiments were performed in which each of these simulation experiments involved a different combination of precautionary measures.

In relation to the results, this research has found that the flood resistance precautionary measures are effective for lightly and moderately flooded manufacturing and retail SMEs. However, the severely flooded manufacturing and retail SMEs simulated with a combination of flood resistance precautionary measures as well as business continuity/risk management tend to maintain higher production levels and service capability profiles, respectively.

11.6 EVALUATION

Based on the evaluation of the ABMS framework, the achievements and weaknesses have been discussed in terms of the framework application. Firstly, the constructed MGE of the two case studies considered in this research has been used to identify the flooded and non-flooded organisations, and to present the visual representation of a series of footprints of the flood water in the geographical areas considered. Next, manufacturing and retail SMEs are modelled as autonomous agents with a set of behaviours, attributes, and precautionary measures, such that they respond

to and recover from flood events. In terms of SME-related organisations, these have been modelled and examined to determine how they have supported SMEs in terms of their immediate response to and short-term recovery from flooding. SMEs and SME-related organisations can communicate and exchange information via messages. For the analysis, two performance metrics have been modelled and managed in order to investigate manufacturing and retail SMEs' performance during the course of a simulation.

11.7 FUTURE WORK

The ABMS framework developed and presented in this thesis could be generalised to other disruptive events and incidents such as extreme weather (e.g. storms, heatwaves or extreme cold), energy loss (e.g. blackouts or power loss), communication failures and epidemics. However, it is first necessary to make some modifications to the ABMS framework to enable the immediate response and short-term recovery of SMEs to such incidents to be modelled and simulated. These modifications should include consideration of the following requirements.

- Behaviours and their related dependency relationships, number of employees required to enact these behaviours (if needed), priority of execution, classification (i.e. a generic behaviour or specific behaviour), and duration range need to be established and managed.
- There is also a need to model a set of attributes to define the modelled agents' identities. Further, there is a need to establish which specific attributes can remain static or may vary during the course of a simulation.
- A set of precautionary measures appropriate for the type of disruptive event considered should be modelled such that they have direct or indirect impacts on agents' performance. This enables the simulation experiments to be set out in terms of the precautionary measure classifications, which, in turn, enables an investigation of agents' performance to be carried out based on this classification.
- There is a need to determine the appropriate performance metrics to be modelled and established in relation to the type of disruptive event considered.

This is to measure each agent's expected operational performance before, during, and after an incident occurs.

Further improvements to the developed ABMS framework are proposed regarding the key elements of the ABMS framework.

- The MGE could be improved by coupling recent flood-event inundation data with the OS MasterMap® layers for the same year. This will increase the accuracy of identifying the flooded and non-flooded organisations.
- For SMEs, more industrial sectors, such as transportation and storage, and real estate activities, could be modelled along with more generic and specific sets of behaviours, attributes, and precautionary measures related to the modelled sectors. This will expand the scope of the framework.
- SME-related organisations could be modelled with the addition of more information. For example, suppliers and customers can be modelled to the same level of detail as SMEs. Specifically, they can be modelled with real data, which will enable them to be modelled with their actual names, classifications, and exact locations. This will enable the developed framework to consider the time required for raw material dispatch and product delivery to reach an SME's premises. Next, insurance companies can be modelled with a larger set of options. For instance, insurance companies can be modelled by ensuring that each group of insurance companies provides a different range of services so that SMEs can subsequently choose their insurer based on the services provided.
- In terms of interactions, SME-related organisation agents may interact among themselves in that they can exchange information related to SMEs. For example, suppliers and customers may exchange information related to traffic flow in order to reach a particular SME's premises successfully. Also, cleaning service providers may interact among themselves so that they can exchange information related to SMEs to offer services to the affected SMEs.
- SMEs' modelled performance metrics could be further developed by including additional dynamic attributes. For example, if more sectors are modelled, these performance metrics can be expanded to measure recently modelled sectors, in addition to the current ones.

References

- Abdel-Maksoud, A., Dugdale, D., & Luther, R. (2005). Non-financial performance measurement in manufacturing companies. *The British Accounting Review*, 37(3), 261-297.
- ABI. (2005). *Financial Risks of Climate Change*. Retrieved from UK: <http://insurance.lbl.gov/documents/abi-climate.pdf>
- ABI. (2007). *Summer Floods 2007: Learning the Lessons*. Retrieved from London: https://www.ambiental.co.uk/wp-content/uploads/2018/07/ABI_2007_Summer_Floods_Review.pdf
- ABI. (2017). *A guide to resistant and resilient repair after a flood*. Retrieved from London, UK: <https://www.abi.org.uk/globalassets/files/publications/public/flooding/abi-guide-to-resistant-and-resilient-repair-after-a-flood-2019.pdf>
- ABI. (2018). *UK Insurance & Long-Term Savings Key Facts*. Retrieved from <https://www.abi.org.uk/globalassets/sitecore/files/documents/publications/public/2016/keyfacts/keyfacts2016.pdf>
- Act, S. B. (2008). Think small first, a “small business act” for Europe. *Communication from the commission to the council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Commission of the European Communities Brussels*, 25, 2008.
- Alexander, D. E. (2002). *Principles of emergency planning and management*: Oxford University Press on Demand.
- Algers, S., Bernauer, E., Boero, M., Breheret, L., Di Taranto, C., Dougherty, M., . . . Gabard, J.-F. (1997). Review of micro-simulation models. *Review Report of the SMARTTEST project*.
- Alharbi, M., & Coates, G. (2017). *An agent-based modelling and simulation framework to assess small businesses' recovery from flooding*. Paper presented at the European Modeling and Simulation Symposium (EMSS), Barcelona, Spain.
- Alharbi, M., & Coates, G. (2018). An Investigation of Small and Medium-Sized Enterprises' Flood Preparation and Insurance Coverage using Agent-Based Modelling. *WIT Transactions on the Built Environment*, 184, 143-152.
- Alharbi, M., & Coates, G. (2019a). *Assessing Flood Recovery of Small Businesses using Agent-Based Modelling and Simulation*. Paper presented at the Proceedings of the 16th International Conference on Information Systems for Crisis Response And Management, Valencia, Spain.
- Alharbi, M., & Coates, G. (2019b). Investigating manufacturing small and medium-sized enterprises' immediate response and short-term recovery from flooding using an agent-based approach. *International Journal of Simulation and Process Modelling*, 14(2), 87-104.
- Allianz. (2018). *Loss Adjuster Frequently Asked Questions*. Retrieved from https://www.allianz.co.uk/content/allianzcouk/en_gb/application/content/documents/business/claims/loss-adjusters-faqs/_jcr_content/documentProperties/currentDocument.res/acom6845-loss-adjusters.pdf

- Alsaedi, N., Burnap, P., & Rana, O. (2017). Can we predict a riot? Disruptive event detection using Twitter. *ACM Transactions on Internet Technology (TOIT)*, 17(2), 18.
- Amouroux, E., Chu, T.-Q., Boucher, A., & Drogoul, A. (2007). *GAMA: an environment for implementing and running spatially explicit multi-agent simulations*. Paper presented at the Pacific Rim International Conference on Multi-Agents.
- Arunachalam, S., Zalila-Wenkstern, R., & Steiner, R. (2008). *Environment mediated multi agent simulation tools—a comparison*. Paper presented at the 2008 Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems Workshops.
- Arvitrida, N. I., Tako, A. A., Robertson, D. A., & Robinson, S. (2017). Duration of collaboration from a market perspective: An agent-based modeling approach.
- Asgary, A., Anjum, M. I., & Azimi, N. (2012). Disaster recovery and business continuity after the 2010 flood in Pakistan: Case of small businesses. *International Journal of Disaster Risk Reduction*, 2, 46-56.
- Ashby, W. R., & Stogdill, R. M. (1970). *The process of model-building in the behavioral sciences*: Ohio State University Press.
- Association of British Insurers. (2016). *Responding to major floods*. Retrieved from <https://www.abi.org.uk/globalassets/sitecore/files/documents/publications/public/2015/property/responding-to-major-floods.pdf>
- Association of British Insurers. (2019). *A guide to resistant and resilient repair after a flood*. Retrieved from <https://www.merseysideprepared.org.uk/media/1387/a-guide-to-resistant-and-resilient-repair-after-a-flood.pdf>
- Axelrod, R. (1997). *The complexity of cooperation: Agent-based models of competition and collaboration* (Vol. 1): Princeton University Press.
- Axelrod, R. (2005). A Guide for Newcomers to Agent-Based Modeling in the Social Sciences. *Handbook of Computational Economics*. L. Tesfatsion and K. Judd. In: Amsterdam, North Holland.
- Ayyagari, M., Demirgüç-Kunt, A., & Beck, T. (2003). *Small and medium enterprises across the globe: a new database*: The World Bank.
- Baird, M. (2010). The recovery phase of emergency management. *Prepared for the Intermodal Freight Transportation Institute, University of Memphis, Tennessee*.
- Bajracharya, K., & Duboz, R. (2013). *Comparison of three agent-based platforms on the basis of a simple epidemiological model (WIP)*. Paper presented at the Proceedings of the Symposium on Theory of Modeling & Simulation-DEVS Integrative M&S Symposium.
- Balbi, S., & Giupponi, C. (2009). Reviewing agent-based modelling of socio-ecosystems: a methodology for the analysis of climate change adaptation and sustainability. University Ca'Foscari of Venice, Dept of Economics Research Paper Series (15_09). *Ca'Foscari University of Venice*.
- Bandini, S., Manzoni, S., & Vizzari, G. (2009). Agent based modeling and simulation: an informatics perspective. *Journal of Artificial Societies and Social Simulation*, 12(4), 4.
- Banks, J., Carson, J., Nelson, B., & Nicol, D. (2001). Verification and validation of simulation models. *Discrete-event system simulation, 3rd Edition, Prentice-Hall, Upper Saddle River (NJ)*, 367-397.
- Bannock, G. (2004). *The economics and management of small business: an international perspective*: Routledge.
- Barenji, A. V., Barenji, R. V., Roudi, D., & Hashemipour, M. (2017). A dynamic multi-agent-based scheduling approach for SMEs. *The International Journal of Advanced Manufacturing Technology*, 89(9-12), 3123-3137.
- Barnett, J. (2001). Adapting to climate change in Pacific Island countries: the problem of uncertainty. *World Development*, 29(6), 977-993.

- Batty, M. (2009). Urban modeling. International encyclopedia of human geography. In: Elsevier, Oxford.
- Beddoes, D. W., & Booth, C. (2011). Property level flood adaptation measures: a novel approach. *International Journal of Safety and Security Engineering*, 1(2), 162-181.
- Benn, H. (2009). *The Government's Response to Sir Michael Pitt's Review of the summer 2007 Floods*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69426/pb13565-pitt-progress-091215.pdf
- Bhattacharya-Mis, N., & Lamond, J. (2014). *An investigation of patterns of response and recovery among flood-affected businesses in the UK: a case study in Sheffield and Wakefield*. Paper presented at the International Conference on Flood Recovery, Innovation and Response.
- Bianchi, C., Cirillo, P., Gallegati, M., & Vagliasindi, P. A. (2007). Validating and calibrating agent-based models: a case study. *Computational Economics*, 30(3), 245-264.
- Richard, E., & Kazmierczak, A. (2009). Resilient homes: Reward-based methods to motivate householders to address dangerous climate change.
- Birkin, M., & Wu, B. (2012). A review of microsimulation and hybrid agent-based approaches. In *Agent-based models of geographical systems* (pp. 51-68): Springer.
- Blackmore, K., Bossomaier, T., Jarratt, D., & Nesbitt, K. (2003). *Intelligent agent framework for modelling the evolution of small and medium sized enterprises*. Paper presented at the Proceeding of the 8th Australian and New Zealand Conference on Intelligent Information Systems.
- Boots, B., & Csillag, F. (2006). Categorical maps, comparisons, and confidence. *Journal of Geographical Systems*, 8(2), 109-118.
- Boston, M., Brooks, D., Nervi, A., & Ulbricht, J. (2012). *Flood Alert Sump Pump Monitoring System*. Retrieved from <https://www.uakron.edu/dotAsset/6af8bae0-561c-4d13-9eea-83f4314f90aa.pdf>
- Bowker, P. (2007). Flood resistance and resilience solutions: an R&D scoping study. *DEFRA Report, London*.
- British Columbia. (2014). *Mutual Aid Agreement Guideline – Ministry of Energy and Mines*. Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/mineral-exploration-mining/documents/health-and-safety/mem_mutual_aid_guideline_may_2014.pdf
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra*, 19(4), 733-752.
- Cameron, D., & Proverbs, D. (2014). Improving the uptake of flood risk adaptation measures for domestic properties in an insurance regime under transition. *Flood Recovery, Innovation and Response IV*, 184, 139-149.
- Carslaw, G. (2013). *Agent based modelling in social psychology*. University of Birmingham.
- Castle, C. J., & Crooks, A. T. (2006). Principles and concepts of agent-based modelling for developing geospatial simulations.
- Chang, S. E. (2010). Urban disaster recovery: a measurement framework and its application to the 1995 Kobe earthquake. *Disasters*, 34(2), 303-327.
- Chappin, E. J., Dijkema, G. P., van Dam, K. H., & Lukszo, Z. (2007). *Modeling strategic and operational decision-making—an agent-based model of electricity producers*. Paper presented at the Proceedings of the 21st annual European Simulation and Modelling Conference (ESM2007), St. Julian's, Malta.
- Chatterton, J., Viavattene, C., Morris, J., Penning-Rowsell, E. C., & Tapsell, S. M. (2010). The costs of the summer 2007 floods in England.

- Chen, D.-N., Jeng, B., Lee, W.-P., & Chuang, C.-H. (2008). An agent-based model for consumer-to-business electronic commerce. *Expert Systems with Applications*, 34(1), 469-481.
- Clarke, K. C. (2014). Cellular automata and agent-based models. In *Handbook of regional science* (pp. 1217-1233): Springer.
- Clifford, N. (2008). Models in geography revisited. *Geoforum*, 39(2), 675-686.
- Coates, G., Alharbi, M., Li, C., Ahilan, S., & Wright, N. (2019a). Evaluating the operational resilience of SMEs to flooding using a computational modelling and simulation approach: a case study of the 2007 flood in Tewkesbury. *Philosophical Transactions A*.
- Coates, G., Hawe, G., Wright, N., & Ahilan, S. (2014). Agent-based modelling and inundation prediction to enable the identification of businesses affected by flooding. *WIT Transactions on Ecology and the Environment*, 184, 13-22.
- Coates, G., Li, C., Ahilan, S., Wright, N., & Alharbi, M. (2019b). Agent-based modeling and simulation to assess flood preparedness and recovery of manufacturing small and medium-sized enterprises. *Engineering Applications of Artificial Intelligence*, 78, 195-217.
- Coates, G., Li, C., Wright, N., & Ahilan, S. (2016). Investigating The Flood Responsiveness Of Small And Medium Enterprises Using Agent-Based Modelling And Simulation. *Flood Risk Management and Response*, 173.
- Codd, E. F. (2014). *Cellular automata*: Academic Press.
- Collier, N., & North, M. (2011). Repast HPC: A platform for large-scale agentbased modeling. *Large-Scale Computing Techniques for Complex System Simulations*, 81-110.
- Coppola, D. P. (2006). *Introduction to international disaster management*: Elsevier.
- Cosgrove, J., Butler, J., Alden, K., Read, M., Kumar, V., Cucurull-Sanchez, L., . . . Coles, M. (2015). Agent-Based Modeling in Systems Pharmacology. *CPT: Pharmacometrics & Systems Pharmacology*, 4(11), 615-629.
- Crichton, D. (2006). *Climate Change and its Effects on Small Businesses in the UK*: Axa Insurance.
- Crooks, A. T. (2008). Constructing and implementing an agent-based model of residential segregation through vector GIS.
- Crooks, A. T., & Castle, C. J. (2012). The integration of agent-based modelling and geographical information for geospatial simulation. In *Agent-based models of geographical systems* (pp. 219-251): Springer.
- Crooks, A. T., & Heppenstall, A. J. (2012). Introduction to agent-based modelling. In *Agent-based models of geographical systems* (pp. 85-105): Springer.
- Curran, J., & Blackburn, R. (2000). *Researching the small enterprise*: Sage.
- Curtis, S., Fair, A., Wistow, J., Val, D. V., & Oven, K. (2017). Impact of extreme weather events and climate change for health and social care systems. *Environmental Health*, 16(1), 128.
- DAB. (2019). *QUICK GUIDE FOR PUMP SELECTION*. Retrieved from https://www.dabpumps.com/sites/default/files/2017-10/60118741_QUICK%20GUIDE%20FOR%20PUMP%20SELECTION_ENG.pdf
- Dawson, R. J., Peppe, R., & Wang, M. (2011). An agent-based model for risk-based flood incident management. *Natural Hazards*, 59(1), 167-189.
- DBEIS. (2018). *Businesses Population Estimates for the UK and regions 2018*. Retrieved from London SW1H OET: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/746599/OFFICIAL_SENSITIVE_-_BPE_2018_-_statistical_release_FINAL_FINAL.pdf

- Defra. (2005). Making space for water: taking forward a new government strategy for flood and coastal erosion risk management in England.
- Dhonau, M., & Rose, C. B. (2016). *A Business Guide to Flood Resilience*. Retrieved from http://www.knowyourfloodrisk.co.uk/sites/default/files/FloodGuide_ForBusinesses.pdf
- Dignum, V., & Tick, C. (2007). *Agent-based analysis of organizations: Formalization and simulation*. Paper presented at the Intelligent Agent Technology, 2007. IAT'07. IEEE/WIC/ACM International Conference on.
- DIY. (2019). Electrical Socket and Light Switch Height Regulations. Retrieved from <https://www.diydoctor.org.uk/projects/socketheight.htm>
- Dlugolecki, A. (2008). Climate change and the insurance sector. *The Geneva Papers on Risk and Insurance-Issues and Practice*, 33(1), 71-90.
- Du, E., Cai, X., Sun, Z., & Minsker, B. (2017). Exploring the role of social media and individual behaviors in flood evacuation processes: An agent-based modeling approach. *Water Resources Research*, 53(11), 9164-9180.
- Dubbelboer, J., Nikolic, I., Jenkins, K., & Hall, J. (2017). An agent-based model of flood risk and insurance. *Journal of Artificial Societies and Social Simulation*, 20(1).
- EAP. (2014). Emergency Action Plan for Retail Food Establishments. In *2014 Conference for Food Protection - Emergency Action Plan for Retail Food Establishments, Second Edition* (Second ed.): Emergency Action Plan Committee of Council III 2012-2014 Conference for Food Protection.
- East Ayrshire Council. (2019). *A Typical Flood Wall Detail*. Retrieved from <https://www.ayrshireroadsalliance.org/Resources/pdf/Consultations/New-Cumnock-Flood-Protection-Scheme---Plan-1.pdf>
- EKOS Consulting Ltd. (2008). Evaluation of Yorkshire Forward's Flood Response. In: EKOS Consulting (UK) Ltd Sheffield.
- Electric Call. (2019). Aylesbury Electrician. Retrieved from <https://www.electric-call.net/electrician-in-aylesbury/?id=electrician-in-aylesbury>
- Environment Agency. (2009). Flooding in England: a national assessment of flood risk. In: Environment Agency Bristol.
- Environment Agency. (2019a). *Egremont Flood Risk Management Scheme*. Retrieved from <https://thefloodhub.co.uk/wp-content/uploads/2019/02/Egremont-Flood-Risk-Management-booklet.pdf>
- Environment Agency. (2019b). Long term flood risk information. Retrieved from <https://flood-warning-information.service.gov.uk/long-term-flood-risk/map>
- Environment Agency. (2019c). *Prepare your property for flooding*. Retrieved from Bristol, UK: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/451622/LIT_4284.pdf
- Environment Agency. (2019d). *What to do before, during and after a flood*. Retrieved from Bristol, UK: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/403213/LIT_5216.pdf
- Epstein, J. M. (1999). Agent-based computational models and generative social science. *Complexity*, 4(5), 41-60.
- European Commission. (2015). User guide to the SME definition. *Luxembourg: Publications Office of the European Union*.
- European Environment Agency. (2011). *Mapping the impacts of natural hazards and technological accidents in Europe: An overview of the last decade*: Publications Office of the European Union.

- FEMA. (2013). *Design Considerations in Floodproofing*. Retrieved from https://www.fema.gov/media-library-data/643d07bceee8ade17eef8e11cf7a2abb/P-936_sec2_508.pdf
- Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*: Cambridge University Press.
- Figari, F., Paulus, A., & Sutherland, H. (2015). Microsimulation and policy analysis. In *Handbook of income distribution* (Vol. 2, pp. 2141-2221): Elsevier.
- Finch, P. (2004). Supply chain risk management. *Supply Chain Management: An International Journal*, 9(2), 183-196.
- Flood Risk Management Guidance*. (2015). Retrieved from Hertfordshire:
- Francis, D., & Hengeveld, H. (1998). Extreme weather and climate change.
- Francis, R., Alker, J., Ford, N., Kershaw, J., & Laski, J. (2016). *Health, Wellbeing & Productivity in Retail: the Impact of Green Building on People and Profit*. Retrieved from <https://www.ukgbc.org/wp-content/uploads/2017/09/UK-GBC-Health-Wellbeing-Retail-Report-2016-WEB.pdf>
- Franklin, S., & Graesser, A. (1996). *Is it an Agent, or just a Program?: A Taxonomy for Autonomous Agents*. Paper presented at the International Workshop on Agent Theories, Architectures, and Languages.
- Fredrick, N. D., Berges, J. A., Twining, B. S., Nuñez-Milland, D., & Hellweger, F. L. (2013). Use of agent-based modeling to explore the mechanisms of intracellular phosphorus heterogeneity in cultured phytoplankton. *Appl. Environ. Microbiol.*, 79(14), 4359-4368.
- Furniture Industry Research Association. (2019). How does office furniture comply with the display screen equipment (DSE) Regulations? Retrieved from <https://www.fira.co.uk/technical-information/ergonomics/how-does-office-furniture-desks-and-chairs-comply-with-the-display-screen-equipment-dse-regulations>
- Gilbert, G., Ahrweiler, P., & Pyka, A. (2010). Learning in innovation networks: some simulation experiments.
- Gilbert, N. (2007). Agent-Based Models. 2007. In: Los Angeles: Sage Publications Inc.
- Gilbert, N., & Banks, S. (2002). Platforms and methods for agent-based modeling. *Proceedings of the National Academy of Sciences*, 99(suppl 3), 7197-7198.
- Gilbert, N., & Terna, P. (2000). How to build and use agent-based models in social science. *Mind & Society*, 1(1), 57-72.
- Gloucestershire County Council. (2015). *Understanding Tewkesbury Borough*. Retrieved from https://www.gloucestershire.gov.uk/media/1521548/understanding_tewkesbury_borough-4.pdf
- Go Compare Insurance. (2019). *Limiting flood risk and damage*. Retrieved from <https://www.gocompare.com/home-insurance/limiting-flood-risk-and-damage/>
- Gomes, C. F., Yasin, M. M., & Lisboa, J. V. (2004). A literature review of manufacturing performance measures and measurement in an organizational context: a framework and direction for future research. *Journal of Manufacturing Technology Management*, 15(6), 511-530.
- Gon, K. T., Zeigler, B. P., & Praehofer, H. (2000). Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems.
- Goodall, D. W. (1972). Building and testing ecosystem models. *Mathematical models in ecology*, 173-194.
- Gordon, S. (2006). The normal distribution. *Mathematics Learning Centre, University of Sydney. Hal*, 1-41.

- Graham, J. D., Habegger, B., Cleeland, B., & Florin, M. V. (2009). *Risk Governance Deficits: An analysis and illustration of the most common deficits in risk governance*: ETH Zurich.
- Griffin, A. S., & Brandyberry, A. A. (2010). System development methodology usage in industry: a review and analysis. *Journal of Information Systems Applied Research*, 3(19), 1-18.
- Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., . . . Huse, G. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological modelling*, 198(1-2), 115-126.
- Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J., & Railsback, S. F. (2010). The ODD protocol: a review and first update. *Ecological modelling*, 221(23), 2760-2768.
- Grimm, V., Polhill, G., & Touza, J. (2017). Documenting social simulation models: The ODD protocol as a standard. In *Simulating Social Complexity* (pp. 349-365): Springer.
- Grimm, V., & Railsback, S. F. (2013). *Individual-based modeling and ecology* (Vol. 8): Princeton university press.
- Gudmundsson, A., & Mohajeri, N. (2013). Entropy and order in urban street networks. *Scientific reports*, 3, 3324.
- Guha, M. (2016). Routine responses to disruption of routines. *International Journal of Learning and Change*, 8(2). doi:10.1504/IJLC.2015.074065
- Gunningham, N. (2002). Regulating small and medium sized enterprises. *Journal of Environmental Law*, 3-32.
- Haer, T., Botzen, W. W., de Moel, H., & Aerts, J. C. (2017). Integrating household risk mitigation behavior in flood risk analysis: an agent-based model approach. *Risk Analysis*, 37(10), 1977-1992.
- Hallberg, K. (1999). Small and medium scale enterprises: A framework for intervention. *The World Bank*, 1-22.
- Hallett, S. (2013). *Community Resilience to Extreme Weather—the CREW Project: Final Report*. 110 pp. Retrieved from <http://www.extreme-weather-impacts.net>
- Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12(1), 14-29.
- Han, J., & Miller, H. J. (2009). *Geographic data mining and knowledge discovery*: CRC Press.
- Hanusz, Z., Tarasinska, J., & Zielinski, W. (2016). Shapiro-Wilk test with known mean. *REVSTAT-Statistical Journal*, 14(1), 89-100.
- Hargrove, W. W., Hoffman, F. M., & Hessburg, P. F. (2006). Mapcurves: a quantitative method for comparing categorical maps. *Journal of Geographical Systems*, 8(2), 187.
- HCTC. (2011). *Keeping the UK moving: The impact on transport of the winter weather in December 2010*. Retrieved from
- Heaslip, K., Louisell, W., Collura, J., & Urena Serulle, N. (2010). *A sketch level method for assessing transportation network resiliency to natural disasters and man-made events*. Retrieved from
- Heath, B., Hill, R., & Ciarallo, F. (2009). A survey of agent-based modeling practices (January 1998 to July 2008). *Journal of Artificial Societies and Social Simulation*, 12(4), 9.
- Heating, V. (2019). Emergency Electricians.
- Henderson, F., & Whittam, G. (2016). Evolutionary or equilibrist? Small businesses resilience to flooding in Scotland. *Studia Miejskie*, 24, 23-41.
- Heppenstall, A. J., Crooks, A. T., See, L. M., & Batty, M. (2011). *Agent-based models of geographical systems*: Springer Science & Business Media.
- HM Government. (2013). Emergency Response and Recovery: Non Statutory Guidance Accompanying the Civil Contingencies Act 2004. In: Cabinet Office London.
- Holland, J. H. (1995). *Hidden order how adaptation builds complexity*.

- Holm, S., Lemm, R., Thees, O., & Hilty, L. M. (2016). Enhancing agent-based models with discrete choice experiments. *Journal of Artificial Societies and Social Simulation*, 19(3).
- Howe, T., Collier, N., North, M., Parker, M., & Vos, J. (2006). *Containing agents: Contexts, projections, and agents*. Paper presented at the Proceedings of the Agent 2006 Conference on Social Agents: Results and Prospects. Argonne, Illinois, USA: Argonne National Laboratory.
- Howick, S., Ackermann, F., Eden, C., & Williams, T. (2009). Understanding the causes and consequences of disruption and delay in complex projects: how system dynamics can help.
- HSE. (2015). *A recipe for safety* (H. a. S. Executive Ed.).
- Hübl, J., Holub, M., & Suda, J. (2005). *Structural mitigation measures*. Paper presented at the 3rd Probabilistic Workshop: Technical Systems+ Natural Hazards, edited by: Bergmeister, K., Rickenmann, D., Strauss, A., Wieshofer, S., Curbach, M., and Proske, D., Universität für Bodenkultur, Department für Bautechnik und Naturgefahren.
- Ideal Response. (2019). Flood Damage Cleaning.
- IFF. (2008). The Annual Survey of Small Businesses' Opinions 2006/07 Summary report of findings among UK SME employers. *IFF Research*.
- Ingirige, & Russell, R. (2015). Investigating SME resilience to flooding: the Braunton report. In: University of Salford.
- Ingirige, B., Proverbs, D., & Wedawatta, G. (2012). Impact of flooding on SME's and their relevance to Chartered Surveyors. *London, RICS*. [Google Scholar].
- IPIECA. (2014). *Mutual Aid Indemnification and Liability* Retrieved from London, UK: <http://www.oilspillresponseproject.org/wp-content/uploads/2017/01/JIP-13-Mutual-aid-indemnification.pdf>
- Islam, M. N., & van Amstel, A. (2018). *Bangladesh I: Climate Change Impacts, Mitigation and Adaptation in Developing Countries*: Springer.
- ISO, I. O. f. S. (2018). ISO 22300: 2018(en) Security and Resilience - Vocabulary. In.
- Jenkins, K., Surminski, S., Hall, J., & Crick, F. (2017). Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Science of the Total Environment*, 595, 159-168.
- Jha, A. K., Miner, T. W., & Stanton-Geddes, Z. (2013). *Building urban resilience: principles, tools, and practice*: The World Bank.
- Johnson, L. (2015). 10. Complexity modelling and application to policy research. *Handbook on Complexity and Public Policy*, 150.
- Jones, K., & Ingirige, B. (2008). *Extreme weather events and business continuity planning*. Paper presented at the CIB W70 International Conference in Facilities Management.
- Jones, O., & Tilley, F. (2003). *Competitive advantage in SMEs: organising for innovation and change*: Wiley.
- Jonkman, S. N., Bočkarjova, M., Kok, M., & Bernardini, P. (2008). Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecological economics*, 66(1), 77-90.
- Jordan, E., & Javernick-Will, A. (2013). Indicators of community recovery: content analysis and Delphi approach. *Natural Hazards Review*, 14(1), 21-28.
- Joseph, R., Proverbs, D., & Lamond, J. (2015). Homeowners' perception of the benefits of property level flood risk adaptation (PLFRA) measures: The case of the summer 2007 event in England. *International Journal of Safety and Security Engineering*, 5(3), 251-265.

- Joseph, R., Proverbs, D., Lamond, J., & Wassell, P. (2011). An analysis of the costs of resilient reinstatement of flood affected properties: A case study of the 2009 flood event in Cockermouth. *Structural Survey*, 29(4), 279-293.
- Kazmierczak, A., & Bichard, E. (2010). Investigating homeowners' interest in property-level flood protection. *International Journal of Disaster Resilience in the Built Environment*, 1(2), 157-172.
- Keogh, D. U., Apan, A., Mushtaq, S., King, D., & Thomas, M. (2011). Resilience, vulnerability and adaptive capacity of an inland rural town prone to flooding: a climate change adaptation case study of Charleville, Queensland, Australia. *Natural Hazards*, 59(2), 699-723.
- Khalili, S., Harre, M., & Morley, P. (2015). A temporal framework of social resilience indicators of communities to flood, case studies: Wagga Wagga and Kempsey, NSW, Australia. *International Journal of Disaster Risk Reduction*, 13, 248-254.
- Khan, H., Vasilescu, L. G., & Khan, A. (2008). Disaster management cycle-a theoretical approach. *Journal of Management and Marketing*, 6(1), 43-50.
- Kim, T. K. (2015). T test as a parametric statistic. *Korean journal of anesthesiology*, 68(6), 540.
- King, A. (1995). Avoiding ecological surprise: Lessons from long-standing communities. *Academy of Management review*, 20(4), 961-985.
- Klügl, F. (2008). *A validation methodology for agent-based simulations*. Paper presented at the Proceedings of the 2008 ACM symposium on Applied computing.
- Kocabas, V., & Dragicevic, S. (2009). Agent-based model validation using Bayesian networks and vector spatial data. *Environment and Planning B: Planning and Design*, 36(5), 787-801.
- Kok, K., Farrow, A., Veldkamp, A., & Verburg, P. H. (2001). A method and application of multi-scale validation in spatial land use models. *Agriculture, Ecosystems & Environment*, 85(1-3), 223-238.
- Kornhauser, D., Wilensky, U., & Rand, W. (2009). Design guidelines for agent based model visualization. *Journal of Artificial Societies and Social Simulation*, 12(2), 1.
- Kreibich, H., Müller, M., Thieken, A. H., & Merz, B. (2007). Flood precaution of companies and their ability to cope with the flood in August 2002 in Saxony, Germany. *Water Resources Research*, 43(3).
- Kreibich, H., Seifert, I., Thieken, A. H., Lindquist, E., Wagner, K., & Merz, B. (2011). Recent changes in flood preparedness of private households and businesses in Germany. *Regional environmental change*, 11(1), 59-71.
- Kreider, D., Lahr, D., & Diesel, S. (2005). *Principles of Calculus Modeling: An Interactive Approach*: Springer, NY.
- Kundzewicz, Z. (2005). Is the frequency and intensity of flooding changing in Europe? In *Extreme Weather Events and Public Health Responses* (pp. 25-32): Springer.
- Landis, J., & Zhang, M. (1998). The second generation of the California urban futures model. Part 2: Specification and calibration results of the land-use change submodel. *Environment and Planning B: Planning and Design*, 25(6), 795-824.
- Lane, S. N. (2008). Climate change and the summer 2007 floods in the UK. *Geography*, 93(2), 91.
- Lauder, D., Boocock, G., & Presley, J. (1994). The system of support for SMEs in the UK and Germany. *European Business Review*, 94(1), 9-16.
- Law, A. M. (2008). *How to build valid and credible simulation models*. Paper presented at the Simulation Conference, 2008. WSC 2008. Winter.
- Law, A. M., Kelton, W. D., & Kelton, W. D. (2000). *Simulation modeling and analysis* (Vol. 3): McGraw-Hill New York.

- Lei, Z., Pijanowski, B. C., Alexandridis, K. T., & Olson, J. (2005). Distributed modeling architecture of a multi-agent-based behavioral economic landscape (MABEL) model. *Simulation*, 81(7), 503-515.
- Leinster, P. (2009). Flooding in England: a national assessment of flood risk. *Environment Agency, Almondsbury*.
- Li, C., & Coates, G. (2016). Design and development of an agent-based model for business operations faced with flood disruption. *Complex Syst.: Fundam. Appl*, 90, 275.
- Li, C., Coates, G., McGuinness, M., & Johnson, N. (2015). Designing an agent-based model of SMEs to assess flood response strategies and resilience.
- Line, B. (2011). *Using People Counting and Conversion Rates to Increase Sales*. Retrieved from <http://envysion.com/media/People-Counting-vFinal-2011-12-01.pdf>
- Linnenluecke, M., & Griffiths, A. (2010). Beyond adaptation: resilience for business in light of climate change and weather extremes. *Business & Society*, 49(3), 477-511.
- Liu, X., & Lim, S. (2018). An agent-based evacuation model for the 2011 Brisbane City-scale riverine flood. *Natural Hazards*, 94(1), 53-70.
- Liu, Y., Okada, N., Shen, D., & Li, S. (2009). Agent-based flood evacuation simulation of life-threatening conditions using vitae system model. *Journal of Natural Disaster Science*, 31(2), 69-77.
- Löfving, M., Säfsten, K., & Winroth, M. (2014). Manufacturing strategy frameworks suitable for SMEs. *Journal of Manufacturing Technology Management*, 25(1), 7-26.
- López-Peláez, J., & Pigeon, P. (2011). Co-evolution between structural mitigation measures and urbanization in France and Colombia: A comparative analysis of disaster risk management policies based on disaster databases. *Habitat international*, 35(4), 573-581.
- Lukács, E. (2005). The economic role of SMEs in world economy, especially in Europe. *European integration studies*, 4(1), 3-12.
- Luke, S., Cioffi-Revilla, C., Panait, L., Sullivan, K., & Balan, G. (2005). Mason: A multiagent simulation environment. *Simulation*, 81(7), 517-527.
- Macal, C. M., & North, M. J. (2005). *Tutorial on agent-based modeling and simulation*. Paper presented at the Proceedings of the Winter Simulation Conference, 2005.
- Macal, C. M., & North, M. J. (2009). *Agent-based modeling and simulation*. Paper presented at the Proceedings of the 2009 Winter Simulation Conference (WSC).
- Macal, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of simulation*, 4(3), 151-162.
- May, P., Emonson, P., Jones, B., & Davies, A. (2014). *Post-Installation Effectiveness of Property Level Flood Protection*. Retrieved from London: <http://goo.gl/q8aEK9>
- McCrum-Gardner, E. (2008). Which is the correct statistical test to use? *British Journal of Oral and Maxillofacial Surgery*, 46(1), 38-41.
- McGregor, G. R., Ferro, C. A., & Stephenson, D. B. (2005). Projected changes in extreme weather and climate events in Europe. In *Extreme Weather Events and Public Health Responses* (pp. 13-23): Springer.
- McKnight, P. E., & Najab, J. (2010). Mann-Whitney U Test. *The Corsini encyclopedia of psychology*, 1-1.
- Medd, W., Deeming, H., Walker, G., Whittle, R., Mort, M., Twigger-Ross, C., . . . Kashefi, E. (2015). The flood recovery gap: a real-time study of local recovery following the floods of June 2007 in Hull, North East England. *Journal of Flood Risk Management*, 8(4), 315-328.
- Meehl, G. A., Karl, T., Easterling, D. R., Changnon, S., Pielke Jr, R., Changnon, D., . . . Kunkel, K. E. (2000). An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bulletin of the American Meteorological Society*, 81(3), 413-416.

- Messner, F. (2007). Evaluating flood damages: guidance and recommendations on principles and methods. *T09-06-01*.
- Mileti, D. (1999). *Disasters by design: A reassessment of natural hazards in the United States*: Joseph Henry Press.
- Mirza, M. M. Q. (2003). Climate change and extreme weather events: can developing countries adapt? *Climate policy*, 3(3), 233-248.
- Mis, N. B., Joseph, R., Proverbs, D., & Lamond, J. (2015). Grass-root preparedness against potential flood risk among residential and commercial property holders. *International Journal of Disaster Resilience in the Built Environment*, 6(1), 44-56.
- Mitton, L., Sutherland, H., & Weeks, M. (2000). *Microsimulation modelling for policy analysis: challenges and innovations*: Cambridge University Press.
- Morrissey, E. (2016). Environment Agency Flood Warnings - What you need to know. Retrieved from <http://www.newground.co.uk/news-events-media/knowledge-centre/environment-agency-flood-warnings-what-you-need-to-know/>
- Nachar, N. (2008). The Mann-Whitney U: A test for assessing whether two independent samples come from the same distribution. *Tutorials in quantitative Methods for Psychology*, 4(1), 13-20.
- NENE. (2015). *NENA Mutual Aid Standard/Model Recommendation*. Retrieved from USA: https://cdn.ymaws.com/www.nena.org/resource/resmgr/Standards/NENA-STA-009.2-2015_Mutual_A.pdf
- NGA. (1979). *Comprehensive emergency management: A governor's guide*. National Governors' Association. Center for Policy Research
- United States. Defense Civil Preparedness Agency: [Department of Defense], Defense Civil Preparedness Agency.
- NHBC. (2016). *Technical Guide* Retrieved from <http://www.nhbc.co.uk/Builders/ProductsandServices/TechZone/NHBCStandards/TechnicalGuidanceDocuments/61/filedownload,65368,en.pdf>
- Niazi, M. A., Hussain, A., & Kolberg, M. (2017). Verification & validation of agent based simulations using the VOMAS (virtual overlay multi-agent system) approach. *arXiv preprint arXiv:1708.02361*.
- Nidirect Government Services. (2019). After a flood - making an insurance claim. Retrieved from <https://www.nidirect.gov.uk/articles/after-flood-making-insurance-claim>
- Nikolai, C., & Madey, G. (2009). Tools of the trade: A survey of various agent based modeling platforms. *Journal of Artificial Societies and Social Simulation*, 12(2), 2.
- Norrington, H., & Underwood, K. (2008). Climate change and small businesses: How directors are responding to the challenges of climate change-Research Findings 2008. *Guildford: Climate South East*.
- North, D., Smallbone, D., & Vickers, I. (2001). Public sector support for innovating SMEs. *Small Business Economics*, 16(4), 303-317.
- North, M. J., Collier, N. T., Ozik, J., Tatara, E. R., Macal, C. M., Bragen, M., & Sydelko, P. (2013). Complex adaptive systems modeling with Repast Symphony. *Complex adaptive systems modeling*, 1(1), 3.
- North, M. J., Collier, N. T., & Vos, J. R. (2006). Experiences creating three implementations of the repast agent modeling toolkit. *ACM Transactions on Modeling and Computer Simulation (TOMACS)*, 16(1), 1-25.
- North, M. J., & Macal, C. M. (2007). *Managing business complexity: discovering strategic solutions with agent-based modeling and simulation*: Oxford University Press.
- NRF. (2008). *National Response Framework*. Retrieved from Washington, DC: <https://www.fema.gov/pdf/emergency/nrf/nrf-core.pdf>
- OECD. (2000). Small and medium-sized enterprises: local strength, global reach. *Policy Brief*.

- Omar, O. E., & Fraser, P. (2010). The role of small and medium enterprise retailing in Britain.
- Ordnance Survey. (2019). Ordnance Survey: Britain's mapping agency. Retrieved from <http://Ordnancesurvey.co.uk>.
- Pablo-Martí, F., García-Tabuenca, A., Gallo, M. T., Santos, J. L., del Val, M. T., & Mancha, T. (2013). *MOSIPS Agent-based model for predicting and simulating the impact of public policies on SMEs*. Paper presented at the Proceedings of the European Conference on Complex Systems 2012.
- Pathak, S., & Ahmad, M. M. (2016). Flood recovery capacities of the manufacturing SMEs from floods: A case study in Pathumthani province, Thailand. *International Journal of Disaster Risk Reduction*, 18, 197-205. doi:10.1016/j.ijdr.2016.07.001
- Paul, B. K. (2011). *Environmental hazards and disasters: contexts, perspectives and management*: John Wiley & Sons.
- Peffer, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of management information systems*, 24(3), 45-77.
- Perdikaki, O., Kesavan, S., & Swaminathan, J. M. (2012). Effect of traffic on sales and conversion rates of retail stores. *Manufacturing & Service Operations Management*, 14(1), 145-162.
- Pitt, M. (2008). The Pitt Review: Learning lessons from the 2007 floods. *London: Cabinet Office*, 20.
- Prasad, M. N., & Chartier, D. A. (1999). *Modeling Organizations Using Agent-Based Simulations*. Paper presented at the Workshop on Agent Simulation: Applications, Models, and Tools.
- Prenger-Berninghoff, K., Cortes, V., Sprague, T., Aye, Z., Greiving, S., Głowacki, W., & Sterlacchini, S. (2014). The connection between long-term and short-term risk management strategies for flood and landslide hazards: examples from land-use planning and emergency management in four European case studies. *Natural Hazards and Earth System Sciences*, 14(12), 3261-3278.
- Prior, J., & Kendon, M. (2011). The UK winter of 2009/2010 compared with severe winters of the last 100 years. *Weather*, 66(1), 4-10.
- Qin, Y., Lu, H., Xu, Y., & Wang, H. (2015). *Saliency detection via cellular automata*. Paper presented at the Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition.
- Qiuyan, T. (2009). *Analysis on the Agent Based Complex Adaptive Growth System of the Small and Medium Enterprises*. Paper presented at the International Small and Medium-sized Enterprises Development Forum.
- Railsback, S. F., Lytinen, S. L., & Jackson, S. K. (2006). Agent-based simulation platforms: Review and development recommendations. *Simulation*, 82(9), 609-623.
- Razali, N. M., & Wah, Y. B. (2011). Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. *Journal of statistical modeling and analytics*, 2(1), 21-33.
- Rhodes, C. (2018). *Business statistics*. Retrieved from <https://researchbriefings.files.parliament.uk/documents/SN06152/SN06152.pdf>
- Richiardi, M., Leombruni, R., Saam, N. J., & Sonnessa, M. (2006). A Common Protocol for Agent-Based Social Simulation. *Journal of Artificial Societies and Social Simulation*, 9(1).
- Rickard, C. (2009). Flood walls and flood embankments. *Fluvial Design Guide*. Environment Agency, UK, London.
- Robertson, D. A. (2005). Agent-based modeling toolkits NetLogo, RePast, and Swarm. In: JSTOR.

- Robinson, S. (2011). *Choosing the right model: conceptual modeling for simulation*. Paper presented at the Proceedings of the Winter Simulation Conference.
- Rose, A., & Lim, D. (2002). Business interruption losses from natural hazards: conceptual and methodological issues in the case of the Northridge earthquake. *Global Environmental Change Part B: Environmental Hazards*, 4(1), 1-14.
- Ruxton, G. D. (2006). The unequal variance t-test is an underused alternative to Student's t-test and the Mann–Whitney U test. *Behavioral Ecology*, 17(4), 688-690.
- Sabzian, H., Shafia, M. A., Maleki, A., Hashemi, S. M. S., Baghaei, A., & Gharib, H. (2019). Theories and Practice of Agent based Modeling: Some practical Implications for Economic Planners. *arXiv preprint arXiv:1901.08932*.
- Sargent, R. G. (2010). *Verification and validation of simulation models*. Paper presented at the Proceedings of the 2010 Winter Simulation Conference.
- Sauser, B., Baldwin, C., Pourreza, S., Randall, W., & Nowicki, D. (2018). Resilience of small- and medium-sized enterprises as a correlation to community impact: an agent-based modeling approach. *Natural Hazards*, 90(1), 79-99.
- Scholl, H. J. (2001). *Agent-based and system dynamics modeling: a call for cross study and joint research*. Paper presented at the Proceedings of the 34th annual Hawaii international conference on system sciences.
- Scott, M., & Bruce, R. (1987). Five stages of growth in small business. *Long range planning*, 20(3), 45-52.
- SEPA. (2019). Floodline | Scottish Environment Protection Agency (SEPA). Retrieved from <https://www.sepa.org.uk/environment/water/flooding/floodline/>
- Serenko, A., & Detlor, B. (2002). Agent toolkits: A general overview of the market and an assessment of instructor satisfaction with utilizing toolkits in the classroom.
- SFF. (2016). *Flood Protection Guide*. Retrieved from Scotland, UK: <https://scottishfloodforum.org/wp-content/uploads/2017/11/SFF-Flood-Protection-Guide-Web-min.pdf>
- Smith, K., & Ward, R. (1998). *Floods: physical processes and human impacts*: Wiley Chichester.
- Smyth, G. K. (2014). Numerical integration. *Wiley StatsRef: Statistics Reference Online*.
- Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., . . . Miller, H. L. (2007). Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007. In: Cambridge University Press, Cambridge.
- Stanislaw, H. (1986). Tests of computer simulation validity: what do they measure? *Simulation & Games*, 17(2), 173-191.
- Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world*.
- Stern, N., & Stern, N. H. (2007). *The economics of climate change: the Stern review*: cambridge University press.
- Stier, D. D., & Goodman, R. A. (2007). Mutual aid agreements: essential legal tools for public health preparedness and response. *American journal of public health*, 97(Supplement_1), S62-S68.
- Storey, D. J. (2016). *Understanding the small business sector*: Routledge.
- Stormguard Flood Plan. (2019). Flood Doors for Homes & Businesses – The Easiest Way to Stop Flood Water Within Seconds. Retrieved from <https://stormguardfloodplan.com/flood-doors/>
- Sullivan-Taylor, B., & Branicki, L. (2011). Creating resilient SMEs: why one size might not fit all. *International Journal of Production Research*, 49(18), 5565-5579.
- Sutton, J., & Tierney, K. (2006). Disaster preparedness: Concepts, guidance, and research. *Colorado: University of Colorado*.
- TEMA. (2006). *Disaster Recovery Plan for the State of Tennessee*. Retrieved from

- Tewkesbury Borough Council. (2018). Tewkesbury floods 2007. Retrieved from <https://www.tewkesbury.gov.uk/flooding#statistics>
- Tewkesbury Borough Council. (2019). Flooding. *Tewkesbury floods 2007*. Retrieved from <https://www.tewkesbury.gov.uk/flooding#tewkesbury-floods-2007>
- Thurston, N., Finlinson, B., Breakspear, R., Williams, N., Shaw, J., & Chatterton, J. (2008). Developing the evidence base for flood resistance and resilience. *R&D Summary Report, Joint Defra/EA Flood and Coastal Erosion, London*.
- Tierney, K., & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR news*(250).
- Tobias, R., & Hofmann, C. (2004). Evaluation of free Java-libraries for social-scientific agent based simulation. *Journal of Artificial Societies and Social Simulation*, 7(1).
- Tonge, J. (2001). A review of small business literature part 1: defining the small business.
- Tonn, G. L., & Guikema, S. D. (2018). An Agent-Based Model of Evolving Community Flood Risk. *Risk Analysis*, 38(6), 1258-1278.
- Tounsi, J., Habchi, G., Boissière, J., & Azaiez, S. (2012). A multi-agent knowledge model for SMEs mechatronic supply chains. *Journal of Intelligent Manufacturing*, 23(6), 2647-2665.
- Tran, H. T., Domercant, J. C., & Mavris, D. N. (2015). Evaluating the agility of adaptive command and control networks from a cyber complex adaptive systems perspective. *The Journal of Defense Modeling and Simulation*, 12(4), 405-422.
- Treby, E. J., Clark, M. J., & Priest, S. J. (2006). Confronting flood risk: Implications for insurance and risk transfer. *Journal of environmental management*, 81(4), 351-359.
- Trefethen, L. N., & Weideman, J. (2014). The exponentially convergent trapezoidal rule. *SIAM Review*, 56(3), 385-458.
- UK's electrical safety experts. (2019). *Minimising risk of damage to electrical installations in domestic premises in flood-prone areas*. Retrieved from <https://www.electricalsafetyfirst.org.uk/media/1512/electrical-installations-in-flood-prone-areas.pdf>
- UN. (2009a). Global Assessment Report on Disaster Risk Reduction: Risk and Poverty in a changing Climate. Invest today for a safer tomorrow. In (pp. 207). Geneva, Switzerland: United Nations International Strategy for Disaster Reduction Geneva.
- UN. (2009b). Terminology on disaster risk reduction from united nations international strategy for disaster reduction.
- United Nations. (2008). *International Standard Industrial Classification of All Economic Activities Revision 4*. New York. https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf
- Van der Veen, A., Vetere Arellano, A., & Nordvik, J.-P. (2003). *In search of a common methodology for damage estimation*. Paper presented at the Joint NEDIES and University of Twente Workshop, Report EUR.
- Van Gils, A. (2005). Management and governance in Dutch SMEs. *European Management Journal*, 23(5), 583-589.
- Wagh, W. (2000). Living with Hazards, Dealing with Hazards. In: New York: ME Sharpe, Inc.
- Wedawatta. (2013). *Resilience of construction SMEs to extreme weather events*. University of Salford,
- Wedawatta, G., & Ingirige, B. (2012). Resilience and adaptation of small and medium-sized enterprises to flood risk. *Disaster Prevention and Management: An International Journal*, 21(4), 474-488.
- Wedawatta, G., Ingirige, B., & Amaratunga, D. (2010). Building up resilience of construction sector SMEs and their supply chains to extreme weather events. *International Journal of Strategic Property Management*, 14(4), 362-375.

- Wedawatta, G., Ingirige, B., & Proverbs, D. (2014). Small businesses and flood impacts: the case of the 2009 flood event in Cockermouth. *Journal of Flood Risk Management*, 7(1), 42-53.
- Weick, K. E., & Sutcliffe, K. M. (2001). *Managing the Unexpected: Assuring High Performance in an Age of Complexity*, published by JosseyBass, a John Wiley & Sons. Inc. Company.
- Werwick, K. (2010). Manufacturing in the UK: An Economic analysis of the sector. *BIS Economics paper*(10A).
- Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy*, 11(1), 115-137.
- White, R., Engelen, G., & Uljee, I. (1997). The use of constrained cellular automata for high-resolution modelling of urban land-use dynamics. *Environment and Planning B: Planning and Design*, 24(3), 323-343.
- White, S. (2016). Business population estimates for the UK and regions 2016. *B. a. I. Skills*(Ed.). Sheffield.
- Wijayanti, P., Zhu, X., Hellegers, P., Budiyo, Y., & van Ierland, E. C. (2017). Estimation of river flood damages in Jakarta, Indonesia. *Natural Hazards*, 86(3), 1059-1079.
- Wilkinson, I. F., Held, F., Marks, R. E., & Young, L. (2012). Developing agent-based models of business relations and networks. *Networks in Society: Links and Language*. Singapore: Pan-Stanford Publishing.
- Willner, S. N., Otto, C., & Levermann, A. (2018). Global economic response to river floods. *Nature Climate Change*, 8(7), 594.
- Wingfield, J., Bell, M., & Bowker, P. (2005). Improving the flood resilience of buildings through improved materials, methods and details: report number WP2c—review of existing information and experience (final report). *Leeds Metropolitan University, Leeds*.
- Winkler, A. (2017). *Sheffield City Report*. Retrieved from Sheffield, UK:
- Wiseman, J., & Parry, E. (2011). Cumbria Business Survey 2010-Research report prepared for Cumbria Intelligence Observatory. *Birmingham: BMG Research*.
- Wiseman, J., & Parry, E. (2016). *Cumbria Business Survey 2015/16 – Final Report*. Retrieved from Birmingham, UK: http://www.cumbriaobservatory.org.uk/wp-content/uploads/2017/04/EconomyEmployment_Data-Source_Cumbria-Business-Survey-2015-16-Full-Report.pdf
- Wolfram, S. (1984). Cellular automata as models of complexity. *Nature*, 311(5985), 419.
- Woodman, P. (2008). *Business continuity management 2008*: Chartered Management Institute London.
- Wooldridge, M., & Jennings, N. R. (1995). Intelligent agents: Theory and practice. *The knowledge engineering review*, 10(2), 115-152.
- Wynarczyk, P., Watson, R., Storey, D., Short, A., & Keasey, K. (1993). Managerial Labour Markets in Small Firms. In: Routledge, London.
- Xiang, X., Kennedy, R., Madey, G., & Cabaniss, S. (2005). *Verification and validation of agent-based scientific simulation models*. Paper presented at the Agent-directed simulation conference.
- Xu, J., Gao, Y., & Madey, G. (2003). *A docking experiment: Swarm and repast for social network modeling*. Paper presented at the Seventh Annual Swarm Researchers Meeting (Swarm2003).
- Yang, L. E., Scheffran, J., Süßner, D., Dawson, R., & Chen, Y. D. (2018). Assessment of flood losses with household responses: Agent-based simulation in an urban catchment area. *Environmental Modeling & Assessment*, 1-20.
- Yell. (2019). The UK Business Directory. Retrieved from <https://www.yell.com/>
- Yoshida, K., & Deyle, R. E. (2005). Determinants of small business hazard mitigation. *Natural Hazards Review*, 6(1), 1-12.

- Zaman, M. (2012). Impact of Recent Flood on the Economy of Small Business at Rockhampton. *Procedia-Social and Behavioral Sciences*, 65, 116-126.
- Zhu, Y. (2017). An Examination of Shopper Conversion among US Online Retail Formats.
- Zobel, C. (2010). *Comparative visualization of predicted disaster resilience*. Paper presented at the Proceedings of the 7th International ISCRAM Conference.
- Zobel, C. (2011a). Representing perceived tradeoffs in defining disaster resilience. *Decision Support Systems*, 50(2), 394-403.
- Zobel, C. (2011b). *Representing the multi-dimensional nature of disaster resilience*. Paper presented at the Proceedings of the 8th International ISCRAM Conference–Lisbon, Portugal.

References of Content of Tables

1. Dawson, R.J., R. Peppe, and M. Wang, An agent-based model for risk-based flood incident management. *Natural hazards*, 2011. 59(1): p. 167-189.
2. Gilbert, N., *Agent-Based Models*. 2007. 2007, Los Angeles: Sage Publications Inc.
3. Heppenstall, A.J., et al., *Agent-based models of geographical systems*. 2011: Springer Science & Business Media.
4. Clarke, K.C., Cellular automata and agent-based models, in *Handbook of regional science*. 2014, Springer. p. 1217-1233.
5. Li, J. and D.M. Sologon, A continuous labour supply model in microsimulation: a life-cycle modelling approach with heterogeneity and uncertainty extension. *PloS one*, 2014. 9(11): p. e111903.
6. Salvini, P. and E.J. Miller, ILUTE: An operational prototype of a comprehensive microsimulation model of urban systems. *Networks and spatial economics*, 2005. 5(2): p. 217-234.
7. Scholl, H.J. Agent-based and system dynamics modeling: a call for cross study and joint research. in *Proceedings of the 34th annual Hawaii international conference on system sciences*. 2001. IEEE.
8. Railsback, S.F., S.L. Lytinen, and S.K. Jackson, Agent-based simulation platforms: Review and development recommendations. *Simulation*, 2006. 82(9): p. 609-623.
9. Amouroux, E., et al. GAMA: an environment for implementing and running spatially explicit multi-agent simulations. in *Pacific Rim International Conference on Multi-Agents*. 2007. Springer.
10. Crooks, A.T. and C.J. Castle, The integration of agent-based modelling and geographical information for geospatial simulation, in *Agent-based models of geographical systems*. 2012, Springer. p. 219-251.

References

11. Robertson, D.A., Agent-based modeling toolkits NetLogo, RePast, and Swarm. 2005, JSTOR.
12. Luke, S., et al., Mason: A multiagent simulation environment. *Simulation*, 2005. 81(7): p. 517-527.
13. Gilbert, N., Agent-based models. 2008: Sage.
14. Nikolai, C. and G. Madey, Tools of the trade: A survey of various agent based modeling platforms. *Journal of Artificial Societies and Social Simulation*, 2009. 12(2): p. 2.
15. North, M.J., N.T. Collier, and J.R. Vos, Experiences creating three implementations of the repast agent modeling toolkit. *ACM Transactions on Modeling and Computer Simulation (TOMACS)*, 2006. 16(1): p. 1-25.
16. North, M.J., et al., Visual agent-based model development with repast symphony. 2007, Tech. rep., Argonne National Laboratory.
17. Balbi, S. and C. Giupponi, Reviewing agent-based modelling of socio-ecosystems: a methodology for the analysis of climate change adaptation and sustainability. University Ca'Foscari of Venice, Dept of Economics Research Paper Series (15_09). Ca'Foscari University of Venice, 2009.
18. Environment Agency, What to do before, during and after a flood, in Practical advice on what to do to protect yourself and your property. 2019: Bristol, UK.
19. Henderson, F. and G. Whittam, Evolutionary or equilibrist? Small businesses resilience to flooding in Scotland. *Studia Miejskie*, 2016. 24: p. 23-41.
20. Mis, N.B., et al., Grass-root preparedness against potential flood risk among residential and commercial property holders. *International Journal of Disaster Resilience in the Built Environment*, 2015. 6(1): p. 44-56.
21. Environment Agency, Prepare your property for flooding, in A guide for householders and small businesses 2019: Bristol, UK.
22. Dhonau, M. and C.B. Rose, A Business Guide to Flood Resilience, in Know your flood risk. 2016.
23. Tagg, A., et al. A new standard for flood resistance and resilience of buildings: new build and retrofit. in *E3S Web of Conferences*. 2016. EDP Sciences.
24. Coates, G., et al., Investigating The Flood Responsiveness Of Small And Medium Enterprises Using Agent-Based Modelling And Simulation. *Flood Risk Management and Response*, 2016: p. 173.
25. Li, C. and G. Coates, Design and development of an agent-based model for business operations faced with flood disruption. *Complex Syst.: Fundam. Appl*, 2016. 90: p. 275.
26. Ingirige and R. Russell, Investigating SME resilience to flooding: the Braunton report. 2015, University of Salford.

27. Wedawatta, G., B. Ingirige, and D. Proverbs, Small businesses and flood impacts: the case of the 2009 flood event in Cockermouth. *Journal of Flood Risk Management*, 2014. 7(1): p. 42-53.
28. Kreibich, H., et al., Flood precaution of companies and their ability to cope with the flood in August 2002 in Saxony, Germany. *Water Resources Research*, 2007. 43(3).
29. Department of Health, Flooding Quick Reference Guide, in What to do before, during, and after a flood. 2019: New Yourk State.
30. Keogh, D.U., et al., Resilience, vulnerability and adaptive capacity of an inland rural town prone to flooding: a climate change adaptation case study of Charleville, Queensland, Australia. *Natural Hazards*, 2011. 59(2): p. 699-723.
31. Jonkman, S.N., et al., Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecological economics*, 2008. 66(1): p. 77-90.
32. Asgary, A., M.I. Anjum, and N. Azimi, Disaster recovery and business continuity after the 2010 flood in Pakistan: Case of small businesses. *International journal of disaster risk reduction*, 2012. 2: p. 46-56.
33. Yang, L.E., et al., Assessment of flood losses with household responses: Agent-based simulation in an urban catchment area. *Environmental Modeling & Assessment*, 2018: p. 1-20.
34. Pathak, S. and M.M. Ahmad, Flood recovery capacities of the manufacturing SMEs from floods: A case study in Pathumthani province, Thailand. *International Journal of Disaster Risk Reduction*, 2016. 18: p. 197-205.
35. Emergency Management Australia, What to do before, during and after a flood. 2005: Austalia.
36. SEPA, Flood insurance, in A GUIDE FOR CUSTOMERS IN SCOTLAND. 2016.
37. Jenkins, K., et al., Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Science of the Total Environment*, 2017. 595: p. 159-168.
38. S Wyke, E.G., A Bennett, T Pottage, O Landeg, A Crossley, J Calkins, R Southgate, K Markiewicz, G Nichols, R Amlôt and P Riley, Guidance on Recovery from Flooding in Essential information for frontline responders. 2014.
39. Li, C., et al., Designing an agent-based model of SMEs to assess flood response strategies and resilience. 2015.
40. Qiuyan, T. Analysis on the Agent Based Complex Adaptive Growth System of the Small and Medium Enterprises. in *International Small and Medium-sized Enterprises Development Forum*. 2009.
41. Bhattacharya-Mis, N. and J. Lamond. An investigation of patterns of response and recovery among flood-affected businesses in the UK: a case study in Sheffield and Wakefield. in *International Conference on Flood Recovery, Innovation and Response*. 2014.

References

42. Piatyszek, E. and G.-M. Karagiannis, A model-based approach for a systematic risk analysis of local flood emergency operation plans: a first step toward a decision support system. *Natural Hazards*, 2012. 61(3): p. 1443-1462.
43. Cameron, D. and D. Proverbs, Improving the uptake of flood risk adaptation measures for domestic properties in an insurance regime under transition. *Flood Recovery, Innovation and Response IV*, 2014. 184: p. 139-149.
44. Ingirige, B. and G. Wedawatta, Impacts of flood hazards on small and medium companies: Strategies for property level protection and business continuity. 2011.
45. Wedawatta, G., B. Ingirige, and Amaratunga, Case study as a research strategy: Investigating extreme weather resilience of construction SMEs in the UK. 2011.
46. Coates, G., et al., Agent-based modelling and inundation prediction to enable the identification of businesses affected by flooding. *WIT Transactions on Ecology and the Environment*, 2014. 184: p. 13-22.
47. Kreibich, H., et al., Recent changes in flood preparedness of private households and businesses in Germany. *Regional environmental change*, 2011. 11(1): p. 59-71.
48. Wedawatta, G. and B. Ingirige, Resilience and adaptation of small and medium-sized enterprises to flood risk. *Disaster Prevention and Management: An International Journal*, 2012. 21(4): p. 474-488.
49. Haer, T., et al., Integrating household risk mitigation behavior in flood risk analysis: an agent-based model approach. *Risk Analysis*, 2017. 37(10): p. 1977-1992.
50. Wedawatta, G., M. Ingirige, and D. Proverbs, Adaptation to flood risk: the case of businesses in the UK. 2011.

List of Figures in Appendices

Figure A.1: A typical agent (Macal & North, 2009)	236
Figure B.1: TopographicArea layer before enhancement	250
Figure B.2: Selection expression for the <i>Building</i> layer	251
Figure B.3: Saving a specific layer in a shapefile extension format.....	251
Figure B.4: Classifying buildings into groups of versions	252
Figure B.5: Overview of the building layer after enhancement	253
Figure B.6: Allocating attributes with the appropriate colours	253
Figure B.7: Overview of the <i>Topography</i> layer after enhancement	254
Figure B.8: Coupling the <i>Building</i> layer along with the <i>Topography</i> layer after enhancement	254
Figure B.9: Overview of the <i>ITN</i> layer after enhancement	255
Figure C.1: Interactions between SMEs and their related organizations.....	263
Figure C.2: Pre-flood behaviours' relationships with sequencing order of behaviour execution indicated in the brackets in each action box	265
Figure C.3: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (1).....	268
Figure C.4: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (2).....	269
Figure C.5: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (3).....	273
Figure C.6: Suppliers and customers	278
Figure C.7: An Overview of the interaction between cleaning service providers and SMEs.....	280
Figure C.8: Insurance companies	282
Figure C.9: Electrical contractors.....	284
Figure D.1: Cumulative average of service capability of 13 flood-affected retail SMEs over time	297
Figure D.2: The <i>overall absolute operational disruption</i> of the lightly, moderately, and severely flooded retail SMEs located in Sheffield geographical area	298
Figure E.1: Simulation experiment E1- manufacturing SMEs located in Sheffield.....	317
Figure E.2: Simulation experiment E2 (A): manufacturing SMEs located in Sheffield	317
Figure E.3: Simulation experiment E2 (B): manufacturing SMEs located in Sheffield	318
Figure E.4: Simulation experiment E2 (C): manufacturing SMEs located in Sheffield	318
Figure E.5: Simulation experiment E2 (D): manufacturing SMEs located in Sheffield	318
Figure E.6: Simulation experiment E3: manufacturing SMEs located in Sheffield.....	319
Figure E.7: Simulation experiment E4: manufacturing SMEs located in Sheffield	319
Figure E.8: Simulation experiment E5 (A): manufacturing SMEs located in Sheffield	319
Figure E.9: Simulation experiment E5 (B): manufacturing SMEs located in Sheffield	320

Figure E.10: Simulation experiment E6 (A): manufacturing SMEs located in Sheffield.....	320
Figure E.11: Simulation experiment E6 (B) : manufacturing SMEs located in Sheffield	320
Figure E.12: Simulation experiment E7: manufacturing SMEs located in Sheffield	321
Figure E.13: Simulation experiment E8: manufacturing SMEs located in Sheffield	321
Figure E.14: Simulation experiment E9: manufacturing SMEs located in Sheffield	321
Figure E.15: Simulation experiment E10: manufacturing SMEs located in Sheffield	322
Figure E.16: Simulation experiment E11: manufacturing SMEs located in Sheffield	322
Figure E.17: Simulation experiment E1: retail SMEs located in Sheffield.....	322
Figure E.18: Simulation experiment E2 (A): retail SMEs located in Sheffield	323
Figure E.19: Simulation experiment E2 (B): retail SMEs located in Sheffield	323
Figure E.20: Simulation experiment E2 (C): retail SMEs located in Sheffield	323
Figure E.21: Simulation experiment E2 (D): retail SMEs located in Sheffield.....	324
Figure E.22: Simulation experiment E3: retail SMEs located in Sheffield.....	324
Figure E.23: Simulation experiment E4: retail SMEs located in Sheffield.....	324
Figure E.24: Simulation experiment E5 (A): retail SMEs located in Sheffield	325
Figure E.25: Simulation experiment E5 (B): retail SMEs located in Sheffield	325
Figure E.26: Simulation experiment E6 (A): retail SMEs located in Sheffield	325
Figure E.27: Simulation experiment E6 (B): retail SMEs located in Sheffield	326
Figure E.28: Simulation experiment E7: retail SMEs located in Sheffield.....	326
Figure E.29: Simulation experiment E8: retail SMEs located in Sheffield.....	326
Figure E.30: Simulation experiment E9: retail SMEs located in Sheffield.....	327
Figure E.31: Simulation experiment E10: retail SMEs located in Sheffield.....	327
Figure E.32: Simulation experiment E11: retail SMEs located in Sheffield.....	327
Figure E.33: Simulation experiment S1 (A): manufacturing SMEs with basic insurance and without funds available.....	328
Figure E.34: Simulation experiment S1 (B): manufacturing SMEs with comprehensive insurance and funds available and choosing to allocate cleaning service provided by the insurance company to clean-up their premises.....	328
Figure E.35: Simulation experiment S1 (C): manufacturing SMEs with comprehensive insurance and funds available, but choose to allocate their own employees to clean-up .	329
Figure E.36: Simulation experiment S2 (A): manufacturing SMEs with a pre-defined mutual aid partner	329
Figure E.37: Simulation experiment S2 (B): manufacturing SMEs without a pre-defined mutual aid partner	329
Figure E.38: Simulation experiment S3 (A): retail SMEs employed companies specializing in refurbishment premises.....	330
Figure E.39: Simulation experiment S3 (B): retail SMEs choose to allocate their own employees to refurbish their premises.....	330
Figure E.40: Simulation experiment E1: manufacturing SMEs located in Tewkesbury	331
Figure E.41: Simulation experiment E2 (A): manufacturing SMEs located in Tewkesbury .	331
Figure E.42: Simulation experiment E2 (B): manufacturing SMEs located in Tewkesbury..	332
Figure E.43: Simulation experiment E2 (C): manufacturing SMEs located in Tewkesbury..	332
Figure E.44: Simulation experiment E2 (D): manufacturing SMEs located in Tewkesbury .	332
Figure E.45: Simulation experiment E3: manufacturing SMEs located in Tewkesbury	333
Figure E.46: Simulation experiment E4: manufacturing SMEs located in Tewkesbury	333

Figure E.47: Simulation experiment E5 (A): manufacturing SMEs located in Tewkesbury ..	333
Figure E.48: Simulation experiment E5 (B): manufacturing SMEs located in Tewkesbury ..	334
Figure E.49: Simulation experiment E6 (A): manufacturing SMEs located in Tewkesbury ..	334
Figure E.50: Simulation experiment E6 (B): manufacturing SMEs located in Tewkesbury ..	334
Figure E.51: Simulation experiment E7: manufacturing SMEs located in Tewkesbury	335
Figure E.52: Simulation experiment E8: manufacturing SMEs located in Tewkesbury	335
Figure E.53: Simulation experiment E9: manufacturing SMEs located in Tewkesbury	335
Figure E.54: Simulation experiment E10: manufacturing SMEs located in Tewkesbury	336
Figure E.55: Simulation experiment E11: manufacturing SMEs located in Tewkesbury	336
Figure E.56: Simulation experiment E1: retail SMEs located in Tewkesbury	337
Figure E.57: Simulation experiment E2 (A): retail SMEs located in Tewkesbury	337
Figure E.58: Simulation experiment E2 (B): retail SMEs located in Tewkesbury	337
Figure E.59: Simulation experiment E2 (C): retail SMEs located in Tewkesbury	338
Figure E.60: Simulation experiment E2 (D): retail SMEs located in Tewkesbury	338
Figure E.61: Simulation experiment E3: retail SMEs located in Tewkesbury	338
Figure E.62: Simulation experiment E4: retail SMEs located in Tewkesbury	339
Figure E.63: Simulation experiment E5 (A): retail SMEs located in Tewkesbury	339
Figure E.64: Simulation experiment E5 (B): retail SMEs located in Tewkesbury	339
Figure E.65: Simulation experiment E6 (A): retail SMEs located in Tewkesbury	340
Figure E.66: Simulation experiment E6 (B): retail SMEs located in Tewkesbury	340
Figure E.67: Simulation experiment E7: retail SMEs located in Tewkesbury	340
Figure E.68: Simulation experiment E8: retail SMEs located in Tewkesbury	341
Figure E.69: Simulation experiment E9: retail SMEs located in Tewkesbury	341
Figure E.70: Simulation experiment E10: retail SMEs located in Tewkesbury	341
Figure E.71: Simulation experiment E11: retail SMEs located in Tewkesbury	342

List of Tables in Appendices

Table A.1: A comparison between the features of different models	239
Table A.2: A comparison between four ABM toolkits	244
Table C.1: Variables of manufacturing and retail SMEs.....	260
Table C.2: Variables of cleaning service providers.....	260
Table C.3: Variables of customers and suppliers	261
Table C.4: Variable of electrical contractors.....	261
Table C.5: Variable of Environment Agency	261
Table C.6: Variables of insurance companies	262
Table C.7: Variables of mutual aid partners.....	262
Table C.8: Information related to SME-related organisations.....	288
Table C.9: SME pre and post-flood behaviours.....	289
Table D.1: Simulation data for the lightly flooded (6) retail SMEs located in Lower Don Valley of Sheffield	300
Table D.2: Simulation data for the moderately flooded (5) retail SMEs located in Lower Don Valley of Sheffield	304
Table D.3: Simulation data for the severely flooded (2) retail SMEs located in Lower Don Valley of Sheffield	306
Table D.4: Insurance coverage and financial status results	309
Table D.5: Manufacturing SME and mutual aid partner results	312
Table D.6: Results for retail SMEs and companies specializing in refurbishing premises ...	315

Appendix A

Computational Models and Software Toolkits

This appendix presents a review of the various types of models and software toolkits that can be used to incorporate the key elements identified in Chapter 2 and 3 and enable the investigation of SME's immediate response to and short-term recovery from flooding. In particular, this appendix aims to provide an overview of a range of the most common computational models, namely agent-based modellings (ABMs), cellular automata (CA) models, microsimulation models (MSMs), and system dynamics models (SDMs). Further, it aims to assess them in terms of the key elements identified in Chapter 2 and 3. This appendix also presents an overview of a selected range of the available software toolkits, namely Repast, NetLogo, SWARM, and MASON, which can be used to carry out the implementation of the selected model (ABMs).

Section A.1 provides an overview of each of the four types of models (ABMs, CA, MSMs, and SDMs). Next, Section A.2 presents a critical assessment of ABMs detailing its features and weaknesses. Following this, Section A.3 presents an overview of ABMs available software. Finally, Section A.4 provides a critical assessment of Repast software detailing its features and weaknesses.

A.1 INTRODUCTION TO MODELS

Models are simplifications of the real world (Robinson, 2011). They are theoretical abstractions that represent systems in such a way so that the essential features crucial to a specific theory and its application can be both identified and highlighted (Batty, 2009). They further act as a vehicle to enhance understanding of a

theory in a predictive sense and can be used to simulate the real world, taking into account a diverse range of circumstances (Gilbert, 2007). Overall, a model has the goal of representing or simulating a real or posited phenomenon (Macal & North, 2009). Furthermore, models have the advantage of defining the relationships between features of the target phenomena in addition to allowing them to be investigated empirically in order to discover facts about it.

A.1.1 Overview of Types of Models

A considerable number of computational models have been considered, in particular, agent-based modellings (ABMs), cellular automata (CAs) models, microsimulation models (MSMs) and system dynamics models (SDMs) (Heppenstall et al., 2011). The following sub-section will provide a brief introduction to each of the aforementioned models.

A.1.1.1 Agent-Based Modelling (ABM)

ABMs are computational constructs that are employed for simulating both the actions and interactions of autonomous agents in order to evaluate their impacts on a system as a whole (Axelrod, 1997; Gilbert, 2007). In terms of agents, it is universally agreed that a precise definition of an agent does not exist (Castle & Crooks, 2006; Macal & North, 2009). However, there is a range of characteristics that describe agents (Epstein, 1999; Franklin & Graesser, 1996; Macal & North, 2005; Wooldridge & Jennings, 1995):

- **Autonomy:** agents are autonomous units in that they interact without centralised control, which, in turn, enables them to exchange information with other agents independently.
- **Heterogeneity:** agents allow the expansion of autonomous individuals (i.e. every agent can have its own attributes; for example, a human agent could have attributes such as name, sex, and age).
- **Active:** agents are active because they have an independent influence within a simulation. This characteristic involves a set of sub-characteristics including:
 - **Pro-active/goal-directed:** agents mostly have a goal to achieve.

- Reactive/perceptive: agents can be implemented with prior knowledge, and thus, they can have an ‘awareness’ or ‘sense’ of their surroundings.
- Bounded rationality: agents can be implemented with ‘bounded’ rationality, which enables them to make inductive, discrete, and adaptive decisions.
- Interactive/Communicative: agents can communicate broadly within the modelled environment.
- Mobility: agents can move independently within the modelled environment.
- Adaptation/Learning: agents can learn and alter their pre-defined knowledge.

Generally, ABMs’ agents are objects that are heterogeneous with a set of dynamic attributes and behavioural rules (Macal & North, 2009) that can interact with the environment and other agents as indicated in Figure A.1.

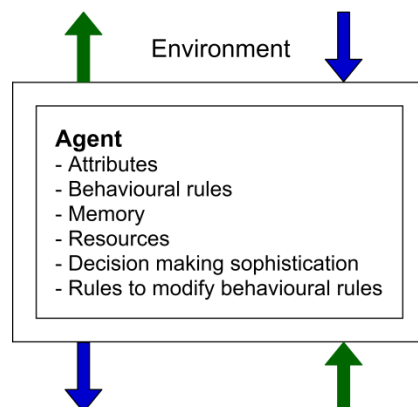


Figure A.1: A typical agent (Macal & North, 2009)

Bandini et al. (2009) and Grimm and Railsback (2013) have pointed out that ABMs are especially suited to supporting the development of models of large numbers of autonomous agents and simulators. They also indicate that ABMs have been successfully used to simulate diverse types of complex systems, such as simulating socio-economic systems. Using ABMs, researchers are able to create, analyse, and experiment with models that consist of a community of individual agents that interact with one another within a given environment - for example, an agent’s virtual environment within a specific geographical area or network (Gilbert, 2007).

Geographical spaces represent the physical features of a given environment - such as a city - where an agent's location is identified by coordinates (Gilbert et al., 2010; Gilbert, 2007). In a network environment, agents are linked together in order to identify the nature of their interconnected relationships.

A.1.1.2 Cellular Automata (CA)

CA models were created by Stanislaw Ulam in 1940 (Clarke, 2014). They are known as discrete spatial-temporal dynamic entities that rely on local rules (Han & Miller, 2009). Wolfram (1984) has explained that CA models are an example of mathematical systems comprised of several similar, simple components which when combined, are able to represent complex behaviour (Gilbert et al., 2010). These models are thus similar to ABMs in their ability to model and simulate complex behaviour (Codd, 2014; Gilbert et al., 2010).

In terms of CA properties, in CA models, cells merely interact locally with their neighbouring cells (Qin et al., 2015; Wolfram, 1984). Furthermore, CAs are preferred if the geometry, scale, basic behaviour of a system, and the probabilities of transitions among these states are known (Clarke, 2014). CA models are also known for their sensitivity to initial conditions such as the states of the cells in a given system. Clarke (2014) has pointed out that CAs have been criticised for being overly consumptive of CPU time. Despite this, they are more favoured in certain cases, such as when a need for modelling dissipative processes arises - land-use change and urban growth (Landis & Zhang, 1998; White et al., 1997).

A.1.1.3 Microsimulation Model (MSM)

MSMs were created by Orcutt in the late 1950s (Birkin & Wu, 2012). MSMs represent an analytical approach that examines the effect of changes in each of the micro-units - such as persons, households, or firms at the micro-level or aggregated level - before and after simulations (Mitton et al., 2000). In general terms, they are intended to model changes in the state or behaviour of micro-level units (Figari et al., 2015). Furthermore, Heppenstall et al. (2011) have indicated that MSM's inputs are often randomly determined or rule-based with a powerfully applied policy focus, such as distinguishing the impact of changes in tax regimes on individual workers and their families.

In terms of MSMs limitations, they are weak in behavioural modelling and lack an appreciation of space and geography (Gilbert, 2007). Furthermore, Algers et al. (1997) have pointed out that MSMs have several limitations, which are also acknowledged by its designers. Firstly, they are deficient in terms of their ability to simulate human behaviour. Secondly, they encounter difficulties in modelling semi-real networks (e.g. modelling city roads). Algers et al. (1997) and Heppenstall et al. (2011) have further elucidated some of the hardware limitations linked to microsimulation such as the need for powerful PCs when modelling large-scale simulations, a lack of graphics and poor links to geographical information systems.

A.1.1.4 System Dynamics Model (SDM)

SDMs were developed in 1969 by Forrester (Griffin & Brandyberry, 2010). They comprise of interacting variables and are capable of processing direct, causal links such as increases in population leading to the depletion of resources and the nature of feedback loops (Algers et al., 1997; Gilbert, 2007). SDMs are feedback-based where they model issues at an aggregate level over time (Sterman, 2000). Therefore, SDMs do not support individual heterogeneity (Gilbert, 2007; Scholl, 2001); they only deal with aggregates rather than individuals. Heppenstall et al. (2011) argue that because SDMs have not been popularised for use with modelling spatial systems harmoniously, they not been extensively expanded in terms of their applications. However, the aggregate system espoused by SDMs is useful when modelling large populations of behaviourally-similar agents (Gilbert, 2007).

A.1.2 Comparisons between Models

Table A.1 presents the differences and the similarities between the four discussed models (ABM, CA, MSM, and SDM) based on some features related to the key elements identified in Chapter 2 and 3.

Models Features	Agent-Based Modelling	Dynamic Systems	Microsimulations	Cellular Automata Models
Interactions	Yes [1-3]	No [1-3]	No [1-3]	Only with adjusting cells [1, 4]
Modelling individual heterogeneity	Yes [1-3]	No [1-3, 5]	Yes [1, 3, 5]	No [1, 2]
Learning or adaptive rules	Yes [2, 3]	No [2, 3]	Yes [6]	Yes [3]
Representation of the Environment	Yes [2, 3]	Yes [3, 7]	Yes [6]	Yes [4]

Table A.1: A comparison between the features of different models

A.2 AGENT-BASED MODELLING (ABM)

ABMs, made up of formalised computer code, represent a set of objective mathematical rules that process inputs into outputs through systematic computation and analysis of a range of possible input values (Wilkinson et al., 2012). Also, they have been described as a tool that can be used by scientists to build models to replicate, test, analyse and predict the behaviour of complex adaptive systems. Johnson (2015) argues that ABMs work as a tool that can anticipate and form hypotheses on the possible states of complex social systems in the past, present, and future. In the same vein, Carslaw (2013) assumes that the goal of ABMs is to reflect specific observed phenomena, and thus, theories generated via the use of ABMs can be used as an explanation for such phenomena. Furthermore, ABMs function by simulating a large number of agents achieving pre-determined behaviours in the context of a specific environment. One of the key components in developing effective models of this type is designating agents and specifying behaviours that match the desired simulation interactions (Johnson, 2015).

Johnson (2015) has pointed out that the flexibility ABMs offer in conducting research and their availability as free-source software have placed them among the most attractive choices in modelling complexity tools. Chappin et al. (2007) have mentioned that while ABMs have been developed from research domains such as Artificial Intelligence and Social Science, ABMs are flexible enough to suit a wide spectrum of applications. Researchers can thus employ ABMs as powerful, predictive and analytical research tools to better understand complex social behaviour and generate new theories (Johnson, 2015). Specifically, Clarke (2014) has pointed out that ABMs are preferred when the goal of the model is the simulation of a behavioural

unit, such as a person or household, and when the model represents interactions among one or more types of agents that produce a spatial model, (i.e. those connected to GIS for data input and display), such as habitat characteristics. Clifford (2008) also confirmed that ABMs are favoured over the other models when decisions or actions are distributed over specific, disparate locations.

A.2.1 Features of Agent-Based Modelling

ABMs have the flexibility of having either fixed or varied numbers of different types of agents based on customised, pre-defined attributes and system rules (Johnson, 2015). Agents also are active (Castle & Crooks, 2006) and have the ability to socialise and communicate within their defined environment. Furthermore, ABMs support reinforcement, and learning and feedback in addition to the adaptation mechanisms that authorise agents to learn from their personal experiences and/or be taught by other agents (Castle & Crooks, 2006; Holland, 1995). In terms of agents' rules, ABMs can be modelled with pre-set rules of behaviour which can govern agent's movements, interactions with other agents, and changes.

A.2.2 Limitations of Agent-Based Modelling

One of the common challenges of using ABMs is the verification and validating of the designed models. Verification and validation are defined as the process of ensuring that the implemented model matches its proposed design and the real world respectively (Heppenstall et al., 2011; North & Macal, 2007). Specifically, verification is the process of testing the model's logic designed via its computer program to ensure that the undertaken processes reflect the model's behaviours whereas validation ensures that the model represents the system being modelled with sufficient accuracy (Casti & Berry, 1997).

ABMs are considered by some authors to be a complementary tool designed to enhance traditional research methods, not replace them (Achorn, 2004). Johnson (2015) has indicated that one of the most challenging aspects of ABMs is the process of transforming qualitative data and theories into a programming language. In particular, translating a complicated model into computer code may create difficulties that could potentially lead to inaccurate initial assumptions or mislead agents as to the exact goal to be achieved (Crooks & Castle, 2012). They have pointed out that ABMs

require users to put in a considerable amount of effort in terms of understanding their design and implementing models within certain toolkits. In some cases, it is too difficult for researchers to model certain complex systems, which means studies can be limited in terms of the applicability of the ABM to real-world phenomena, as they cannot model every nuance. Johnson (2015) explains that achieving a model that emulates real-life phenomena exactly is impossible because researchers do not have perfect knowledge of all the aspects of the complex systems they intend to study. Furthermore, critical variables, interactions, assumptions, and mechanisms may be ignored or unknown, which may also add to the inaccuracy of results. It is thus important to note that the use of ABMs does not guarantee that precise predictions will be made. However, in spite of these limitations, ABMs still have a lot to offer researchers in terms of its ability to push forward the boundaries of research.

A.3 SOFTWARE TOOLKITS FOR AGENT-BASED MODELLING

Designing ABMs requires software platforms that provide a variety of features and thus choosing the appropriate software toolkit is determined by the project's needs in addition to the programmer's past experience (Nikolai & Madey, 2009). According to Crooks and Castle (2012), there are over 100 available toolkits, however, Heppenstall et al. (2011), state that the most commonly used ones include the highly popular Recursive Porous Agent Simulation Toolkit (Repast), NetLogo, SWARM, and Multi Agent Simulation Of Neighbourhood (MASON). Furthermore, they point out that these toolkits can be linked to other software libraries (e.g. OpenMap, GeoTools) due to the available libraries of pre-defined methods that can be integrated with ABMs (Crooks & Heppenstall, 2012). In addition, it is indicated that these toolkits (Repast, NetLogo, SWARM, and MASON) are continually updated, developed, widely used, and well supported (Crooks & Castle, 2012). In this thesis, an overview of Repast, NetLogo, SWARM, and MASON toolkits will be given before moving on to a detailed examination of the Repast software toolkit specifically.

A.3.1 Repast Software

Repast is open-source software (North et al., 2006) that has a large set of libraries for developing models (Robertson, 2005; Xu et al., 2003). Repast deals with several languages - Java, Microsoft.NET, and Python scripting. Repast also has built-in adaptive features such as genetic algorithms (Gilbert & Bankes, 2002; Serenko &

Detlor, 2002; Tobias & Hofmann, 2004). Furthermore, several available sample models can be downloaded and run as tutorials (Robertson, 2005). However, extending any of the standard models it offers requires in-depth programming experience. In addition, the time required to develop a new model is likely to be extensive. Robertson (2005) and Railsback et al. (2006) have indicated that one of Repast's strengths is that it was created and developed by social scientists, which means that it supports projects which entail social networks, generic algorithms, systems dynamics and geographical information systems (GIS). It is also supported by a community of model builders, which aids new Repast members.

A.3.2 NetLogo Software

Netlogo is a free, open-source platform (Bajracharya & Duboz, 2013), and is viewed as one of the easiest software packages to use in terms of installation and operation (Robertson, 2005). It also features an extensive and well-documented model library that enables users to explore many different types of models. NetLogo provides simple visualisation tools as it was originally developed for educational purposes (Bajracharya & Duboz, 2013) where users are not required to have an extensive technical background in order to explore models (Robertson, 2005). Railsback et al. (2006) have reported that NetLogo's animation display is automatically linked to the program in addition to the chart and optional graphical controls. They also demonstrate that Netlogo has its own language, which is considered simpler to use than Java or Objective-C. However, most scientists regard NetLogo's framework as too limited for serious ABMs (Railsback et al., 2006).

A.3.3 SWARM Software

SWARM is an open-source toolkit available for free download available in two versions "Objective-C SWARM" and "Java SWARM" (Crooks & Castle, 2012; Railsback et al., 2006). However, the Java version of SWARM is less mature than the objective-C version, and in addition, it is known for weak error handling and a lack of developer tools. It is also very commonly used, being one of the older toolkits and has been available since 1996 (Castle & Crooks, 2006). Thus, it is still used by experts. Xu et al. (2003) list some of SWARM's features, such as display, control, and analysis tools. Railsback et al. (2006) mention that SWARM is able to rapidly execute simple models but that it is among the slowest for more complex ones. Other drawbacks,

according to Robertson (2005), are that SWARM is not well supported and is unsuitable for Social-Science applications. In addition, installation and successful operation are reported as being difficult to achieve.

A.3.4 MASON Software

MASON, an open-source, agent-based modelling library, provides core services that can be combined with other libraries (Luke et al., 2005; North et al., 2013). Researchers have indicated that MASON is a small but high-speed library which is simple-to-understand and modify (Luke et al., 2005; North et al., 2013; Railsback et al., 2006). According to Crooks and Castle (2012), MASON supports GIS vector data to be imported and exported. Furthermore, North et al. (2013) propound that MASON was designed with the objective of maximising execution speed and ensuring complete reproducibility across hardware in mind. MASON also allows the detachment and re-attachment of graphical interfaces as well as the ability to stop the simulation and move it to different computers (Railsback et al., 2006). However, they also report that due to MASON's limited capabilities in terms of graphing and random number distribution - which are still under development - it is the least mature toolkit among Netlogo, Repast, and SWARM.

A.3.5 Comparison between Agent-Based Modelling (ABM) Software Toolkits

Table A.2 presents a comparison of the similarities and differences between Repast, NetLogo, SWARM, and MASON software that could be used to design an ABM and perform simulations. Each of the toolkits discussed has specific benefits and limitations. However, the Repast toolkit is the most suitable package for the current research for a number of reasons. Firstly, the literature points out that Repast is well developed and supported by an academic group that can help with any minor issues encountered. In addition, Repast's developers have provided many examples of use that are easy to follow and enable users to become familiar with its features. Furthermore, it provides other benefits, such as GIS and high execution speeds.

Toolkits Features	Repast	SWARM	NetLogo	MASON
Geographical Information System (GIS)	Good, but the examples should be followed [9]	Partial (complicated) [8, 9]	Partial (raster) [9]	Available via an additional tool [10]
Main Strength	Well-developed libraries. It has many users and is well supported by the Repast community [11]	SWARM Concept [9]	Easy to install and use [8, 11]	Speed [9, 12]
Main Weakness	Difficult to use by modellers [9]	Complexity [9]	No support for complex models [9]	Complexity [8, 9]
Example Models	Many [11]	Few [3, 11, 13]	Many [3, 11, 13]	Few [8, 14]
Limitation	Requiring at least some knowledge of Java to extend models [11]	Installation difficulty, not well supported [11]	Impossible to extend the built models [11]	
Support from Academic Community	High [3, 11, 13]	Relatively low [3, 11, 13]	High [3, 11, 13]	Basic capabilities [8]
Modelling language	Java, Python [3, 13, 15], .Net [15, 16]	Objective-C, Java [3, 11, 13]	NetLogo [3, 11, 13]	Increasing [3, 13]
Support for Geographical User Interface	Good [3, 13]	Limited [3, 13]	Easy to Create [3, 13]	Java [3, 8, 13]
Speed of Execution	Fast [3, 13]	Moderate [3, 13]	Moderate [3, 13]	Fastest [3, 13]
Programming Experience	Strong [3, 8, 17]	Strong [3]	Basic [3]	Strong [3]

Table A.2: A comparison between four ABM toolkits

A.4 REPAST SOFTWARE

Repast is a free, open source environment that is commonly used for agent-based modelling and as a simulation toolkit (Crooks & Castle, 2012; Heppenstall et al., 2011). It was developed at the University of Chicago by Sallach and Collier in 2000. Repast has been subsequently supervised by the not-for-profit volunteer Repast Organization for Architecture and Design (ROAD). It is also overseen by members of industrial organisations, a range of government departments, and academics, in addition to many other stakeholders that contribute to its development (North et al., 2013; North et al., 2006).

Repast 3 refers to: (i) Repast for Java (Repast J), (ii) Repast for .NET, and (iii) Repast for Python Scripting (Repast Py). Furthermore, the most recent version of Repast is called Repast Symphony (Repast S) which was built on the strengths of Repast 3 but uses a new codebase that is designed with extra features, such as data sources, data sinks, and data sets (North et al., 2013; North & Macal, 2007). In previous versions of Repast (Repast 3), users were required to set up and configure an appropriate, integrated, development environment, whereas Repast Symphony is pre-configured with Eclipse-based IDE (Heppenstall et al., 2011; North et al., 2006). Repast Symphony's runtime includes facilities for data analysis and presentation in addition to advanced features for behavioural activation, display, agent storage, and watchers, which were not available in Repast 3 (Heppenstall et al., 2011; Macal & North, 2005).

According to Collier and North (2011), Repast is capable of supporting large, individual model runs and offers generic components according to the requirements of the contexts and projections at hand. North et al. (2006) have indicated that Repast supports the integration of raster - the pixels that are referred to as grid cells - and vector datasets (e.g. points, lines, or polygons). North et al. (2013) also state that Repast is capable of handling large-scale-agent-simulation-application development after launching a number of releases. It has become a reusable, infrastructure software tool able to support "...rapid Social Science discovery..." (North et al., 2013) after it was expanded by Argonne National Laboratory as a reusable software infrastructure based on extensive computational experimentation. Furthermore, the output code has a highly-modular, plug-in architecture in the form of a software module that extends the features of a host program using a well-defined programming interface. This plug-in incorporates individual components such as logging, networks, and time scheduling.

According to Tobias and Hofmann (2004) and Balbi and Giupponi (2009), Repast is the most appropriate framework for the applied modelling of social interventions based on current theories and data. Arunachalam et al. (2008) and Railsback et al. (2006) have also indicated that Repast is among the most effective simulation toolkits in the market. However, Tobias and Hofmann (2004) believe other alternative ABM toolkits are preferred in the field of economics (e.g. Netlogo or SWARM). Indeed, Tobias and Hofmann (2004) conducted a study comparing four ABM's toolkits, RePast, SWARM, Quicksilver, and VSEit. Their study aimed to

assess and determine the most suitable simulation toolkit for theory and data-based modelling of social interventions, such as information campaigns. They developed a rating system that relies on diverse criteria such as official program documentation, user's and developer's statements, and the experiences and impressions of the evaluators. Their study concluded that Repast's environment is superior. Furthermore, concerning the time, effort and energy saved by scientists, Repast outperformed the other toolkits examined.

Arunachalam et al. (2008) conducted a study assessing three ABM toolkits including Repast, MASON, NetLogo. The study focuses on (i) design criteria, (ii) model specification criteria, (iii) model execution criteria, and (v) documentation. Each of these criteria is evaluated as scoring low, medium, high, or very high. Regarding Repast's design criteria, its environment structure was rated very high due to its ability to represent the environment as a graph and agents moving as entities to achieve their goals. In addition, NetLogo and MASON were rated low and high respectively. However, regarding environment distribution, Repast was rated medium because it only contains distributed processing capabilities, whereas Netlogo and MASON were rated very high and low respectively. In terms of simulation-execution criteria, Repast was rated high especially for the quality of its continuous representation of agents' movement within a geographic structure.

A.4.1 Repast Symphony

Repast Symphony provides a series of helpful guides in addition to technical specifications that enable learners to quickly become familiar with the software (Arunachalam et al., 2008; Heppenstall et al., 2011; Howe et al., 2006; North et al., 2006). Repast Symphony also offers several major simulation functions such as time scheduling, space administration, random number generation, and behaviour activation (Heppenstall et al., 2011; North & Macal, 2007). In relation to behaviours execution, Repast Symphony provides conditional and unconditional annotation methods, which enables any method within the model to be executed (North et al., 2013). These annotation methods require the setting of a few parameters (e.g. time and priority of execution). In terms of the conditional annotation method, the watcher mechanism is an example of Repast Symphony's conditional annotation method that can be used to activate behaviours. The unconditional annotation method can be used

to schedule any method to be executed at a specific time interval without the need to explicitly name it (as in Java). Furthermore, Repast Symphony introduces interoperability with two-dimensional or three-dimensional geographical information system (GIS), and other model views (Arunachalam et al., 2008; Balbi & Giupponi, 2009; Heppenstall et al., 2011; North et al., 2006; Tobias & Hofmann, 2004).

In relation to visualisation, Repast Symphony provides users with the ability to view running models in 2D and 3D to enable designers to gather and store information from a simulation while it is running; known as data collection (Heppenstall et al., 2011; North et al., 2013). It additionally enables the designers to pause, serialise or checkpoint the state of the simulation for later execution. Furthermore, Repast Symphony allows almost any third-party applications to be linked (e.g. GeoTools).

A.4.2 Limitations of Repast Symphony

Repast Symphony lacks some of the fundamental elements such as a built-in method to randomise the agents' order of execution and a lack of enough tools to allow the effective communication and documentation of the software (Heppenstall et al., 2011; Railsback et al., 2006). Repast also can be only learned via the examples provided, which encompass some of Repast's most important features (Amouroux et al., 2007). In addition, Repast's agents cannot be modified while actions are scheduled (Heppenstall et al., 2011). Repast is also seen as incomplete regarding the statistical-calculation capabilities it offers. For example, the DataRecorder object and the statistical calculations are limited to functions such as recording and writing data from different sources in a tabular format to a file.

A.5 SUMMARY

This appendix has discussed a selected range of computational models, namely agent-based modelling (ABM), cellular automata (CA) models, microsimulation models (MSMs), and system dynamics models (SDMs) and provided a table of comparison with regard to some features related to the key elements identified in Chapter 2 and 3. Subsequently, the agent-based modelling framework has been selected due to its capability in terms of handling interactions, modelling individual heterogeneity, and representation of the environment. Furthermore, a range of ABM software toolkits, namely Repast, NetLogo, SWARM, and MASON, have also been

discussed before selecting the Repast toolkit. Finally, the Repast toolkit has been reviewed in terms of its features and limitations.

Appendix B

Visual Enhancement

B.1 TOPOGRAPHY LAYER VISUALISATION ENHANCEMENT

This section outlines the enhancement process carried out on the *Topography* layer using QGIS software before modelling the geographical environment as a pre-agent-based model implementation. Recall, the GML extension format focuses on the representation of geographic data rather than how the data should be presented (Gudmundsson & Mohajeri, 2013). Thus, QGIS was used to improve the *Topography* layer's visualisation, which was downloaded in a GML extension format, and enable the conversion of its extension format. Subsequently, the *Topography* layer was then imported into QGIS as an input and separated into multiple sub-layers (e.g. BoundaryLine, CartographicSymbol, CartographicText, TopographicArea, TopographicLine, and TopographicPoint) (see Figure B.1(a)) to remove some of its unrelated sub-layers (e.g. BoundaryLine, CartographicSymbol, CartographicText, TopographicLine, and TopographicPoint). Only one of these sub-layers, namely the TopographicArea, was selected and the remainder were removed because they do not provide any essential information required in this research.

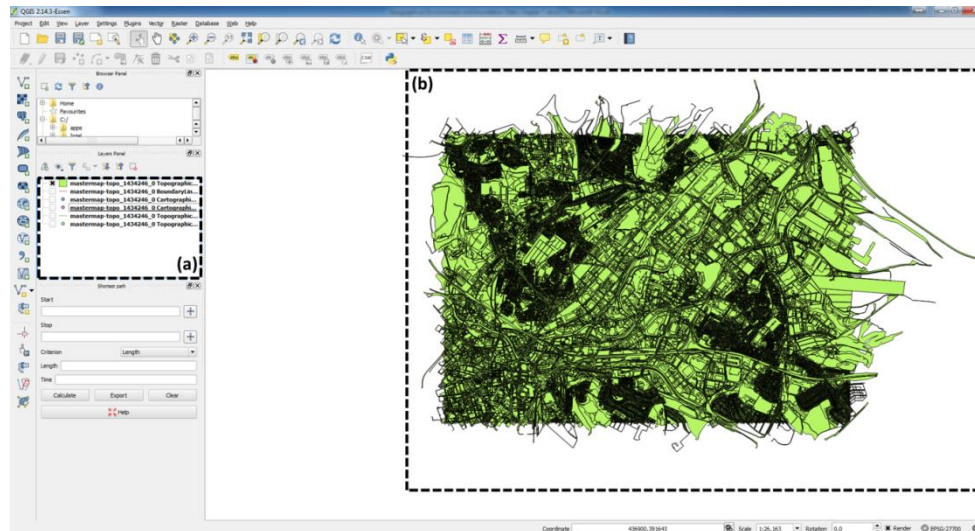


Figure B.1: TopographicArea layer before enhancement

The TopographicArea was also separated into two layers, namely the Building (i.e. the layer that holds information about every individual property) and the *Topography* (i.e. the reminder layers of TopographicArea) layers. This split was performed to enable each of these layers (Building and *Topography*) to highlight their themes using different sets of colours. Note that if the Building layer was not separated into a separate layer, it would not be possible to highlight buildings that were assigned different colours.

As presented in Figure B.2 (a), to enable the building layer to be separated, the selection expression ("theme" = 'Buildings') was implemented to select the building theme among the other themes presented in Figure B.2 (c); this was then saved as a separate layer in a shapefile extension format.

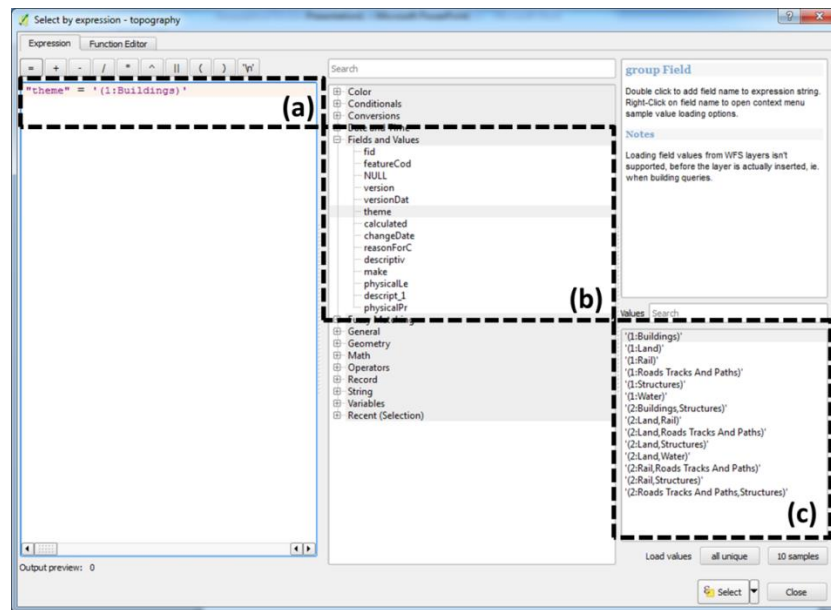


Figure B.2: Selection expression for the *Building* layer

The selected theme could then be saved as an individual layer with a shapefile extension format, namely Building layer. Subsequently, the ‘save only selected features’ option (see Figure B.3 (a)) must be selected to confirm that only the selected theme will be saved.

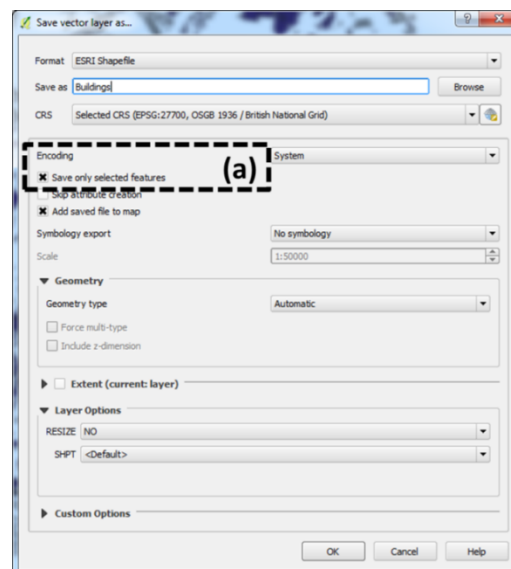


Figure B.3: Saving a specific layer in a shapefile extension format

In relation to the *Topography* layer, this was the TopographicArea layer saved without the building layer in which each of its themes was highlighted with the appropriate colour (see Section B.1.2).

B.1.1 Building Layer

The Building layer provides information about each property located in the selected geographical area. In terms of visualisation, buildings were classified according to the version theme (see Figure B.4 (a)) to enable each group of these buildings to be assigned a distinct colour. Consequently, these buildings were then classified into 29 groups of versions in which each group has a different colour (see Figure B.4 (b)).

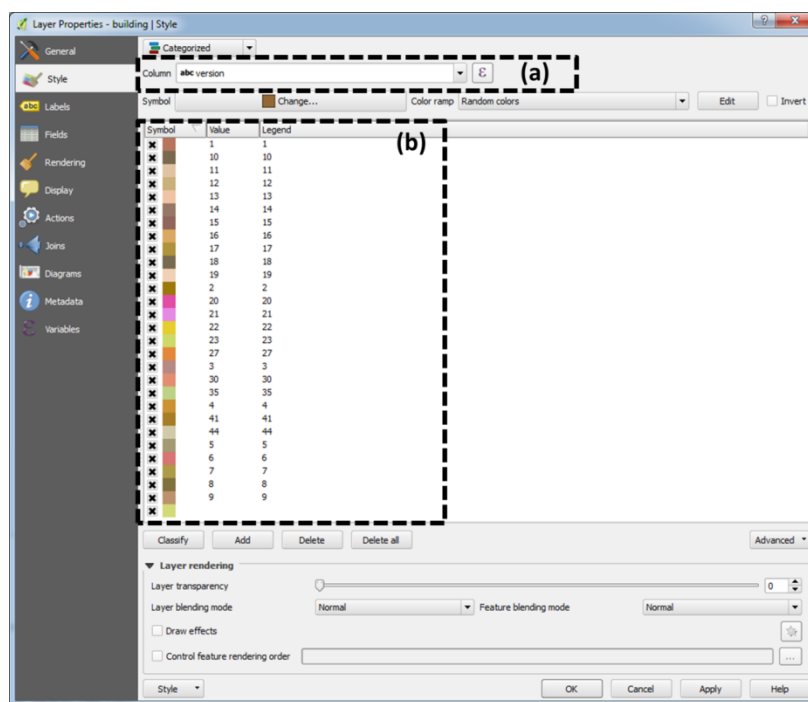


Figure B.4: Classifying buildings into groups of versions

Finally, the Building layer was saved into two files, namely “building layer.shp” and “building layer.sld”. The shapefile stores the geographical coordinates along with the corresponding attributes of each feature whereas the SLD file maintains the overall styles. An overview of the Building layer is presented in Figure B.5.

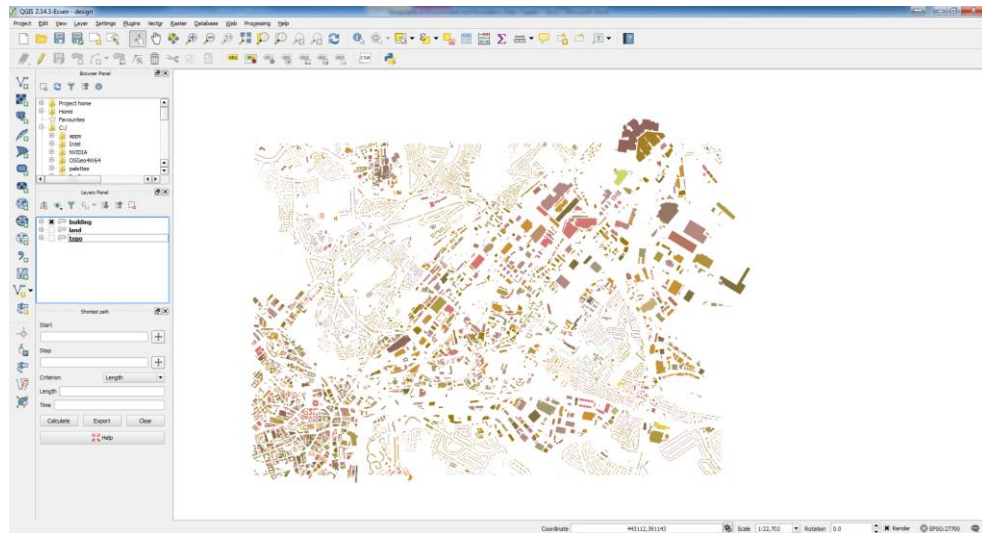


Figure B.5: Overview of the building layer after enhancement

B.1.2 Topography Layer

This layer includes all the TopographicArea layer's remaining themes, such as roads, structures, and areas of water, along with their associated information. In QGIS, this layer's visualisation was enhanced by allocating each theme to its appropriate colour (such as blue and grey for water and roads, respectively) as shown in Figure B.6.

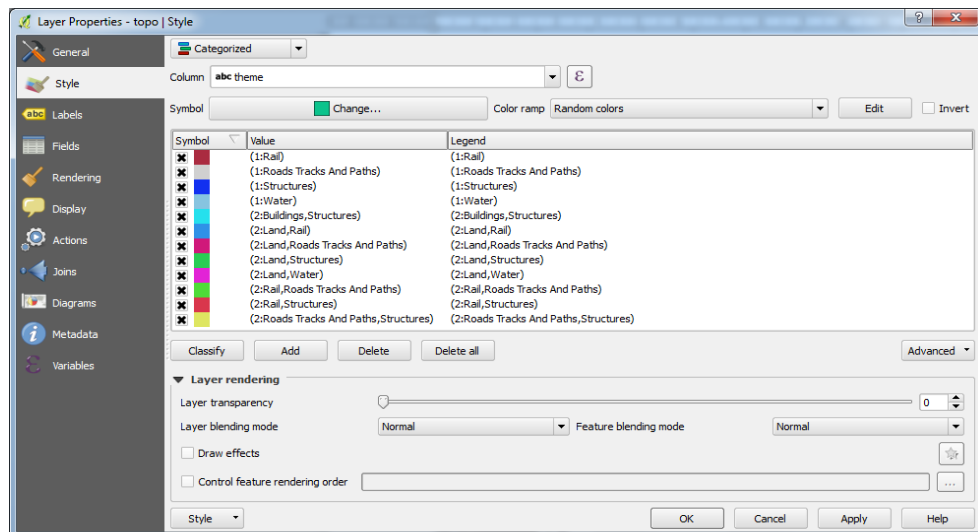


Figure B.6: Allocating attributes with the appropriate colours

As Figure B.7 illustrates, the *Topography* layer themes (e.g. railways, roads, and areas of water) were highlighted with their respective colours to significantly improve the overall view.

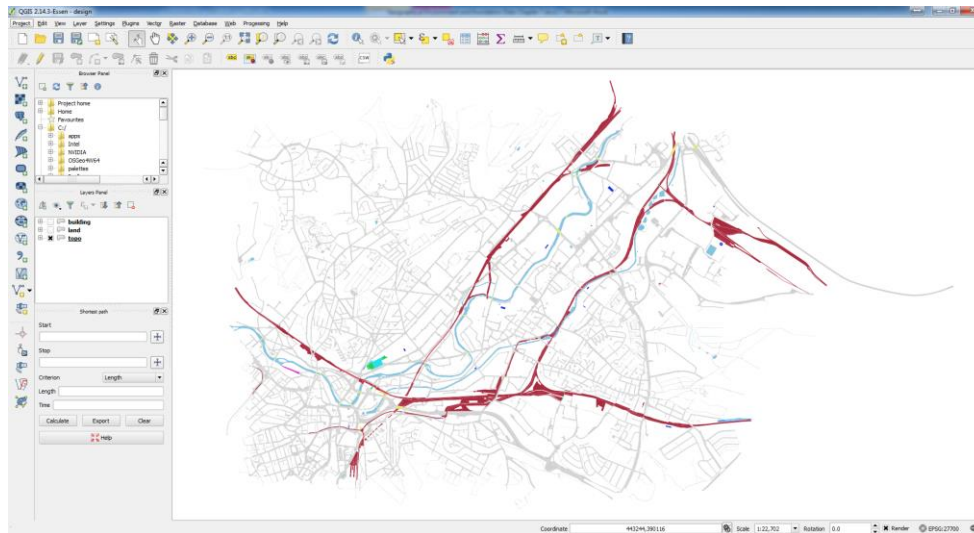


Figure B.7: Overview of the *Topography* layer after enhancement

B.1.3 Coupling the Building and *Topography* Layers

The Building and *Topography* layers were coupled together using QGIS into a single layer, namely the *Topography* layer as shown in Figure B.8.

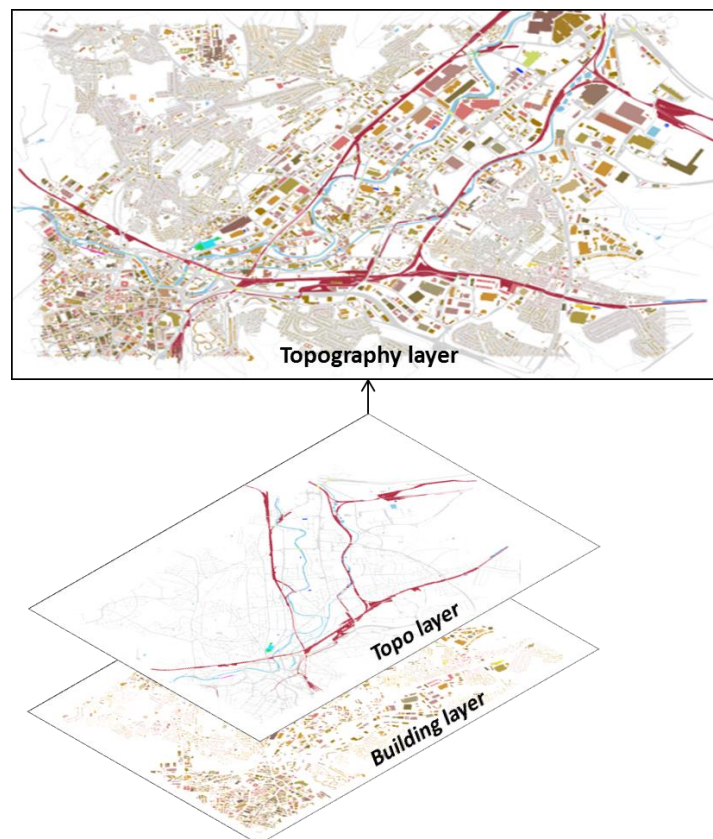


Figure B.8: Coupling the *Building* layer along with the *Topography* layer after enhancement

B.2 INTEGRATED TRANSPORT NETWORK (ITN) LAYER ENHANCEMENT

The *ITN* layer provides information on the street network and transport information such as the road-link codes. This layer consists of a number of connected lines representing the road network. In QGIS, this layer visualization was enhanced by: (i) changing the colours of the connected lines to grey and (ii) increasing the thicknesses of these lines to ensure their clarity once incorporated with the *Topography* layer. The *ITN* layer is presented in Figure B.9 after applying the aforementioned enhancements.

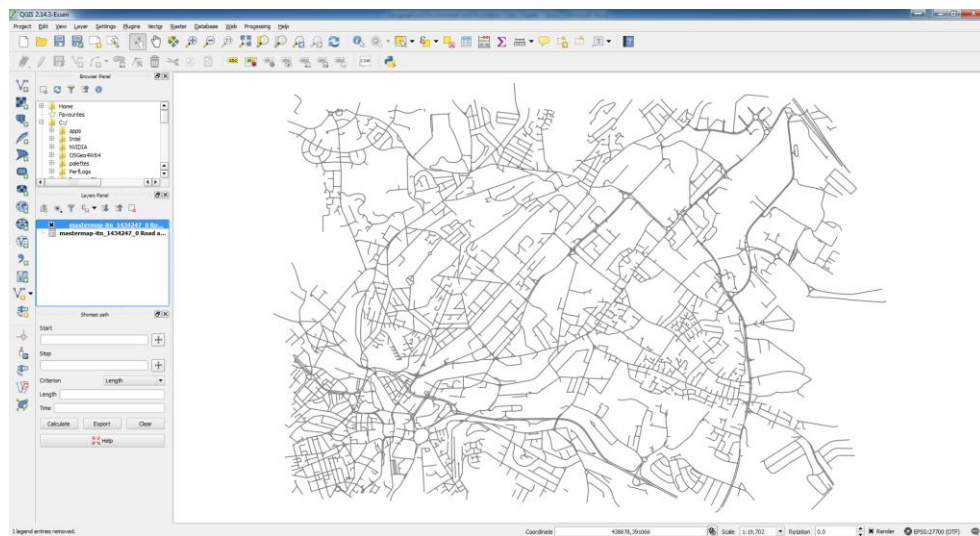


Figure B.9: Overview of the *ITN* layer after enhancement

Appendix C

ODD Protocol

Appendix C presents the ODD protocol along with its related elements. Some of the text or figures provided in this appendix may have appeared previously in some parts of this thesis. However, these have been copied or paraphrased in this appendix rather than referring to them in their locations to support the reading flow of this appendix.

C.1 PURPOSE

The purpose of this research is to develop an agent-based model and simulation (ABMS) framework to investigate manufacturing and retail SMEs' immediate response to and short-term recovery from a flood event to evaluate the effectiveness of combinations of flood precautionary measures.

C.2 ENTITIES, STATE VARIABLES AND SCALES

One time step, or simulation tick, represents a half-hour period, which corresponds with the time between flood depths given in the inundation data for each location in the modelled geographic environment. Simulations were run representing approximately 37 working days (i.e. 1748 simulation ticks) for SMEs located in Sheffield and approximately 45 working days (i.e. 2132 simulation ticks) for those located in Tewkesbury. The flood event was simulated as described in the Chapter 8. In the Lower Don Valley of Sheffield, based on the *AddressBase Plus* layer used to construct the MGE coupled with the inundation data, a total of 6224 organizations were identified where 906 had been flooded at some point during the 45.5-hour flood event modelled. For Tewkesbury, a total of 920 organisations were identified in Tewkesbury geographical area in which 207 had been flooded at some point during the 318.5 hours

simulated. The manufacturing and Retail SMEs associated state variables are provided in Table C.1 while the state variables associated with SME-related organisations are provided in Table C.2 to Table C.7.

C.2.1 Manufacturing and Retail SMEs

Variable name	Brief description
Identifier	Unique identifier for an SME.
SME name	SME's name obtained from OS MasterMap's Address layer.
Business classification code	Code associated with an SME's business classification obtained from OS MasterMap's Address layer.
Business classification name	Name associated with an SME's business classification obtained from OS MasterMap's Address layer.
Easting	Geographic coordinates associated with an SME obtained from OS MasterMap's Address layer.
Northings	
SME size	Micro, small or medium according to the number of employees.
Clock time list	A list of clock times (half-hour periods) throughout the simulation. This is used to keep a record of the time at which an SME's actions were performed during a simulation.
Simulation ticks list	A list of ticks throughout the simulation; each tick represents a half-hour period.
Days list	A list of days through the simulation; each clock time and simulation tick is associated with a day.
Inundation data list	A list of the water depth(s) at each simulation tick associated with the location of an SME.
Suppliers' unique identifier list	A list of suppliers' unique identifiers to enable communication with them when needed during a simulation (pre- and post-flood).
Electricians' unique identifier list	A list of electricians' unique identifiers to enable communication with them when needed during a simulation (post-flood).
Plumbers' unique identifier list	A list of plumbers' unique identifiers to enable communication with them when needed during a simulation (post-flood).
Plumber at premises?	True if a plumber is present at an SME's premises.
Insurance company's identifier	Insurance company's unique identifier to enable communication with it when needed during a simulation (post-flood).
Cleaning service providers' unique identifier list	A list of cleaning service providers' unique identifiers to enable communication with them when needed during a simulation (post-flood).
Inbox list	A list of messages received from other agents.
Maximum depth of flood water reaches in an SME's premises	The maximum depth the flood water reaches at an SME's premises obtained from the inundation data list.
Funds?	True if an SME has funds available.
Compensation?	True if an SME has received financial compensation from its insurer.
Cleaning service provider at premises?	True if the cleaning service provider is present at an SME's premises.
Allocated employees to clean-up?	True if an SME decides to allocate employees to clean-up the premises rather than requesting a cleaning service

Variable name	Brief description
	provider or accepting a provided cleaning service from its insurer.
Arrival time of cleaning equipment	The arrival time of the necessary cleaning tools acquired for use by an SME's employees.
Power availability?	True if an SME has power available at its premises.
Electrician at premises?	True if an electrician is present at an SME's premises.
Trust EA alert?	True if an SME trusts, and so acts on, an EA alert.
Height location of paper documents held above ground level	The height at which paper documents are stored in an SME's premises.
Total number of employees list	A list of the total number of employees available at an SME's premises at each simulation tick.
Raise the level at which paper documents are kept	True if paper documents are kept at a raised location at an SME's premises.
Build bund wall?	True if a bund-wall is erected around an SME's premises.
Maintain sandbags on site?	True if sandbags are available at an SME's premises.
Install flood-proof doors?	True if flood-proof doors are installed at an SME's premises.
Install flood barriers at doorways?	True if flood barriers are installed at an SME's premises.
Install flood-proof windows?	True if flood-proof windows are installed at an SME's premises.
Paint brickwork with waterproofing substances?	True if the exterior of an SME's premises has been painted with waterproofing substances.
Maintain an electricity generator?	True if an SME maintains an electricity generator at its premises?
Raise the level at which electrical sockets are located?	True if electrical sockets are at raised locations at an SME's premises.
Raise the level at which electrical consumer boards are located?	True if electrical consumer boards are at raised locations at an SME's premises.
Install flood-resilient flooring?	True if flood-resilient flooring is installed at an SME's premises.
Installed 'below-ground' water-proof materials?	True if 'below-ground' water-proof materials are implemented at an SME's premises.
Install anti-backflow valves?	True if anti-backflow valves are installed at an SME's premises.
Maintain/use sump pumps?	True if an SME has a sump-pump system available to remove flood water from its premises.
Maintain an emergency flood plan?	True if an SME maintains an emergency flood plan for business continuity.
Perform emergency flood exercises?	True if an SME's employees regularly perform an emergency flood exercise.
Display emergency flood plan instructions?	True if an SME displays its emergency flood plan.
Maintain an emergency financial reserve?	True if an SME maintains an emergency financial reserve.
Register for Environment Agency (EA) flood alerts?	True if an SME has registered for EA alerts.
Register for Environment Agency (EA) flood warnings?	True if an SME has registered for EA warnings.
Obtain comprehensive insurance cover?	True if an SME holds comprehensive insurance.
Obtain basic insurance cover?	True if an SME holds basic insurance.
Specific variables for manufacturing SMEs	
Backed-up IT data?	True if a manufacturing SME holds all documentation electronically and maintain backups of them.
Customers' unique identifier list	A list of customers' unique identifiers to enable communication with them when needed (pre and post flood).
Have pre-existing mutual aid partner(s)?	True if a manufacturing SME has a pre-existing agreement(s) with mutual aid partner(s).

Appendix C. ODD Protocol

Variable name	Brief description
Height location of IT equipment held above ground level	The height above ground at which IT equipment is stored at a manufacturing SME's premises.
Height location of products held above ground level	The height above ground at which products are stored in an manufacturing SME's premises.
Height location of raw materials held above ground level	The height above ground at which raw materials are stored in a manufacturing SME's premises.
Identify mutual aid partner(s)?	True if a manufacturing SME identifies a mutual aid partner(s) during a simulation.
IT specialist at premises?	True if the IT specialist is present at a manufacturing SME's premises.
IT specialists' unique identifier list	A list of IT specialists' unique identifiers to enable communication with them when needed during a simulation (post-flood).
Maximum capacity of products that can be stored above ground level	Maximum capacity of products that can be stored above ground level at a manufacturing SME's premises.
Maximum capacity of raw material that can be stored above ground level	Maximum capacity of raw materials that can be stored above ground level at a manufacturing SME's premises.
Percentage of machines available list	A list of the percentage of machines available for production at a manufacturing SME's premises at each simulation tick.
Production level list	A list of the percentage of production level at a manufacturing SME's premises at each simulation tick.
Products manufactured list	A list of the total quantity of products manufactured at a manufacturing SME's premises at each simulation tick.
Proportion of products located above ground level list	A list of the proportion of products located above ground level at a manufacturing SME's premises at each simulation tick.
Proportion of products on the ground list	A list of the proportion of products kept at ground level at a manufacturing SME's premises at each simulation tick.
Proportion of raw materials located above ground level list	A list of the proportion of raw materials located above ground level at a manufacturing SME's premises at each simulation tick.
Proportion of raw materials on the ground list	A list of the proportion of raw materials kept at ground level at a manufacturing SME's premises at each simulation tick.
Raise the level at which IT equipment is located?	True if IT equipment is raised above ground level (on platforms or attached to a wall) at a manufacturing SME's premises.
Raise the level at which machines are located?	True if machines are raised above ground level (on platforms) at a manufacturing SME's premises.
Raise the level at which products are stored	True if a proportion of products are stored at a raised location at a manufacturing SME's premises.
Raise the level at which raw materials are stored	True if a proportion of raw materials are stored at a raised location at a manufacturing SME's premises.
Raw materials available list	A list of the total quantity of raw materials available at a manufacturing SME's premises for production at each simulation tick.
Request mutual aid?	True if a manufacturing SME request mutual aid.
Total number of non-production employees list	A list of the total number of non-production employees available at a manufacturing SME's premises at each simulation tick.
Total number of production employees list	A list of the total number of production employees available at a manufacturing SME's premises at each simulation tick.
Total number of production employees working on production list	A list of the total number of production employees working on production at a manufacturing SME's premises at each simulation tick.
Type of products	Type of products: e.g. light, medium or heavy.

Variable name	Brief description
Specific state variables for retail SMEs	
Arrival time of sales equipment	The arrival time of the new sales equipment ordered for use by a retail SME's employees.
Environment condition list	A list of the percentage of the validity of the environmental conditions for operation at each simulation tick at a retail SME's premises.
Height location of sales equipment	The height at which the sales equipment is stored.
Height location of stock	The height above ground at which stock is stored in a retail SME's premises.
Raise the level at which stock is stored	True if a proportion of stock is stored at a raised location at a retail SME's premises.
Refurbishment companies' unique identifier list	A list of refurbishment companies' unique identifiers to enable communication with them when needed (post-flood).
Refurbishment company at premises?	True if the refurbishment company is present at a retail SME's premises.
Sales equipment list	A list of the percentage of working sales at each simulation tick at a retail SME's premises.
Total number of employees serving customers list	A list of the total number of employees working on customer service at a retail SME's premises at each simulation tick.

Table C.1: Variables of manufacturing and retail SMEs

C.2.2 SME-Related Organisations

C.2.2.1 Cleaning Service Providers

Variable name	Brief description
Identifier	Unique identifier for the cleaning service provider modelled.
Service type	Cleaning service provider
Status	Available or busy.
Inbox list	A list of messages received from other agents (SMEs or insurance companies).
Senders' unique identifier list	A list of the senders' unique identifiers to enable communication with them when needed during a simulation (post flood).
Teams' status list	A list of the status for every team within the cleaning-service provider signifying the current status, i.e. available or busy.
Number of teams	The number of teams making up the cleaning service provider.
Number of staff in each team	The number of staff in each team within this cleaning service provider.
Insurance companies' unique identifier list	A list of insurance companies' unique identifiers that have a contract with this cleaning service provider.
SMEs' unique identifier list	A list of SMEs' unique identifiers that have a contract with this cleaning service provider.

Table C.2: Variables of cleaning service providers

C.2.2.2 Customers and Suppliers

Variable name	Brief description
Identifier	Unique identifier for the agent modelled.
Service type	Customer or supplier.
Inbox	A list of messages received from SME agents.
Senders' unique identifier list	A list of the SME senders' unique identifiers to enable communication with them when needed during a simulation (pre and post flood).
SMEs' unique identifier list	A list of SMEs' unique identifiers that have a contract with this customer or supplier.
Schedule list	A list of customer delivery times or supplier dispatch times.

Table C.3: Variables of customers and suppliers

C.2.2.3 Service Provider Organisations (electricians, plumbers, IT specialists, and refurbishment companies)

Variable name	Brief description
Identifier	Unique identifier for the agent modelled.
Service type	Electrical contractor.
Status	Available or busy.
Inbox	A list of messages received from SME agents.
Senders' unique identifier list	A list of the SME senders' unique identifiers to enable communication with them when needed during a simulation (post flood).

Table C.4: Variable of electrical contractors

C.2.2.4 Environment Agency (EA)

Variable name	Brief description
Identifier	Unique identifier for the agent modelled.
Name	The Environment Agency.
Clock time list	A list of clock times (half-hour periods) throughout the simulation.
Simulation ticks list	A list of ticks throughout the simulation; each tick represents a half-hour period.
Days list	A list of days through the simulation; each clock time and simulation tick is associated with a day.
Inundation data list	A list of the water depth(s) at each simulation tick associated with the location of an SME.
Registered SMEs' unique identifiers list	A list of SMEs' unique identifiers that have registered for EA alerts and warnings.

Table C.5: Variable of Environment Agency

C.2.2.5 Insurance Companies

Variable name	Brief description
Identifier	Unique identifier for the agent modelled.

Variable name	Brief description
Service type	Insurance company
Inbox	A list of messages received from SME agents.
Senders' unique identifier list	A list of the senders' unique identifiers to enable communication with them when needed during a simulation (post flood).
SMEs' unique identifiers list	A list of SMEs' unique identifiers that are insured with this insurance company.
Cleaning service providers unique identifiers list	A list of cleaning service providers' unique identifiers that have a contract with this insurance company.

Table C.6: Variables of insurance companies

C.2.2.6 Mutual aid Partners

Variable name	Brief description
Identifier	Unique identifier for a mutual aid partner.
Mutual aid partner name	Mutual aid partner's name obtained from OS MasterMap's Address layer.
Business classification code	Code associated with a mutual aid partner's business classification obtained from OS MasterMap's Address layer.
Business classification name	Name associated with a mutual aid partner's business classification obtained from OS MasterMap's Address layer.
Easting	Geographic coordinates associated with a mutual aid partner obtained from OS MasterMap's Address layer.
Northing	
Mutual aid partner size	Micro, small or medium according to the number of employees.
Clock time list	A list of clock times (half-hour periods) throughout the simulation.
Simulation ticks list	A list of ticks throughout the simulation; each tick represents a half-hour period.
Days list	A list of days through the simulation; each clock time and simulation tick is associated with a day.
Inbox list	A list of messages received from other agents.
Percentage of machines allocated to SME seeking mutual aid list	A list of the percentage of machines allocated to an SME seeking mutual aid to carry out production at the mutual aid partner's premises at each simulation tick.
Raw materials available list	A list of the total quantity of raw materials available at a mutual aid partner's premises for production at each simulation tick.
Production level list	A list of the percentage of production level at a mutual aid partner's premises at each simulation tick.
Products manufactured list	A list of the total quantity of products manufactured at a mutual aid partner's premises at each simulation tick.

Table C.7: Variables of mutual aid partners

C.3 PROCESS OVERVIEW AND SCHEDULING

The 'process overview and scheduling' element of the ODD protocol aims to present the time when the state variables are updated. However, due to the large size of the model, the process overview is presented as a list. This is in accordance with

Grimm et al. (2017) in which it is indicated that it is preferable to demonstrate large models that consist of a repeated sequence of actions as a list of actions. Thus, at each time step (i.e. half-hour period) the following processes occur, in which bold font is used to represent the implemented actions within each of the agents modelled. Please note that Figure C.1 indicates the interaction between SME agents (manufacturing and retail SMEs) and other agents.

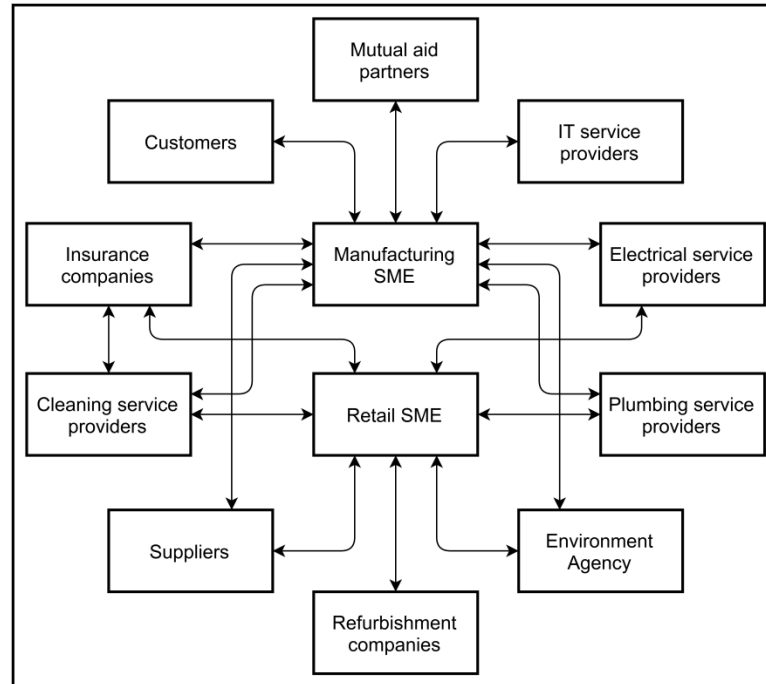


Figure C.1: Interactions between SMEs and their related organizations

C.3.1 Environment Agency

The EA agent sends alerts and warnings to the registered SMEs at intervals prior to the onset of the flood event.

C.3.2 Manufacturing SMEs

For manufacturing and retail SMEs, the **record information** action will be executed initially to update the simulation's current information, such as list of days, list of clock times, and list of simulation ticks. Furthermore, the **check inbox** action will be executed to check if a flood alert or warning has been received from the EA, or if any new messages have been received from other agents, i.e. suppliers and customers. If no alert or warning is received, manufacturing SMEs will execute the **production** action whereas retail SMEs will execute **service**. However, if an alert or

warning is received, both manufacturing and retail SMEs will execute the **emergency** action.

In relation to manufacturing SMEs, the **production** action includes a range of actions such as the (i) employee **allocation strategy** action, which decides how many employees will be allocated to work on production or other behaviours if needed, and if applicable (ii) the **duration** action, which updates the duration of related behaviours.

For retail SMEs, the **service** action consists of a range of actions such as the employee **allocation strategy** action the **duration** action. This will update several attributes ('environment condition', 'sales equipment', and 'sales capability'). However, if manufacturing or retail SMEs have received alerts or warnings from the EA, the **emergency** action will then be executed and the following will occur.

For manufacturing and retail SMEs, the **emergency** action triggers the **allocation strategy** action and the **behaviour** action, which enacts the potential pre-flood behaviours which are presented in Figure C.2.

Implementing the **production** action for manufacturing SMEs or the **service** for retail SMEs along with the **emergency** actions (for both manufacturing and retail SMEs) will update the following state variables: production level; products manufactured; raw materials available.

In relation to the **behaviour** action, the duration associated with each behaviour enacted will be updated as it is undertaken at each simulation tick.

C.3.2.1 Pre-Flood Behaviours

The pre-flood behaviours, which are indicated in Figure C.2, are enacted either concurrently or sequentially according to the number of employees available.

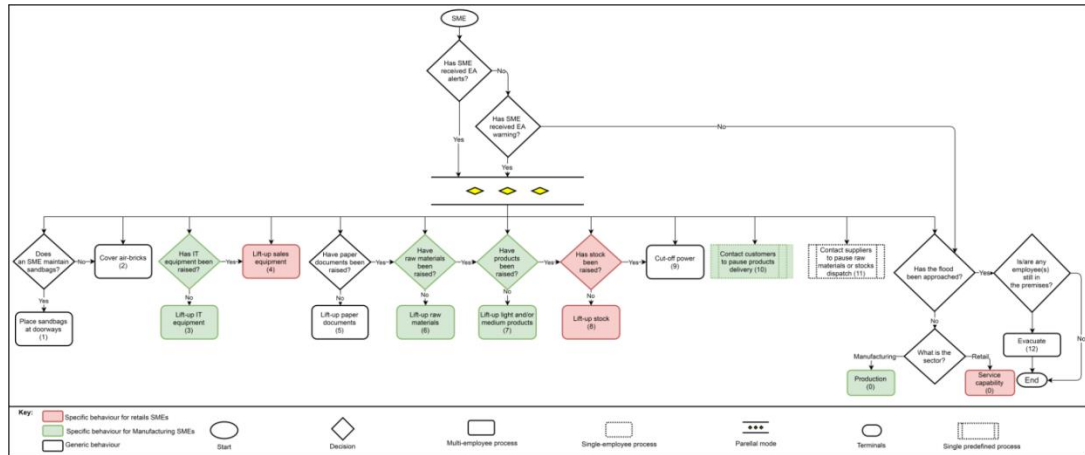


Figure C.2: Pre-flood behaviours' relationships with sequencing order of behaviour execution indicated in the brackets in each action box

To follow, pseudo code of the behaviours indicated in Figure C.2 is presented.

- **Maintain sandbags on site**

```

1. if 'maintained sandbags on site' = true
2. {
3.   if 'built bund-wall' = false
4.   {
5.     if 'installed flood-proof doors' = false
6.     {
7.       if 'installed flood barriers at doorways' = false
8.       {
9.         do place sandbags at doorways
10.        update the following attributes:
11.        'duration of placing sandbags at doorways'
12.        'completion of placing sandbags at doorways'
13.      }
14.    }
15.  }
16. }

```

- **Cover air-bricks**

```

1. do Cover air-bricks
2. update the following attributes:
3. 'duration of covering air-bricks'
4. 'completion of covering air-bricks'

```

- **Lift-up IT equipment**

```

1. if 'sector' = manufacturing
2. {
3.   if 'raised the location at which IT equipment is placed' = false
4.   {
5.     do Lift-up IT equipment
6.     update the following attributes:
7.     'duration of lifting-up IT equipment'
8.     'location height of IT equipment'
9.     'completion of lifting-up IT equipment'
10.  }

```

```
11. }
```

- **Lift-up paper documents**

```
1. if 'raised the locations at which documents are stored' = false
2. {
3.   do Lift-up paper documents
4.   update the following attributes:
5.     'duration of lifting-up paper documents'
6.     'location height of paper documents'
7.     'completion of lifting-up paper documents'
8. }
```

- **Lift-up raw materials**

```
1. if 'sector' = manufacturing
2. {
3.   if 'quantity of raw materials on the ground' > 0
4.   {
5.     if 'raw materials above ground space' < 'maximum capacity can be placed
        above          ground'
6.     {
7.       do Lift-up raw materials
8.       update the following attributes:
9.         'duration of lifting-up raw materials'
10.        'completion of lifting-up raw materials'
11.      }
12.    }
13. }
```

- **Lift-up products**

```
1. if 'sector' = manufacturing
2. {
3.   if 'quantity of products available' > 0
4.   {
5.     if 'type of products' is light or medium
6.     {
7.       if 'storage of products' < 'maximum capacity of storage of products'
8.       {
9.         do Lift-up products
10.        update the following attributes:
11.          'duration of lifting-up products'
12.          'location height of products'
13.          'completion of lifting-up products'
14.        }
15.      }
16.    }
17. }
```

- **Lift-up stock**

```
1. if 'sector' = retail
2. {
3.   if 'raised the location at which stock is placed' = false
4.   {
5.     do Lift-up stock
6.     update the following attributes:
7.       'duration of lifting-up stock'
8.       'location height of stock'
9.       'completion of lifting-up stock'
```

```
10. }  
11. }
```

- **Contact customers to pause product delivery**

```
1. if 'sector' = manufacturing  
2. {  
3.   do Contact customers to pause products delivery  
4.   update the following attributes:  
5.     'duration of contacting customers to pause products delivery'  
6.     'completion of contacting customers to pause products delivery'  
7.  
8. }
```

- **Contact suppliers to pause raw material dispatch**

```
1. do Contact suppliers to pause raw materials dispatch  
2. update the following attributes:  
3.   'duration of contacting suppliers to pause raw materials dispatch'  
4.   'completion of contacting suppliers to
```

- **Evacuation**

```
1. if 'number of employees in a premises' > 0  
2. {  
3.   do Evacuation  
4.   update the following attributes:  
5.     'duration of evacuation'  
6.     'completion of evacuation'  
7. }
```

C.3.2.2 Post-Flood Behaviours

After evacuation, manufacturing and retail SMEs will be affected by the flood event according to the 'inundation data' associated with every individual SME; the degree to which a manufacturing or retail SME is affected will depend on the flood precautionary measures it has in place.

When the water recedes from a manufacturing or retail SME premises, the **recovery** action will be invoked to execute the **behaviour** action, which will enact the potential post-flood behaviours (see Figure C.3, Figure C.4, and Figure C.5). Following this, the **allocation strategy** action will be invoked to allocate the appropriate number of employees to work on production for manufacturing or customer service for retail SMEs and other behaviours. As indicated in the pre-flood behaviours, the duration associated with each behaviour enacted will be updated as it is undertaken at each simulation tick.

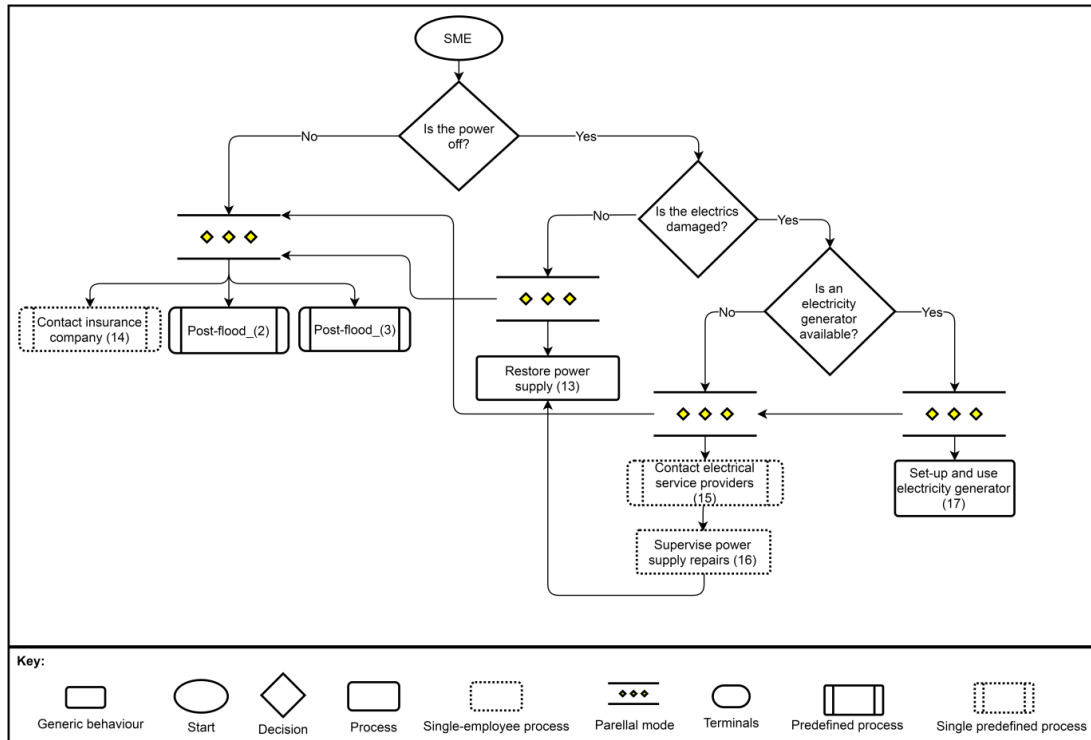


Figure C.3: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (1)

Pseudo-code of the behaviours indicated in Figure C.3 is presented below.

- **Restore power**

```

1. if 'maximum level of water depth in a premises' = 0 or 'completion repair power' = true
2. {
3.   do Restore Power
4.   update the following attributes:
5.   'duration of restoring power'
6.   'power availability'
7.   'completion of restoring power'
8. }
    
```

- **Contact insurance company**

```

1. if 'insurance' = true
2. {
3.   do Contact insurance company
4.   update the following attributes:
5.   'duration of contacting insurance company'
6.   'compensation of contacting insurance company'
7. }
    
```

- **Contact electrical service providers**

```

1. if 'funds' = true or 'compensation' = true
2. {
3.   if 'maximum level of water depth in a premises' > 0 or 'maximum level of water depth in a premises' >=
    
```

```

4.   'level of sockets'
5.   {
6.     do Contact electrical service providers
7.     update the following attributes:
8.       'duration of contacting service electrical providers'
9.       'completion of contacting electrical service providers'
10.    'electrician at premises'
11.  }
12. }

```

- **Supervise the necessary repair**

```

1.  if 'electrician at premises' = true
2.  {
3.    do Supervise the necessary repair
4.    update the following attributes:
5.      'duration of supervising power repair'
6.      'completion of power repair'
7.      'electrician at premises'
8.  }

```

- **Set-up electricity generator**

```

1.  if 'maintain an electricity generator on site' = true
2.  {
3.    if 'power availability' = false
4.    {
5.      do Set-up electricity generator
6.      update the following attributes:
7.        'duration of setting-up electricity generator'
8.        'completion of setting-up electricity generator'
9.        'power availability'
10.    }
11. }

```

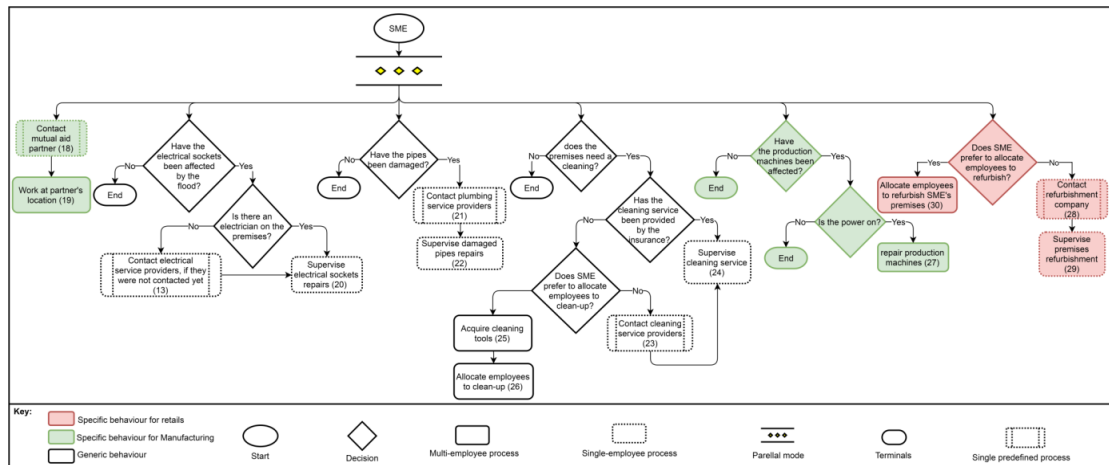


Figure C.4: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (2)

Pseudo-code of the behaviours indicated in Figure C.4 is presented below.

- **Contact mutual aid partner**


```
1. if 'sector' = manufacturing
2. {
3.   if 'has pre-existing mutual aid partner' = true
4.   {
5.     if 'total number of production employees' > 1
6.     {
7.       do contact mutual aid partner
8.       update the following attributes:
9.         'duration of contacting mutual aid partner'
10.        'completion of contacting mutual aid partner'
11.     }
12.   }
13. }
```

- **Work at partner's premises**

```
1. if 'sector' = manufacturing
2. {
3.   if 'completion of contacting mutual aid partner' = true
4.   {
5.     do work at partner's premises
6.     update the following attributes:
7.       'duration of working at partner's premises'
8.       'production level made at partner's premises'
9.   }
10. }
```

- **Contact plumbing service providers**

```
1. if 'funds' = true or 'compensation' = true
2. {
3.   if 'maximum level of water depth in a premises' > 0
4.   {
5.     do Contact plumbing service providers
6.     update the following attributes:
7.       'duration of contacting plumbing service providers'
8.       'completion of contacting plumbing service providers'
9.       'plumber at premises'
10.   }
11. }
```

- **Supervise damaged pipes repairs**

```
1. if 'plumber at premises' = true
2. {
3.   do Supervise damaged pipes repairs
4.   update the following attributes:
5.     'duration of supervising damaged pipes repairs'
6.     'completion of damaged pipes repairs'
7.     'plumber at premises'
8. }
```

- **Contact cleaning service providers**

```
1. if 'funds' = true or 'compensation' = true
2. {
3.   if 'allocated employees to clean up' = false
4.   {
5.     if 'maximum level of water depth in a premises' > 0
6.     {
7.       do Contact cleaning contractors
8.       update the following attributes:
```

```
9.      'duration of contacting cleaning service providers'
10.     'cleaning service providers at premises'
11.     'completion of contacting cleaning service providers'
12.   }
13. }
14. }
```

- **Supervise cleaning service provider**

```
1. if 'cleaning service providers at premises' = true
2. {
3.   do supervise the cleaning providers
4.   update the following attributes:
5.   'duration of supervising cleaning service'
6.   'completion of clean-up'
7.   'cleaning service providers at premises'
8. }
```

- **Acquire the necessary cleaning tools**

```
1. if 'funds' = true or 'compensation' = true
2. {
3.   if 'allocated employees to clean up' = true
4.   {
5.     if 'maximum level of water depth in a premises' > 0
6.     {
7.       do Acquire the necessary cleaning equipment
8.       update the following attributes:
9.       'duration of acquiring the necessary cleaning equipment'
10.      'arrival time of cleaning equipment'
11.      'completion of acquiring the necessary cleaning equipment'
12.    }
13.  }
14. }
```

- **Allocate employees to clean-up**

```
1. if 'allocated employees to clean up' = true
2. {
3.   if 'arrival time of cleaning equipment' >= the current time step 'tick'
4.   {
5.     do Allocate employees to clean-up
6.     update the following attributes:
7.     'duration of clean-up'
8.     'completion of clean-up'
9.   }
10. }
```

- **Repair production machines**

```
1. if 'sector' = manufacturing
2. {
3.   if 'power availability' = true or 'completion of setting up electricity
generator' = true
4.   {
5.     if 'maximum level of water depth in a premises' > 'the location of at
which production machines are placed'{
6.       do Repair production machines
7.       update the following attributes:
8.       'duration of repairing production machines'
9.       'percentage of machines available'
```

```
10.   }
11.   }
12. }
```

- **Contact refurbishment company**

```
1.  if 'sector' = retail
2.  {
3.    if 'funds' = true or 'compensation' = true
4.    {
5.      if 'maximum level of water depth in a premises' > 0
6.      {
7.        do Contact refurbishment companies
8.        update the following attributes:
9.        'duration of contacting refurbishment companies'
10.       'completion of contacting refurbishment companies'
11.       'refurbishment company at premises'
12.     }
13.   }
14. }
```

- **Supervise refurbishment company**

```
1.  if 'sector' = retail
2.  {
3.    if 'refurbishment company at premises' = true
4.    {
5.      do supervise refurbishment company
6.      update the following attributes:
7.      'duration of supervising refurbishment company'
8.      'completion of refurbishment company'
9.      'refurbishment company at premises'
10.   }
11. }
```

- **Allocate employees to refurbish SME's premises**

```
1.  if 'sector' = retail
2.  {
3.    if 'allocated employees to refurbish SME's premises' = true
4.    {
5.      do Allocate employees to refurbish SME's premises
6.      update the following attributes:
7.      'duration of refurbishing SME's premises'
8.      'completion of refurbishing SME's premises'
9.    }
10. }
```

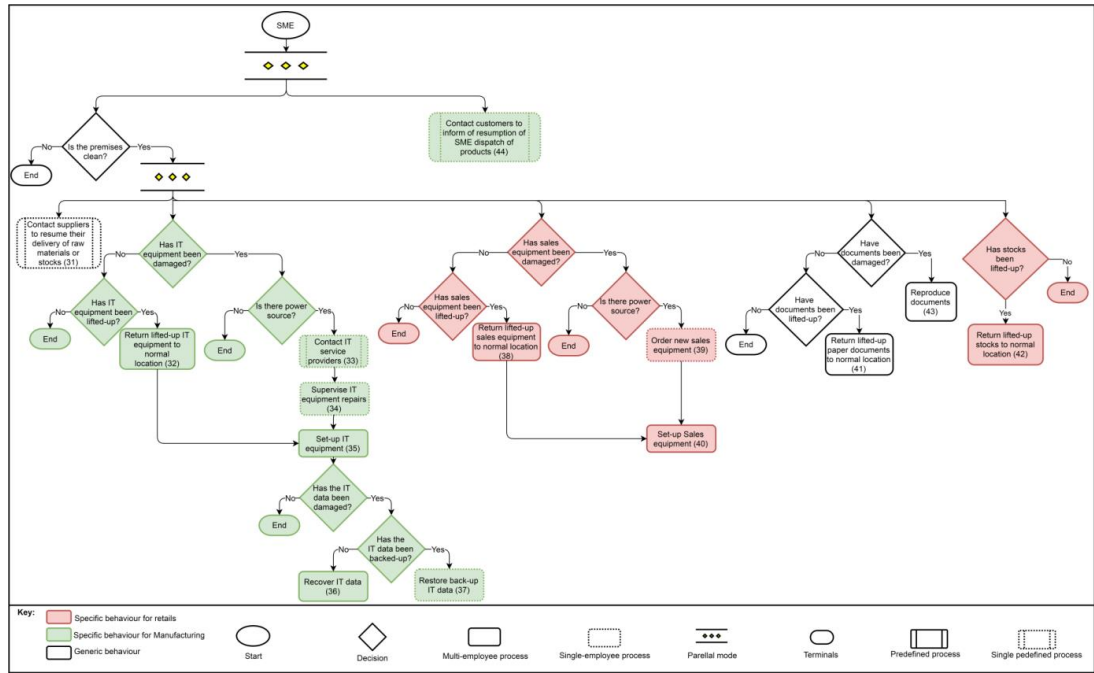


Figure C.5: Post-flood behaviours' relationship with sequencing order of behaviour execution indicated in the brackets in each action box (3)

Pseudo-code of the behaviours indicated in Figure C.5 is presented below.

- **Contact suppliers**

```

1. if ('maximum level of water depth in a premises' > 0 and 'completion of clean-up' = true) or 'maximum level of water depth in a premises' = 0
2. {
3.   do Contact suppliers
4.   update the following attributes:
5.   'duration of contacting suppliers to resume raw materials or stock dispatch'
6.   'completion of contacting suppliers to resume raw materials or stock dispatch'
7. }
    
```

- **Return lifted-up IT equipment to normal location**

```

1. if 'sector' = manufacturing
2. {
3.   if 'completion of lifting-up IT equipment' = true
4.   {
5.     if 'completion of clean-up' = true or 'maximum level of water depth in a premises' = 0
6.     {
7.       if 'maximum level of water depth in a premises' < 'location height of IT equipment'
8.       {
9.         do Return IT equipment to normal location
10.        update the following attributes:
11.        'duration of returning IT equipment to normal location'
12.        'location height of IT equipment'
13.        'completion of returning IT equipment to normal location'
14.      }
    }
  }
}
    
```

```
15.     }
16.   }
17. }
```

- **Contact IT specialist**

```
1.  if 'sector' = manufacturing
2.  {
3.    if 'funds' = true or 'compensation' = true
4.    {
5.      if 'power availability' = true
6.      {
7.        if 'completion of clean-up' = true
8.        {
9.          if 'location height of IT equipment' < 'maximum level of water dept
h in a premises'
10.         {
11.           do Contact IT specialist
12.           update the following attributes:
13.             'duration of contacting IT specialists'
14.             'completion of contacting IT specialists'
15.             'IT specialist at premises'
16.         }
17.       }
18.     }
19.   }
20. }
```

- **Supervise IT equipment repairs**

```
1.  if 'sector' = manufacturing
2.  {
3.    if 'IT specialist at premises' = true
4.    {
5.      do Supervise IT equipment repairs:
6.      update the following attributes:
7.        'duration of supervising IT equipment repairs'
8.        'completion of supervising IT equipment repairs'
9.        'IT specialist at premises'
10.   }
11. }
```

- **Set-up IT equipment**

```
1.  if 'sector' = manufacturing
2.  {
3.    if 'power availability' = true
4.    {
5.      if 'completion of returning IT equipment to normal location' = true or
'complet          ion of supervising IT
equipment repairs' = true
6.      {
7.        do Set-up IT equipment
8.        update the following attributes:
9.          'duration of setting-up IT equipment'
10.         'completion of setting-up IT equipment'
11.       }
12.     }
13. }
```

- **Recover IT data**

```
1. if 'sector' = manufacturing
2. {
3.   if 'completion of supervising IT equipment repairs' = true
4.   {
5.     if 'back-up IT data' = false
6.     {
7.       do Recover IT data
8.       update the following attributes:
9.       'duration of recovering IT data'
10.      'completion of recovering IT data'
11.    }
12.  }
13. }
```

- **Restore backed-up IT data**

```
1. if 'sector' = manufacturing
2. {
3.   if 'completion of supervising IT equipment repairs' = true
4.   {
5.     if 'back-up IT data' = true
6.     {
7.       do Restore backed-up IT data
8.       update the following attributes:
9.       'duration of restoring backed-up IT data'
10.      'completion of restoring backed-up IT data'
11.    }
12.  }
13. }
```

- **Return lifted-up sales equipment to normal location**

```
1. if 'sector' = retail
2. {
3.   if 'completion of lifting-up sales equipment' = true
4.   {
5.     if 'completion of clean-up' = true
6.     {
7.       do Return lifted-up sales equipment to normal location
8.       update the following attributes:
9.       'duration of returning sales equipment to normal location'
10.      'completion of returning sales equipment to normal location'
11.      'location height of sales equipment'
12.    }
13.  }
14. }
```

- **Order new sales equipment**

```
1. if 'sector' = retail
2. {
3.   if 'funds' = true or 'compensation' = true
4.   {
5.     if 'location height of sales equipment' < 'maximum level of water depth
    in a premises'
6.     {
7.       if 'completion of clean-up' = true
8.       {
9.         do Order new sales equipment
10.        update the following attributes:
11.        'duration of ordering new sales equipment'
12.        'completion of ordering new sales equipment'
13.        'arrival time of sales equipment'
```

```
14.     }
15.   }
16. }
17. }
```

- **Set-up sales equipment**

```
1. if 'sector' = retail
2. {
3.   if 'power availability' = true
4.   {
5.     if 'completion of returning sales equipment to normal location' = true
6.     or 'arrival time of sales equipment' = true
7.     {
8.       do Set-up sales equipment
9.       update the following attributes:
10.      'duration of setting-up sales equipment'
11.      'completion of setting-up sales equipment'
12.    }
13. }
```

- **Return paper documents to normal location**

```
1. if 'completion of lifting-up paper documents' = true
2. {
3.   if 'completion of clean-up' = true
4.   {
5.     do Return paper documents to normal location
6.     update the following attributes:
7.     'duration of returning documents to normal location'
8.     'completion of returning documents to normal location'
9.     'location height of documents'
10.  }
11. }
```

- **Reproduce documents**

```
1. if 'maximum level of water depth in a premises' > 'location height of paper
   documents'
2. {
3.   do Reproduce documents
4.   update the following attributes:
5.   'duration of reproducing documents'
6.   'completion of reproducing documents'
7.   'location height of paper documents'
8. }
```

- **Return lifted-up stock to normal location**

```
1. if 'sector' = retail
2. {
3.   if 'completion of lifting-up stock' = true
4.   {
5.     if 'completion of clean-up' = true
6.     {
7.       do Return stock to normal location
8.       update the following attributes:
9.       'duration of returning stock to normal location'
10.      'completion of returning stock to normal location'
11.      'location height of documents'
12.    }
13. }
```

```
13. }  
14. }
```

- **Contact customers**

```
1. if 'sector' = manufacturing  
2. {  
3.   if 'power availability' = true  
4.   {  
5.     if 'completion of clean-up' = true  
6.     {  
7.       if 'quantity of products available' > 0  
8.       {  
9.         do Contact customers  
10.        update the following attributes:  
11.        'duration of contacting customers to resume product delivery'  
12.        'completion of contacting customers to resume products delivery'  
13.      }  
14.    }  
15.  }  
16. }
```

After implementing pre- and post-flood behaviours, the **production** action for manufacturing SMEs or the **service** action for retail SMEs will be invoked. This will update a set of attributes including production level for manufacturing SMEs and service capability for retail SMEs. All the aforementioned processes occur at each simulation tick within the model.

C.3.3 Suppliers and Customers

Suppliers and customers are businesses or organizations that are modelled to interact with SMEs to preserve SMEs' operational continuity. However, they are not modelled to the same level of detail as SMEs given the focus of this research is investigating SMEs immediate response to and short-term recovery from flood events. Suppliers provide manufacturing and retail SMEs with raw material or stock respectively. However, customers, who only interact with manufacturing SMEs, take delivery of products from these businesses.

As indicated in Figure C.6, SMEs interact with suppliers and/or customers (only manufacturing SMEs). In preparing for a particular flood event, SMEs' behaviours include contacting their suppliers and customers (only manufacturing) in order to suspend manufacturing raw material or retail stock and product dispatch. Subsequently, once an SME is in a position to recommence production or service for manufacturing or retail (a) its supplier is contacted to resume raw material delivery,

and (b) customers (only for manufacturing) are informed of the resumption of product dispatch.

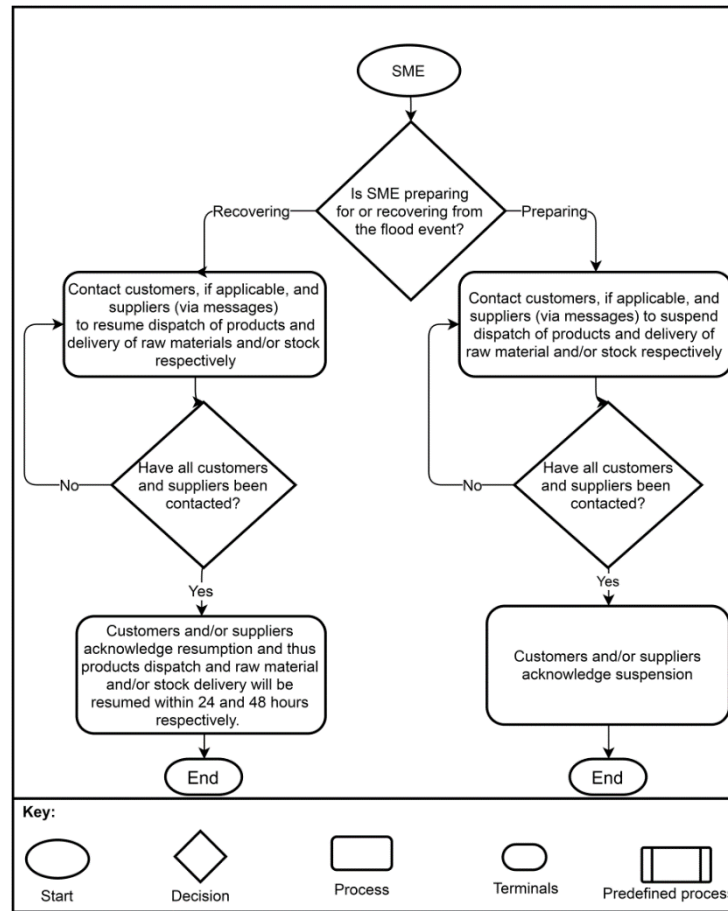


Figure C.6: Suppliers and customers

Suppliers interact with manufacturing and retail SMEs at regular intervals to provide them with raw materials or stock. Within this agent, at each simulation tick, the **check inbox** action is implemented; if the inbox is empty, the **dispatch** action will be executed to continue the dispatch of raw materials if due. However, if a new message was received, the message will be passed to the **interpret message** action, which interprets the received messages along with the sender details such as ‘sender unique identifier’. Subsequently, the appropriate action will be triggered. If the interpreted message indicates a despatch suspension due to the flood event, then the **suspension** action will be executed to update the dispatch schedule list. In addition, the **send message** action will be invoked to respond to the sender (SME) appropriately. If the received message indicates despatch resumption, the **resumption** action will be invoked to update the dispatch schedule list.

The interaction between manufacturing SMEs and customers is similar to that described for suppliers; however, rather than dispatch of raw materials the focus is on the delivery of products.

C.3.4 Cleaning Service Providers

Cleaning service providers are businesses that interact with manufacturing or retail SMEs and insurance companies. For the latter, cleaning service providers could have a pre-defined contract with insurance companies to provide such a service to insured SMEs if required. SMEs with comprehensive insurance receive assistance in the form of a cleaning service in addition to financial compensation.

Cleaning-service providers can interact with SMEs to provide them with clean-up assistance. As indicated in Figure C.7, SMEs will contact regional cleaning-service providers before contacting national cleaning-service providers. The latter are only contacted if an SME is unable to secure the services of a regional provider. In terms of arrival times, regional organizations arrive at the SME's premises between 2 and 24 hours whereas the national organizations arrive later (e.g. 24-48 hours) than regional service providers although they are more numerous.

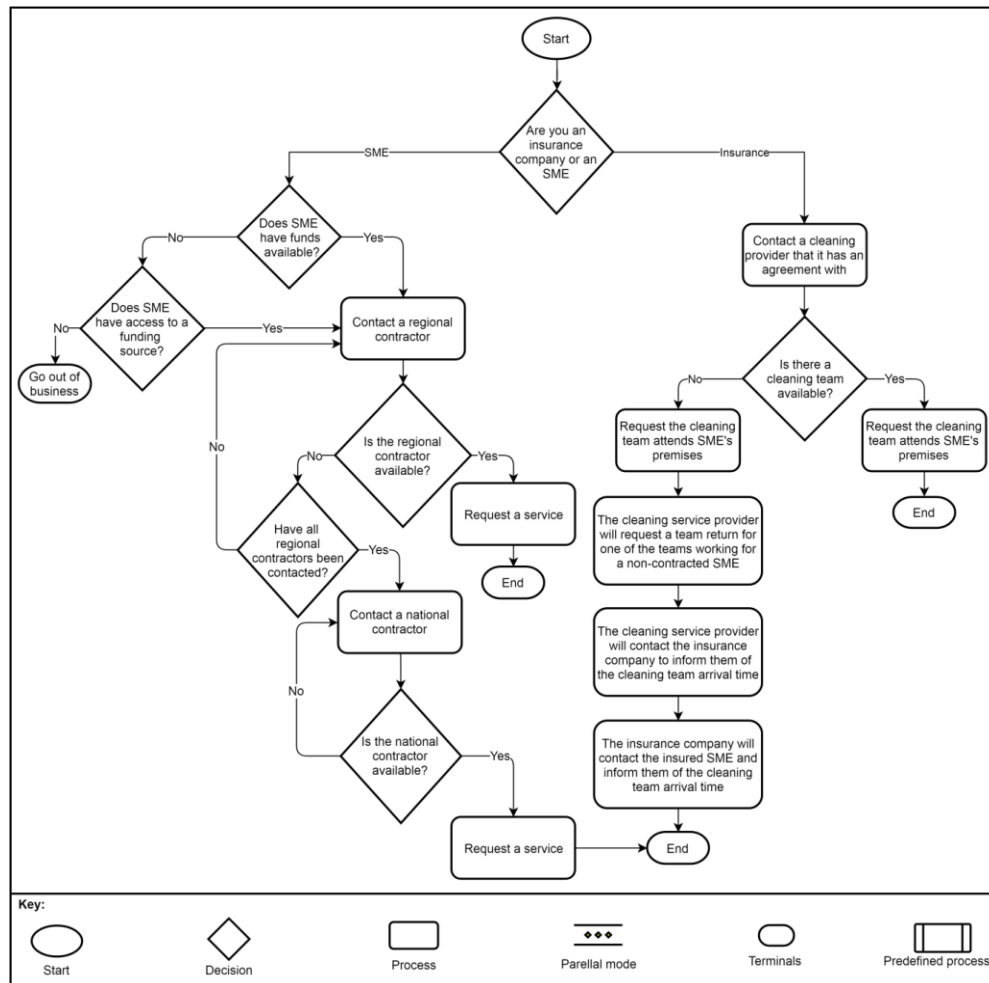


Figure C.7: An Overview of the interaction between cleaning service providers and SMEs

At each simulation tick, cleaning service providers execute the **check inbox** action to check if any new messages have been received. If so, they will initially forward the received message(s) to the **interpret message** action, which will interpret the received message along with the sender information (i.e. ‘sender unique identifier’). Also, the check **team availability** action will be executed to inspect if any cleaning team of this service provider is available. If so, the **generate time** action will be invoked to determine a time for sending this team and thus the ‘time to send team’ attribute will be updated. Subsequently, the cleaning service provider will execute the **send message** action to reply to the sender.

C.3.5 Insurance Company

Insured SMEs with comprehensive cover will receive, via its insurance company, assistance from a cleaning service provider in addition to receiving financial compensation. In contrast, SMEs with basic insurance cover will only receive the latter.

As indicated in Figure C.8, if the insurance company is contacted by an SME, a loss adjuster will be sent within three days to assess the damage and produce a report followed by payment being released within five working days of the visit. During this period, SMEs may choose to allocate their own employees to work on post-flood behaviours, such as clean-up the premises rather than waiting for the cleaning service provided by the insurance to arrive.

SME and thus ‘compensation time’ will be updated and passed to the **pay compensation** action.

C.3.6 Service Providers Organisations

Service provider organizations include electrical, plumbing, IT, and refurbishment service providers. These service provider organisations are not the same as the cleaning service providers (defined previously in Section 7.2.4). Cleaning service providers are modelled to interact with both SMEs and insurance companies whereas these service provider organisations are modelled to *only* interact with SMEs. In terms of the interaction, the service provider organisations interact with SMEs via messages to attend at an SME’s premises after a flood event. This is to assist with SMEs’ to return to the normal operation (pre-flood). This is to assist with SMEs’ to return to the normal operation (pre-flood).

In relation to Figure C.9, SMEs must have funds available or access to cash, or they will go out of business. Funds can be derived from three defined sources: (i) insurance compensation, or (ii) emergency financial reserves. Insurance compensation represents the most common source of funds, but an SME may have to wait for longer period to receive it. In terms of emergency financial reserves, SMEs can proceed with the short-term recovery process immediately. With sufficient funds available, SMEs will contact the regional service providers. However, if they are unable to secure the services of a regional provider, they will contact the national service provider organisations.

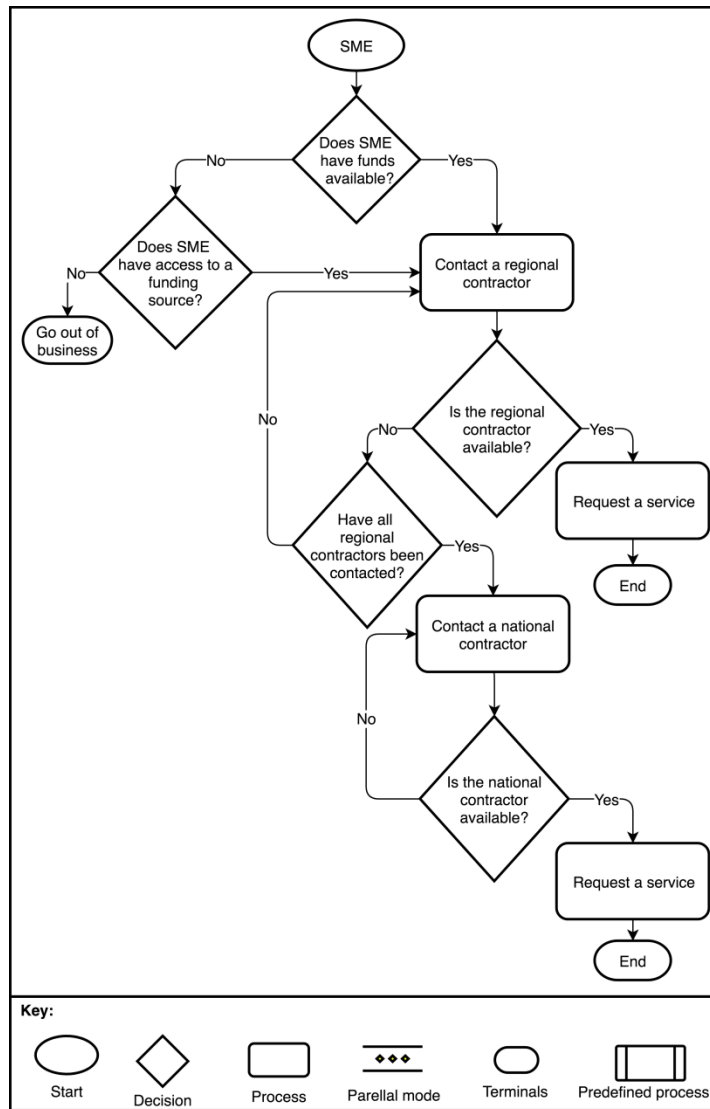


Figure C.9: Electrical contractors

At each simulation tick, electrical contractors run the **check inbox** action along with the **go to SMEs** action. If a new message is received, the received message will be passed to the **interpret message** action that interprets the received text along with the sender details (i.e. ‘sender unique identifier’). Service provider organisations will check their status and reply. If the status is free, they will update the ‘time to go’ attribute and then pass it to the **go to SMEs** action, which is checked at each simulation tick. Also, electricians will invoke the **send message** action to respond to the affected SME(s). However, if the status is ‘busy’, electricians will respond to the affected SME appropriately.

C.3.7 Mutual Aid Partners

Mutual aid partners are none-flooded manufacturing SMEs modelled to assess the flooded manufacturing SMEs when needed. At every tick, mutual aid partner executes the **check inbox** action. If a new message is received, the received message will be passed to the **interpret message** action that interprets the received text along with the sender details (i.e. ‘sender unique identifier’). Subsequently, the **ID Identification** action will be executed to validate if the sender has a pre-defined contract with this mutual aid partner. If so, this mutual aid partner will review the contract and allocates the agreed percentage of machines to the affected SME, which should start working from the next day. Finally, mutual aid partners will evoke the **send message** to respond to the affected SME(s) appropriately.

C.4 DESIGN CONCEPTS

C.4.1 Basic Principles

The research reported in this thesis builds on earlier work (Coates et al., 2014; Coates et al., 2016; Li & Coates, 2016; Li et al., 2015) with the aim to develop an agent-based modelling and simulation (ABMS) framework to investigate the effect of manufacturing SMEs’ behaviours, and flood precautionary measures that can be put in place, to maintain business continuity and speed-up short-term recovery from flooding. This ABMS framework consists of three main components: (i) flood-event simulation; (ii) a modelled geographical environment (MGE); and (iii) agent-based modelling and simulation. First, flood-event simulation represents the input (inundation) data that feeds into the MGE component, which provides a common platform for the flood-event simulation and the agent-based modelling and simulation. Specifically, the MGE combines Ordnance Survey (OS) MasterMap® data (i.e. *Topography*, Integrated Transport Network (*ITN*), and *AddressBase Plus* layers) with the input from the flood-event simulation to enable the identification of the flooded and non-flooded organisations. Consequently, a proportion of these identified organisations, and particularly SMEs from manufacturing sectors, are modelled as autonomous agents and simulated over three stages, namely pre-flood, flood (no operation), and post-flood. In addition, SME-related organisations (e.g. suppliers, customers, electrical contractors, IT specialists, cleaning contractors, the Environment Agency (EA), and insurance companies) are also modelled as autonomous agents and

simulated to support SMEs' operation and/or recovery. In terms of manufacturing SMEs, they are modelled as autonomous agents with different sets of attributes (e.g. static and dynamic), behaviours (e.g. pre- and post-flood), and pre-defined precautionary measures (e.g. flood resistance, flood resilience, and business continuity/risk management). Production level is computed at each simulation tick for every manufacturing SME modelled, respectively, to determine their performance throughout the simulation.

C.4.2 Emergence

Not applicable to this model.

C.4.3 Adaptation

Manufacturing and retail SMEs that have implemented flood precautionary measures tend to respond better and recover more quickly than those implementing none of them. For example, a manufacturing SME that has machines raised on platforms/plinths above the level at which the flood water reaches in its premises will not need to allocate employees to repair them. Similarly, SMEs that have registered for EA alerts and warnings may enact pre-flood behaviours, which will potentially reduce the damage caused by flood water entering its premises.

C.4.4 Objectives

Manufacturing and retail SMEs want to minimise production level loss and service capability loss, respectively, throughout the period simulated by implementing a number of or all of the flood precautionary measures. The Environment Agency wants to help minimise disruption to SMEs by sending alerts and warnings to all those registered. Suppliers aim to provide manufacturing and retail SMEs with raw materials and stock, respectively, so as to enable operation at SMEs. Insurance companies aim to assist manufacturing and retail SMEs with financial compensation for any flood damage and, if covered sufficiently, send a cleaning service provider to attend its premises. Cleaning-service providers aim to clean-up manufacturing and retail SMEs' premises when requested, thus accelerating recovery. Service provider organisations (electrical service providers, plumbing service providers, IT specialists, refurbishment companies) aim to provide the necessary repairs at an SME's premises when requested in order to accelerate recovery.

C.4.5 Learning

The model focuses on investigating how SMEs' behaviours and flood precautionary measures, and combinations of them, impact pre-flood immediate response and post-flood short-term recovery. Thus, within a simulation, SMEs do not learn from the other agents.

C.4.6 Prediction

This model does not predict future conditions SMEs will experience.

C.4.7 Sensing

Manufacturing and retail SME agents within the model save all information related to them, including the flood precautionary measures in place, which influences the choice of behaviours they enacted and the duration of these behaviours. Recording all information related to agents allows an analysis of production level for manufacturing SMEs and service capability for retail SMEs throughout the simulation period to be carried out, which then enables the operational disruption coefficient to be determined over three stages, i.e. pre-flood, during flood, and post-flood.

C.4.8 Interaction

Manufacturing and retail SMEs interact with other organisations via messages. As indicated in Table C.8, SMEs can interact with organisations pre and/or post flood.

SME-Related Organisation		Period of Interaction	Function
Suppliers		Pre- and post-flood	Provide SMEs with raw material or stock.
Customers		Pre- and post-flood	Take delivery of products from manufacturing SMEs.
Environment Agency		Pre-flood	Send alerts and warnings to SMEs that have registered for these services.
Insurance companies		Post-flood	Provide insured SMEs with assistance in the form of a cleaning service, if insured sufficiently, in addition to financial compensation.
Service provider organisations	Electricians	Post-flood	Provide the necessary repairs to support SMEs' recovery.
	Plumbers	Post-flood	
	IT specialists	Post-flood	
	Refurbishment companies	Post-flood	Provide renovation and redecoration for retail SMEs' premises.

SME-Related Organisation	Period of Interaction	Function
Cleaning service providers	Post-flood	Provide a cleaning service to SMEs.
Mutual aid partners	Post-flood	Share a certain percentage of its own production machines with its pre-defined mutual aid partner when requested.

Table C.8: Information related to SME-related organisations

C.4.9 Stochasticity

Each of a manufacturing and retail SME's behaviours (see Table C.9) have an associated duration range obtained from transcripts of semi-structured interviews with SMEs having experience of flooding or being at risk of flooding. In addition, the duration of pre- and post-flood behaviours can be affected by the flood precautionary measures implemented by a manufacturing or retail SME.

Code	Duration parameters of behaviours
B₁	Place sandbags at doorways
B₂	Cover air-bricks
B₃	Lift-up IT equipment
B₄	Lift-up sales equipment
B₅	Lift-up paper documents
B₆	Lift-up raw materials
B₇	Lift-up light or medium products
B₈	Lift-up stocks
B₉	Cut-off electricity
B₁₀	Contact customers to inform of suspension in dispatch of products from SME
B₁₁	Contact suppliers to suspend their delivery of raw materials
B₁₂	Evacuation (immediately if floodwater enters an SME's premises)
B₁₃	Restore power supply
B₁₄	Contact insurance company
B₁₅	Contact electrical service providers
B₁₆	Supervise power supply repairs
B₁₇	Set-up and use electricity generator
B₁₈	Contact mutual aid partner
B₁₉	Work at partner's location
B₂₀	Supervise electrical sockets repairs
B₂₁	Contact plumbing service providers
B₂₂	Supervise damaged pipes repairs
B₂₃	Contact cleaning service providers
B₂₄	Supervise cleaning service
B₂₅	Acquire cleaning equipment
B₂₆	Allocate employees to clean up
B₂₇	Repair production machines
B₂₈	Contact refurbishment company
B₂₉	Supervise premises refurbishment
B₃₀	Allocate employees to refurbish SME's premises
B₃₁	Contact suppliers to resume their delivery of raw materials or stocks

Code	Duration parameters of behaviours
B₃₂	Return lifted-up IT equipment to normal location
B₃₃	Contact IT service providers
B₃₄	Supervise IT equipment repairs
B₃₅	Set-up IT equipment
B₃₆	Recover IT data
B₃₇	Restore back-up IT data
B₃₈	Return lifted-up sales equipment to normal location
B₃₉	Order new sales equipment
B₄₀	Set-up sales equipment
B₄₁	Return lifted-up paper documents to normal location
B₄₂	Return lifted-up stocks to normal location
B₄₃	Reproduce documents
B₄₄	Contact customers to inform of resumption of SME dispatch of products

Table C.9: SME pre and post-flood behaviours

C.4.10 Collectives

Not applicable.

C.4.11 Observation

In a simulation, data are collected on a half-hourly basis for each manufacturing and retail SME. In relation to manufacturing SMEs, based on values related to the availability of employees, machines, raw materials and power, the key manufacturing SME performance metric, namely production level (at each simulation tick) is determined. For retail SMEs, the key retail SME performance metric, namely service capability (at each simulation tick) is determined based on the availability of power, stock, sales equipment, employees, and environment condition.

C.5 INITIALIZATION

This developed framework consists of a number of agents representing different types of organisation; all agents are created at the beginning of the simulation. At the same time, agent variables are assigned. Most variables are set the same for each manufacturing or retail SME agent; however, some are randomly assigned such as number of employees, behaviour durations (with a specified range).

C.6 INPUT

In terms of external sources, the model uses input data from Ordnance Survey MasterMap© (*Topography layer, AddressBased Plus layer and Integrated Transport*

Network layer). In addition, the model uses inundation data provided from flood modelling and simulation.

C.7 SUB-MODELS

C.7.1 Environment Agency (EA)

For this agent, the **Watch-flood** action is scheduled to run at each simulation tick. The pseudo code (see Algorithm C.1) presents a simplified overview process of the **watch-flood** action that sends alerts and warnings to the registered SMEs.

```
1. if (tick = 1)
2. {
3.   flood commencing time in Sheffield = updated flood times();
4.   flood commencing time in Tewkesbury = updated flood times();
5. }
6. else
7. {
8.   if (tick = flood commencing time in Sheffield - 36 hours) then
9.   {
10.    implement send alerts to SMEs located in Sheffield
11.   }
12.   if (tick = flood commencing time in Tewkesbury - 36 hours) then
13.   {
14.    implement send alerts to SMEs located in Tewkesbury
15.   }
16.   if (tick = flood commencing time in Sheffield - 3 hours) then
17.   {
18.    implement send warnings to SMEs located in Sheffield
19.   }
20.   if (tick = flood commencing time in Tewkesbury - 3 hours) then
21.   {
22.    implement send warnings to SMEs located in Tewkesbury
23.   }
24. }
```

Algorithm C.1: EA watch flood process

In relation to the Algorithm C.1, at the first tick, the update flood time method will be evoked to update the flood commencing time in Sheffield and flood commencing time in Tewkesbury attributes with the actual flood time for both geographical areas (lines 1 to 5). Next, **send alerts to SMEs located in Sheffield** and **send alerts to SMEs located in Tewkesbury** actions are implemented 36 before the flood occurs (line 6-15). In terms of the flood warnings, they are sent three hours before the flood occurs (lines 16-24).

C.7.2 Manufacturing SME

For manufacturing SME agents, the production level is used as the performance metric. Production level is related to availability of raw materials (RM), machines (M), employees (E) and power (P). The relationships between these dynamic attributes are presented in Algorithm C.2.

```

19. if P=1 then
20. {
21.   if raw materials at time t,  $RM_t \geq \min \{E, M\}$  then
22.   {
23.      $PL = \min \{E, M\} \times 100$ 
24.      $RM_{t+1} = RM_t - \min \{E, M\}$ 
25.   }
26.   else if  $RM_t < \min \{E, M\}$ 
27.   {
28.      $PL = RM_t \times 100$ 
29.      $RM_{t+1} = 0$ 
30.   }
31. }
32. else if P=0
33. {
34.    $PL = 0$ 
35.    $RM_{t+1} = RM_t$ 
36. }

```

Algorithm C.2: Determining production level (PL) of a manufacturing SME

In relation to Algorithm C.2, for each simulation tick (i) production level and (ii) raw materials available at the next tick, are determined depending on whether power is available at the SME's premises (lines 1 to 13) or not (lines 14 to 18). For situations in which power is available, and depending on the amount of raw materials available at the current tick, both (i) and (ii) are determined according to the relationship between ratios of employees working on production to total number of employees, and machines available to total number of machines respectively.

C.7.3 Retail SME

In the **Sales** action, retail SMEs are assessed in terms of their sales capability. In particular, several factors contribute into retail SMEs service capability (SC), such as power (P), Stock (S), Sales Equipment (SE), Employees (E), and Environment Condition (EC). Algorithm C.3 defines how the service capability (SC) in a 30-minute period, i.e. a simulation tick, is determined.

```

9. if P=1 and EC=1 then
10. {
11.    $SC = \min \{S, SE, E_{per}\}$ 

```

```
12. }  
13. else if P=0 or EC=0  
14. {  
15.     SC=0  
16. }
```

Algorithm C.3: Determining service capability (SC) of a retail SME

In Algorithm C.3, for each simulation tick, service capability, is determined depending on whether power is available and environment condition is acceptable at an SME's premises ($P = 1$ and $EC = 1$) (lines 1 to 4) or not ($P = 0$ or $EC = 0$) (lines 5 to 8). For the latter, the service capability cannot be resumed (i.e. $SC = 0$). However, for situations in which power is available and working conditions are acceptable, the service capability is determined according to the relationship between (i) percentage of stock, ST , (ii) percentage of sales equipment, SE , (iii) percentage of employees available, E_E respectively.

C.7.4 Emergency

The **emergency** action is implemented within a manufacturing SME; this action invokes three different actions: (a) **duration**, (b) **allocation strategy**, (c) **behaviours** as presented in the Algorithm C.4.

```
1. if tick=1 then  
2. {  
3.     implement Duration  
4. }  
5. implement Allocation Strategy  
6. Implement Behaviours
```

Algorithm C.4: Emergency action

In relation to the **duration** action, it is executed in the first tick of the simulation to initialize the durations of the behaviours' listed in Table C.9.

C.7.5 Allocation Strategy of Employees

The **allocation strategy** action is invoked to allocate the appropriate number of employees to behaviours. Four employee allocation strategies ('normal', 'flood is possible', 'immediate action', and 'recovery') are considered in which each of these is implemented in different situations. The 'normal' strategy is implemented prior to receiving flood alerts, in which all the employees are allocated to work on production respectively. The 'flood is possible' allocation strategy begins after receiving a flood

alert; this may last until the time at which flood warnings are received or a flood commences. In the ‘*flood is possible*’ strategy, a proportion of employees will prepare for the potential event while the rest will work on production. The ‘*immediate action*’ strategy is implemented after receiving a flood warning, at which time employees are allocated to prepare for the potential event before evacuating, or evacuating immediately. During the flood, employees are not at an SME’s premises. In the aftermath, the ‘*recovery*’ strategy is implemented in which the main focus is restarting production for manufacturing SMEs and service for retail SMEs.

A simplified overview of the allocation strategy action is presented in the following Algorithm C.5.

```
1. if period = pre-flood then
2. {
3.   if alert = false and warning = false then
4.   {
5.     implement normal
6.   }
7.   if alert = true and warning = false then
8.   {
9.     if trust alert = true then
10.    {
11.      implement flood is possible
12.    }
13.    else if trust alert = false then
14.    {
15.      implement normal
16.    }
17.  }
18.  else if warning = true then
19.  {
20.    implement immediate action
21.  }
22. }
23. else if period = post-flood then
24. {
25.   if post-flood behaviours have not been completed then
26.   {
27.     implement recovery
28.   }
29.   else if post flood behaviours have been completed then
30.   {
31.     implement normal
32.   }
33. }
```

Algorithm C.5: Employees allocation strategy

In relation to Algorithm C.5, for each simulation tick, the appropriate strategy is determined depending on whether the period is pre-flood or post-flood. Within the pre-flood period (lines 1 to 22), three strategies may be invoked: (i) the ‘normal’ strategy,

(ii) the ‘flood is possible’ strategy and (iii) the ‘immediate action’ strategy. In the post-flood period (lines 23 to 33), if some of the post-flood behaviours are incomplete, or yet to be enacted, then the ‘recovery’ strategy will be implemented. However, if all the post-flood behaviours have been enacted, the ‘normal’ strategy will be implemented with all employees working on production.

The *flood is possible* allocation strategy allocates one and two employee(s) to the single and multiple employee pre-flood behaviours respectively. At the same time, all employees unallocated to these behaviours work on production. This strategy aims to provide pre-flood behaviours with the minimum possible number of employees required to enact them (see Algorithm C.6).

```
1. for i = 1 to n, where n is the number of the pre-flood behaviours
2. {
3.   while the number of employees available at an SME premises > 0
4.   {
5.     if number of employees available at an SME premises > 1, then
6.     {
7.       if behaviour requires multi-employee, then
8.       {
9.         this behaviour is allocated two employees
10.        allocated number of employees = 2
11.      }
12.     else if behaviour requires a single employee, then
13.     {
14.       this behaviour is allocated one employee
15.       allocated number of employees = 1
16.     }
17.     else if number of employees available at an SME premises = 1
18.     {
19.       this behaviour is allocated one employee
20.       allocated number of employees = 1
21.     }
22.   else
23.   {
24.     break
25.   }
26.   update allocated number of employees
27. }
28. }
```

Algorithm C.6: Flood is possible strategy

In relation to them Algorithm C.6, for each simulation tick, every behaviour is allocated employees based on the number of employees available. For each pre-flood behaviour yet to be enacted, and while all employees are yet to be allocated, if the total number of employees available is greater than one, then the appropriate number of employees (i.e. one or two) will be allocated to the behaviour. However, if only one

employee is available, then that employee will be allocated to the behaviour under consideration.

The *immediate action* allocation strategy allocates all the available employees to work on non-production behaviours. Employees will evacuate: (i) when all these behaviours are enacted, (ii) at the end of the working day, or (iii) when the flood event occurs. Note that, if the EA alert or warning was not received, then the *immediate action* strategy will not be implemented, and employees will evacuate when the flood event occurs.

The *recovery* allocation strategy ensures that all an SME's employees are allocated to production if power is supplied to the premises and there are sufficient raw materials and machines available. However, if all production employees are available to work on production but there are some post-flood behaviours yet to be completed, then one production employee will be allocated to complete those behaviours; the remainder will work on production. Note that if more production employees are available than there are able to work on production, then the surplus of these employees is allocated to work on other behaviours.

Appendix D

Results and Discussion for Retail SMEs and SME-Related Organisations

D.1 OVERVIEW

The modelled retail SMEs located in Lower Don Valley of Sheffield were simulated over approximately 37 days (i.e. 1748 ticks). As mentioned in Chapter 8, this duration (1748 ticks) was selected as it encapsulates the time frame from the beginning of the flood event through to the point where all the retail SMEs resume to normal operation, $SC=100\%$. At each tick, the service capability was computed based on a range of inputs (power (P), stock (ST), sales equipment (SE), employees (E), and environment condition (EC) (see Chapter 7, Section 7.1.6)). The average of service capability of the 6 lightly, 5 moderately, and 2 severely flooded retail SMEs was computed before computing the cumulative average of the 10 simulation runs undertaken. The cumulative average of retail SMEs was used to compute the *operational disruption* as well as the *absolute operational disruption* values (see Chapter 8, Section 8.2.1) for every stage of the simulation period, i.e. pre-flood, during flood (non-operation), and post-flood.

D.2 RETAIL SMES

The simulation experiments include all 13 flooded retail SMEs identified in the Lower Don Valley of Sheffield along with the inundation data associated with each of them. For all 16 experiments defined in Chapter 8, the figures (E.17 – E.32) illustrating the cumulative average of service capability for lightly, moderately, and severely

flooded retail SMEs are provided in Section E.2 of Appendix E. These are to present the performance of the lightly, moderately, and severely flooded retail SMEs once implementing different sets of precautionary measures. It is important to note that these figures do not correspond explicitly to a particular SME, rather they represent the cumulative average service capability resulting from 10 simulation runs of 6 lightly, 5 moderately, and 2 severely flooded retail SMEs. The data (cumulative average of service capability) associated with each of the figures, which are presented in Section E.1 of Appendix E, were used to quantify the service capability loss, which is represented in the *operational disruption* as well as the *absolute operational disruption* values, for every stage of the simulation period, i.e. pre-flood, during flood (non-operation), and post-flood.

Figure D.1 presents the cumulative average of service capability of the lightly, moderately, and severely flooded retail SMEs in simulation experiment E1 (indicated in Chapter 8, Section 8.3.1), which corresponds to the scenario in which SMEs *only* set-up and maintain an emergency financial reserve (see Figure E.17 Appendix E), and simulation experiment E11, which corresponds to the scenario in which *most* the precautionary measures are in place (see Figure E.32 Appendix E).

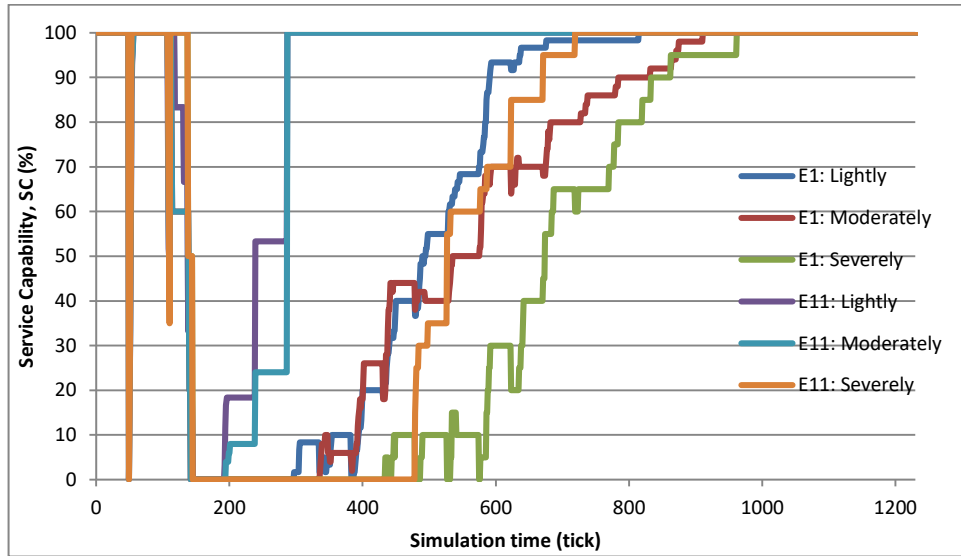


Figure D.1: Cumulative average of service capability of 13 flood-affected retail SMEs over time

The cumulative average of service capability of all the 6 lightly, 5 moderately, and 2 severely flooded manufacturing SMEs was used to compute the OD_{ABS}^{pre} , OD_{ABS}^{none} , and OD_{ABS}^{all} .

OD_{ABS}^{post} , and $OD_{ABS}^{overall}$ values for each of these categories. For the sixteen simulation experiments undertaken (E1 to E11), Figure D.2 presents a visual representation of the $OD_{ABS}^{overall}$ values, which were calculated from the cumulative averages of the lightly, moderately, and severely flooded retail SMEs service capability using equation (8.15). The $OD_{ABS}^{overall}$ values of the lightly, moderately, and severely flooded retail SMEs presented in Figure D.1 are derived from Table D.1 (see page 300), Table D.2 (see page 304), and Table D.3 (see page 306).

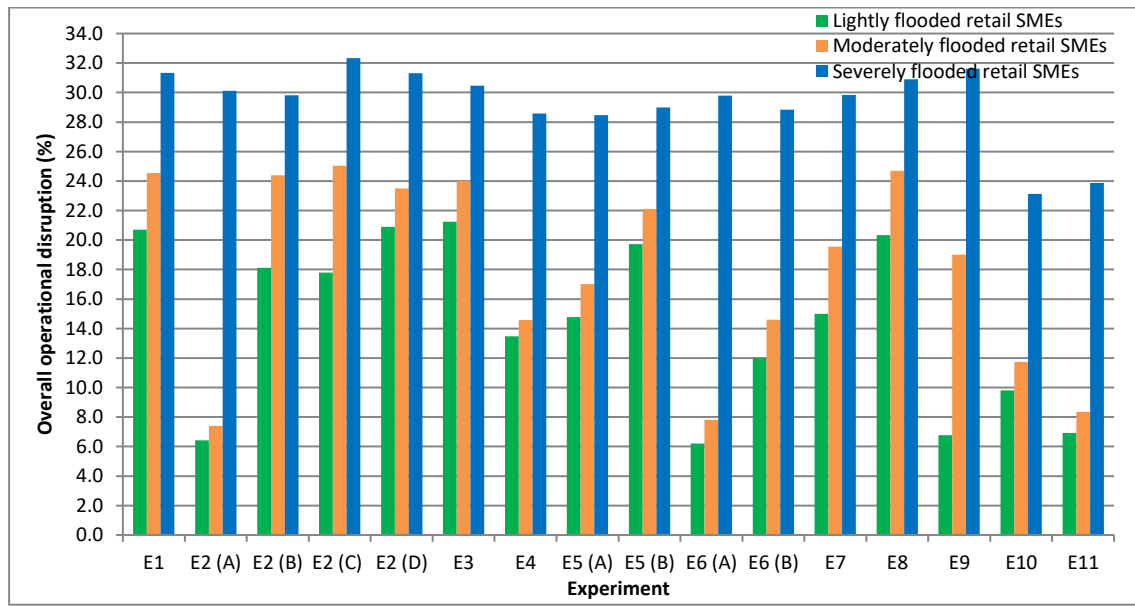


Figure D.2: The *overall absolute operational disruption* of the lightly, moderately, and severely flooded retail SMEs located in Sheffield geographical area

As shown in Figure D.2, the $OD_{ABS}^{overall}$ values associated with the lightly flooded retail SMEs are always lower than the $OD_{ABS}^{overall}$ values associated with the moderately and severely flooded retail SMEs for all 16 simulation experiments. This is because the lower level of floodwater ($W_d < 0.3m$) reached in the lightly flooded retail SMEs caused less damage to their respective premises, paper documents, and sales equipment, and thus, the time required for premises refurbishment and cleaning is subsequently shorter than that required for the moderately and severely flooded retail SMEs (see Chapter 7, Section 7.1.2).

In terms of the severely flooded retail SMEs, they always achieve greater $OD_{ABS}^{overall}$ values, i.e. greater than 23% for all simulation experiments. This is due to the higher level of floodwater ($W_d > 1.5m$) reached in the severely flooded retail

SMEs' premises (which exceeded all the implemented resistance and resilience precautionary measures) and caused damage to these SMEs' premises, documents, sales equipment, and stock. Thus, these retail SMEs had to order new sales equipment, reproduce/prepare documents, and refurbish their premises, in order to return to the normal operation ($SC = 100\%$). Furthermore, the time required for premises refurbishment and cleaning was subsequently longer than that required by the lightly and moderately flooded retail SMEs.

D.2.1 Lightly Flooded Retail SMEs

For all simulation experiments, as indicated in Table D.1, all the lightly flooded retail SMEs inundated on day 3 at clock time ($t_c=19:00$) and simulation tick ($t_s=118$), i.e. 2 hours after the manufacturing SMEs. This is due to the geographical locations of the retail SMEs simulated; in other words, the time at which the floodwater reaches a particular SME's premises varies slightly depending on the actual geographical location of the property in the flood-affected area.

Please note that the cumulative average of service capability data of the six lightly flooded retail SMEs used in equations (8.2), (8.8), (8.10), and (8.12) to (8.15) to compute the values presented in Table D.1 is provided here (<https://github.com/meshal9090/ABMS-Framework.git>).

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t ₁ to t ₂)																	
Start (t ₁)	Day (d)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0
	Time (t _c)	19:00	19:00	19:00	19:00	19:00	19:00	19:00	19:00	19:00	19:00	19:00	08:30	19:00	08:30	08:30	08:30
	Tick (t _s)	118.0	118.0	118.0	118.0	118.0	118.0	118.0	118.0	118.0	118.0	118.0	49.0	118.0	49.0	49.0	49.0
End (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t _c)	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00
	Tick (t _s)	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0
Durations (ticks)		27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	96.0	27.0	96.0	96.0	96.0
Pre-flood operational disruption (units) (OD _{pre})		875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	1,393.3	875.0	1,455.0	1,258.3	1,320.0
Pre-flood absolute operational disruption (%) (OD _{ABS} ^{pre})		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8	0.5	0.8	0.7	0.8
Non-operation (t ₂ to t ₃)																	
Start (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t _c)	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00
	Tick (t _s)	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0
End (t ₃)	Day (d)	7.0	5.0	5.0	5.0	7.0	7.0	5.0	8.0	7.0	5.0	5.0	7.0	7.0	5.0	6.0	5.0
	Time (t _c)	12:00	07:30	08:30	07:30	12:30	12:00	15:00	09:30	10:00	07:30	08:30	09:30	12:30	07:30	09:00	08:00
	Tick (t _s)	296.0	191.0	193.0	191.0	297.0	296.0	206.0	339.0	292.0	191.0	193.0	291.0	297.0	191.0	242.0	192.0
Durations (ticks)		152.0	47.0	49.0	47.0	153.0	152.0	62.0	195.0	148.0	47.0	49.0	147.0	153.0	47.0	98.0	48.0
Non-operation operational disruption (units) (OD _{none})		15,200.0	4,700.0	4,900.0	4,700.0	15,300.0	15,200.0	6,200.0	19,500.0	14,800.0	4,700.0	4,900.0	14,700.0	15,300.0	4,700.0	9,800.0	4,800.0
Non-operation absolute operational disruption (%) (OD _{ABS} ^{none})		8.7	2.7	2.8	2.7	8.8	8.7	3.5	11.2	8.5	2.7	2.8	8.4	8.8	2.7	5.6	2.7
Post-flood (t ₃ to t ₄)																	
Start (t ₃)	Day (d)	7.0	5.0	5.0	5.0	7.0	7.0	5.0	8.0	7.0	5.0	5.0	7.0	7.0	5.0	6.0	5.0
	Time (t _c)	12:00	07:30	08:30	07:30	12:30	12:00	15:00	09:30	10:00	07:30	08:30	09:30	12:30	07:30	09:00	08:00
	Tick (t _s)	296.0	191.0	193.0	191.0	297.0	296.0	206.0	339.0	292.0	191.0	193.0	291.0	297.0	191.0	242.0	192.0
End (t ₄)	Day (d)	18.0	7.0	16.0	16.0	16.0	16.0	10.0	11.0	17.0	7.0	10.0	11.0	16.0	7.0	8.0	7.0
	Time (t _c)	07:00	07:00	12:00	08:00	13:00	12:30	15:30	12:00	10:00	07:00	14:30	09:00	12:00	07:00	15:30	07:00
	Tick (t _s)	814.0	286.0	728.0	720.0	730.0	729.0	447.0	488.0	772.0	286.0	445.0	482.0	728.0	286.0	351.0	286.0
Durations (ticks)		518.0	95.0	535.0	529.0	433.0	433.0	241.0	149.0	480.0	95.0	252.0	191.0	431.0	95.0	109.0	94.0
Operational disruption (units) (OD _{post})		20,095.0	5,660.0	25,898.3	25,528.3	20,340.0	21,038.3	16,491.7	5,435.0	18,791.7	5,260.0	15,205.0	10,116.7	19,361.7	5,661.7	6,093.3	5,970.0
Post-flood absolute operational disruption (%) (OD _{ABS} ^{post})		11.5	3.2	14.8	14.6	11.6	12.0	9.4	3.1	10.8	3.0	8.7	5.8	11.1	3.2	3.5	3.4
Overall operational disruption (units) (OD _{overall})		36,170.0	11,235.0	31,673.3	31,103.3	36,515.0	37,113.3	23,566.7	25,810.0	34,466.7	10,835.0	20,980.0	26,210.0	35,536.7	11,816.7	17,151.7	12,090.0
Overall absolute operational disruption (%) (OD _{ABS} ^{overall})		20.7	6.4	18.1	17.8	20.9	21.2	13.5	14.8	19.7	6.2	12.0	15.0	20.3	6.8	9.8	6.9

Table D.1: Simulation data for the lightly flooded (6) retail SMEs located in Lower Don Valley of Sheffield

As presented in Table D.1, the lightly flooded retail SMEs simulated in E2 (A), E6 (A), E9, and E11, yielded the lowest $OD_{ABS}^{overall}$ values of 6.4%, 6.2%, 6.8%, and 6.9%, respectively. This is because all the retail SMEs simulated in these experiments were able to secure all the floodwater entry points (PM_5 , PM_6 , PM_7 , and PM_8) and deployed different resistance precautionary measures at doorways (bun-walls (PM_1) for SMEs simulated in E2 (A), E6 (A), and E11; and sandbags (PM_2) for those simulated in E9). However, as mentioned previously, the bund-wall precautionary measure is a financially and structurally costly option and is only suitable for detached SMEs. It is acknowledged that the lightly flooded retail SMEs simulated in E9 and E11 had additionally implemented a combination of all the business continuity/risk management precautionary measures without alternatives (PM_{19} , PM_{20} , PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}), which included registering for EA alerts and warnings (PM_{19} and PM_{20}). The latter enabled the retail SMEs simulated in E9 to cover air-bricks. Otherwise, they would have been flooded as happened in E2 (D). For the remaining set of business continuity/risk management precautionary measures (PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}) implemented in E9 and E11, these were ineffective because the SMEs were not flooded.

The lightly flooded retail SMEs simulated in E1, E2 (D), E3, and E8 achieved the greatest $OD_{ABS}^{overall}$ values of 20.7%, 20.9, 21.2%, and 20.3% respectively. This is because all the retail SMEs simulated in these experiments did not implement any flood resistance precautionary measure at doorways to prevent floodwater ingress into their premises. Also, they did not lift-up or raise their documents, sales equipment, and stock above the likely flood level. Therefore, all the retail SMEs simulated in E1, E2 (D), E3, and E8 became flooded and thus all their documents, sales equipment, and stock were damaged. In particular, the retail SMEs simulated in E1 had only set-up and maintained an emergency financial reserve, whereas the retail SMEs simulated in E2 (D) had enacted a combination of all the resistance precautionary measures without alternatives (PM_2 , PM_5 , PM_6 , PM_7 , and PM_8). In E2 (D), however, sandbags (PM_8) were not placed at doorways because these SMEs did not receive EA alerts or warnings. For simulation experiment E3, the retail SMEs were flooded because the implemented flood-resistance precautionary measures (PM_5 , PM_6 , PM_7 , and PM_8) were inadequate to protect SMEs' premises from floodwater ingress, which penetrated their premises via doorways. This floodwater ingress into SMEs' premises caused

damage to their respective premises, documents, and stock that had not been lifted-up as post-flood behaviours or raised as precautionary measures. In terms of the lightly flooded retail SMEs simulated in E8, these SMEs implemented a combination of the continuity/risk management precautionary measures without alternatives (PM_{23} , PM_{27} , PM_{28} , PM_{29} , PM_{30} , and PM_{31}). In E8, the floodwater entered SMEs premises via the doorways which were not secured and damage SMEs' premises, documents, and stock. Therefore, the lightly flooded retail SMEs simulated in E1 and E2 (D), E3, and E8 had to allocate employees to enact the same set of post-flood behaviours (contact electricians and plumber to carry out the necessary repairs; supervise electrician and plumber repairs; restore power; acquire cleaning tools; clean-up premises; reproduce documents; order new sales equipment; contact suppliers to resume stock deliver; and refurbish premises (see Chapter 7, Section 7.1.2)). These post-flood behaviours are necessary to enable retail SMEs to return to the normal operation ($SC = 100\%$).

D.2.2 Moderately Flooded Retail SMEs

The moderately flooded retail SMEs that implemented a combination of *all* the resistance precautionary measures without alternatives (PM_1 , PM_5 , PM_6 , PM_7 , and PM_8), as in E2 (A), E6 (A), and E11, yielded the lowest $OD_{ABS}^{overall}$ values of 7.4%, 7.8%, and 8.3%, respectively (see Table D.2). The retail SMEs simulated in these experiments had erected a bund-wall around their premises as a flood-resistance precautionary measure, which was able to provide protection against flooding up to a level of 1.5m (see Chapter 7, Section 7.1.3.1).

In contrast to the lightly flooded retail SMEs, the moderately flooded retail SMEs simulated in E9 yielded a $OD_{ABS}^{overall}$ value of 19% (12.2% greater than the lightly flooded retail SMEs simulated in the same experiment). This is because the floodwater level reached in the moderately flooded retail SMEs' premises exceeded the protection level provided by sandbags (see 0.3m, Chapter 7, Section 7.1.3.1.1) and the floodwater subsequently damaged these SMEs' premises, stock, sockets, consumer boards, sales equipment.

It is recognised that the moderately flooded retail SMEs simulated in E1, E2 (B), E2 (C), E2 (D), and E3 achieved the greatest $OD_{ABS}^{overall}$ values of 24.5%, 24.4%, 25%, 23.5%, and 24%, respectively. For the moderately retail SMEs simulated in E1, E2

(D), and E3, none of the five retail SMEs simulated in these experiments secured their doorways by implementing any resistance precautionary measures. Also, they did not lift-up or raise their documents, sales equipment, and stock above the likely flood level. Therefore, all the five retail SMEs simulated in E1, E2 (D), E3, and E8 were moderately flooded and thus all their documents, sales equipment, and stock were damaged. For those simulated in E2 (B), E2 (C), all the five retail SMEs simulated were able to secure their doorways by installing flood-proof doors and flood barriers, respectively. However, air-bricks were not covered because EA alerts or warnings were not received, and thus all the retail SMEs' premises were moderately flooded.

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t ₁ to t ₂)																	
Start (t ₁)	Day (d)	3	3	3	3	3	3	3	3	3	3	3	2	3	2	2	2
	Time (t _c)	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	16:30	08:30	16:30	08:30	08:30	08:30
	Tick (t _s)	113	113	113	113	113	113	113	113	113	113	113	49	113	49	49	49
End (t ₂)	Day (d)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Time (t _c)	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30
	Tick (t _s)	141	141	141	141	141	141	141	141	141	141	141	141	141	141	141	141
Durations (ticks)		29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	93.0	29.0	93.0	93.0	93.0
Pre-flood operational disruption (units) (OD _{pre})		1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,200.0	1,732.0	1,200.0	1,708.0	1,606.0	1,620.0
Pre-flood absolute operational disruption (%) (OD ^{pre} _{ABS})		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1.0	0.7	1.0	0.9	0.9
non-operation (t ₂ to t ₃)																	
Start (t ₂)	Day (d)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Time (t _c)	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30	06:30
	Tick (t _s)	141	141	141	141	141	141	141	141	141	141	141	141	141	141	141	141
End (t ₃)	Day (d)	8	5	7	7	8	8	7	8	8	5	7	7	8	8	7	5
	Time (t _c)	07:30	07:30	15:30	15:30	07:30	11:00	11:00	16:30	10:00	08:30	09:00	14:30	08:00	07:00	07:00	09:00
	Tick (t _s)	335	191	303	303	335	342	294	353	340	193	290	301	336	334	286	194
Durations (ticks)		194.0	50.0	162.0	162.0	194.0	201.0	153.0	212.0	199.0	52.0	149.0	160.0	195.0	193.0	145.0	53.0
Non-operation operational disruption (units) (OD _{none})		19,400.0	5,000.0	16,200.0	16,200.0	19,400.0	20,100.0	15,300.0	21,200.0	19,900.0	5,200.0	14,900.0	16,000.0	19,500.0	19,300.0	14,500.0	5,300.0
Non-operation absolute operational disruption (%) (OD ^{none} _{ABS})		11.1	2.9	9.3	9.3	11.1	11.5	8.8	12.1	11.4	3.0	8.5	9.2	11.2	11.0	8.3	3.0
Post-flood (t ₃ to t ₄)																	
Start (t ₃)	Day (d)	8	5	7	7	8	8	7	8	8	5	7	7	8	8	7	5
	Time (t _c)	07:30	07:30	15:30	15:30	07:30	11:00	11:00	16:30	10:00	08:30	09:00	14:30	08:00	07:00	07:00	09:00
	Tick (t _s)	335	191	303	303	335	342	294	353	340	193	290	301	336	334	286	194
End (t ₄)	Day (d)	20	7	19	18	18	20	12	12	16	7	11	16	19	16	9	7
	Time (t _c)	07:00	07:00	14:00	16:00	10:30	11:30	07:00	12:30	15:00	07:00	13:30	07:00	16:00	10:30	11:30	07:00
	Tick (t _s)	910	286	876	832	821	919	526	537	734	286	491	718	880	725	391	286
Durations (ticks)		575.0	95.0	573.0	529.0	486.0	577.0	232.0	184.0	394.0	93.0	201.0	417.0	544.0	391.0	105.0	92.0
Operational disruption (units) (OD _{post})		22,298.0	6,722.0	25,222.0	26,362.0	20,482.0	20,672.0	9,000.0	7,348.0	17,536.0	7,254.0	9,414.0	16,432.0	22,468.0	12,206.0	4,414.0	7,666.0
Post-flood absolute operational disruption (%) (OD ^{post} _{ABS})		12.8	3.8	14.4	15.1	11.7	11.8	5.1	4.2	10.0	4.1	5.4	9.4	12.9	7.0	2.5	4.4
Overall operational disruption (units) (OD _{overall})		42,898.0	12,922.0	42,622.0	43,762.0	41,082.0	41,972.0	25,500.0	29,748.0	38,636.0	13,654.0	25,514.0	34,164.0	43,168.0	33,214.0	20,520.0	14,586.0
Overall absolute operational disruption (%) (OD ^{overall} _{ABS})		24.5	7.4	24.4	25.0	23.5	24.0	14.6	17.0	22.1	7.8	14.6	19.5	24.7	19.0	11.7	8.3

Table D.2: Simulation data for the moderately flooded (5) retail SMEs located in Lower Don Valley of Sheffield

D.2.3 Severely Flooded Retail SMEs

In contrast to the lightly and moderately flooded retail SMEs, the severely flooded retail SMEs simulated in E10 and E11 achieved the lowest $OD_{ABS}^{overall}$ values of 23.1% and 23.9%, respectively (see Table D.3). This is because the floodwater level reached in the two severely flooded retail SMEs exceeded the height of the bund-wall erected around their premises and damaged all the raised documents, sales equipment, stock, sockets, and consumer boards. However, the two severely flooded retail SMEs simulated in E10 and E11 maintained electricity generator, which enabled them to resume the post-flood behaviours before the main power was restored. Also, they maintained and displayed an emergency flood plan, which in turn, enabled them to complete some of the post-flood behaviours quicker than the other SMEs (see Chapter 7, Section 7.1.3.2). Indeed, E7, E8, and E9 also include the same combination of the business continuity/risk management precautionary measures implemented in E10 and E11, although they achieved higher $OD_{ABS}^{overall}$ values of 19.5%, 24.7%, and 19%. This is because the retail SMEs simulated in E7, E8, and E9 had to return stock, sales equipment, and paper documents that had been lifted-up (to protect them from damage) to their normal locations, which was not the case in E10 and E11.

D.2.4 Recommendations for Retail SMEs

The lightly, moderately, and severely flooded retail SMEs are recommended to implement the same set of recommendations tailored for the corresponding categories from the manufacturing SMEs (see Chapter 9, Section 9.4). However, due to the differences between the various SME sectors, there are a few sector-specific flood-resilience precautionary measures. For example, retail SMEs are recommended to raise consumer boards and electrical sockets above the likely floodwater level along with raising the height at which their documents and stock are stored. In terms of the business continuity/risk management precautionary measures, retail SMEs are advised to implement the same set of precautionary measures as manufacturing SMEs (with the exception of the mutual aid partner because it is not applicable to this sector).

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		Simulation Experiments															
		E1	E2				E3	E4	E5		E6		E7	E8	E9	E10	E11
			A	B	C	D			A	B	A	B					
Pre-flood (t ₁ to t ₂)																	
Start (t ₁)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.0	4.0	2.0	2.0	2.0
	Time (t _e)	05:00	05:00	05:00	05:00	05:00	05:00	05:00	05:00	05:00	05:00	05:00	08:30	05:00	08:30	08:30	08:30
	Tick (t _s)	138.0	138.0	138.0	138.0	138.0	138.0	138.0	138.0	138.0	138.0	138.0	49.0	138.0	49.0	49.0	49.0
End (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t _e)	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00
	Tick (t _s)	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0
Durations (ticks)		7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	96.0	7.0	96.0	96.0	96.0
Pre-flood operational disruption (units) (OD _{pre})		325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	805.0	325.0	925.0	790.0	715.0
Pre-flood absolute operational disruption (%) (OD _{ABS} ^{pre})		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.2	0.5	0.5	0.4
Non-operation (t ₂ to t ₃)																	
Start (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t _e)	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00	08:00
	Tick (t _s)	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0	144.0
End (t ₃)	Day (d)	10.0	9.0	10.0	9.0	10.0	9.0	9.0	9.0	9.0	9.0	9.0	11.0	9.0	11.0	11.0	11.0
	Time (t _e)	08:30	12:30	08:00	16:30	09:00	11:30	13:00	13:00	13:30	14:30	14:00	16:00	15:30	14:30	07:00	07:00
	Tick (t _s)	433.0	393.0	432.0	401.0	434.0	391.0	394.0	394.0	395.0	397.0	396.0	496.0	399.0	493.0	478.0	478.0
Durations (ticks)		289.0	249.0	288.0	257.0	290.0	247.0	250.0	250.0	251.0	253.0	252.0	352.0	255.0	349.0	334.0	334.0
Non-operation operational disruption (units) (OD _{none})		28,900.0	24,900.0	28,800.0	25,700.0	29,000.0	24,700.0	25,000.0	25,000.0	25,100.0	25,300.0	25,200.0	35,200.0	25,500.0	34,900.0	33,400.0	33,400.0
Non-operation absolute operational disruption (%) (OD _{ABS} ^{none})		16.5	14.2	16.5	14.7	16.6	14.1	14.3	14.3	14.4	14.5	14.4	20.1	14.6	20.0	19.1	19.1
Post-flood (t ₃ to t ₄)																	
Start (t ₃)	Day (d)	10.0	9.0	10.0	9.0	10.0	9.0	9.0	9.0	9.0	9.0	9.0	11.0	9.0	11.0	11.0	11.0
	Time (t _e)	08:30	12:30	08:00	16:30	09:00	11:30	13:00	13:00	13:30	14:30	14:00	16:00	15:30	14:30	07:00	07:00
	Tick (t _s)	433.0	393.0	432.0	401.0	434.0	391.0	394.0	394.0	395.0	397.0	396.0	496.0	399.0	493.0	478.0	478.0
End (t ₄)	Day (d)	21.0	21.0	19.0	21.0	21.0	20.0	18.0	17.0	19.0	19.0	19.0	19.0	19.0	20.0	15.0	16.0
	Time (t _e)	08:30	08:30	16:00	08:00	08:00	14:00	14:30	12:30	07:00	13:30	10:00	15:30	13:00	07:30	09:00	07:00
	Tick (t _s)	961.0	961.0	880.0	960.0	960.0	924.0	829.0	777.0	862.0	875.0	868.0	879.0	874.0	911.0	674.0	718.0
Durations (ticks)		528.0	568.0	448.0	559.0	526.0	533.0	435.0	383.0	467.0	478.0	472.0	383.0	475.0	418.0	196.0	240.0
Operational disruption (units) (OD _{post})		25,525.0	27,410.0	22,985.0	30,505.0	25,410.0	28,220.0	24,635.0	24,445.0	25,245.0	26,455.0	24,895.0	16,140.0	28,185.0	19,450.0	6,245.0	7,620.0
Post-flood absolute operational disruption (%) (OD _{ABS} ^{post})		14.6	15.7	13.1	17.5	14.5	16.1	14.1	14.0	14.4	15.1	14.2	9.2	16.1	11.1	3.6	4.4
Overall operational disruption (units) (OD _{overall})		54,750.0	52,635.0	52,110.0	56,530.0	54,735.0	53,245.0	49,960.0	49,770.0	50,670.0	52,080.0	50,420.0	52,145.0	54,010.0	55,275.0	40,435.0	41,735.0
Overall absolute operational disruption (%) (OD _{ABS} ^{overall})		31.3	30.1	29.8	32.3	31.3	30.5	28.6	28.5	29.0	29.8	28.8	29.8	30.9	31.6	23.1	23.9

Table D.3: Simulation data for the severely flooded (2) retail SMEs located in Lower Don Valley of Sheffield

D.3 SME-RELATED ORGANISATIONS

This section aims to investigate: (i) the possible influence of different types of insurance coverage and financial status on SME's immediate response to and short-term recovery from different levels of flooding, (ii) the possible interactions between manufacturing SMEs and mutual aid partners, and (iii) the possible interactions between retail SMEs and companies specializing in refurbishing premises. As mentioned previously, the remainder of the SME-related organisations (suppliers, customers, electricians, and plumbers) provide fewer options to enable them to be investigated individually, such as the case in the insurance companies or cleaning service providers.

D.3.1 Insurance Companies

SMEs can obtain either basic or comprehensive insurance plans; SMEs with comprehensive insurance receive assistance in the form of a cleaning service in addition to financial compensation, whereas those with basic insurance only receive the latter. However, some of the flood-affected SMEs may choose not to contact their insurer to avoid a potential increase in their future insurance premiums. In such cases, these SMEs require sufficient funds to be in place to contact electricians, plumbers, cleaning service providers, and IT specialists. In terms of the comprehensive insurance plan, although SMEs may contact their insurer, they may choose to either (i) allocate their own employees to clean-up the premises rather than waiting for the cleaning service provided by the insurance to arrive, or (ii) contact cleaning service providers, if sufficient funds are available.

As presented in Table D.4, this investigation involves three simulation experiments:

- (i) simulation experiment S1 (A), which correspond to SMEs with basic insurance and without funds available;
- (ii) simulation experiment S1 (B), which corresponds to SMEs with comprehensive insurance and funds available, but choose to allocate their own employees to clean-up the premises rather than waiting for the cleaning service provided by the insurance to arrive; and

(iii) simulation experiment S1 (C), which corresponds to SMEs with comprehensive insurance and funds available and choosing to allocate the cleaning service provided by the insurance company to clean up their premises

These combinations of insurance coverage and financial status are implemented with the manufacturing SMEs simulated in E1 in which PM₂₃ is the only precautionary measure implemented.

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		SME-Related Organisations Simulation Experiments								
		Lightly Flooded SMEs			Moderately Flooded SMEs			Severely Flooded SMEs		
		S1 (A)	S1 (B)	S1 (C)	S1 (A)	S1 (B)	S1 (C)	S1 (A)	S1 (B)	S1 (C)
Pre-flood ($t_1 - t_2$)										
Start (t_1)	Day (d)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	Time (t_e)	17:00	17:00	17:00	16:30	16:30	16:30	15:30	15:30	15:30
	Tick (t_s)	114.0	114.0	114.0	113.0	113.0	113.0	111.0	111.0	111.0
End (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_e)	10:30	10:30	10:30	10:00	10:00	10:00	09:30	09:30	09:30
	Tick (t_s)	149.0	149.0	149.0	148.0	148.0	148.0	147.0	147.0	147.0
Durations (ticks)		36.0	36.0	36.0	36.0	36.0	36.0	37.0	37.0	37.0
Pre-flood operational disruption (units) (OD_{pre})		1,265.7	1,266.3	1,264.8	1,894.2	1,893.8	1,894.2	1,654.5	1,654.3	1,654.9
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		0.7	0.7	0.7	1.1	1.1	1.1	0.9	0.9	0.9
Non-operation ($t_2 - t_3$)										
Start (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_e)	10:30	10:30	10:30	10:00	10:00	10:00	09:30	09:30	09:30
	Tick (t_s)	149.0	149.0	149.0	148.0	148.0	148.0	147.0	147.0	147.0
End (t_3)	Day (d)	10.0	7.0	10.0	10.0	7.0	10.0	11.0	7.0	11.0
	Time (t_e)	11:00	07:00	13:30	10:30	11:00	14:00	08:30	16:30	12:00
	Tick (t_s)	438.0	286.0	443.0	437.0	294.0	444.0	481.0	305.0	488.0
Durations (ticks)		289.0	137.0	294.0	289.0	146.0	296.0	334.0	158.0	341.0
Non-operation operational disruption (units) (OD_{none})		28,900.0	13,700.0	29,400.0	28,900.0	14,600.0	29,600.0	33,400.0	15,800.0	34,100.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		16.5	7.8	16.8	16.5	8.4	16.9	19.1	9.0	19.5
Post-flood ($t_3 - t_4$)										
Start (t_3)	Day (d)	10.0	7.0	10.0	10.0	7.0	10.0	11.0	7.0	11.0
	Time (t_e)	11:00	07:00	13:30	10:30	11:00	14:00	08:30	16:30	12:00
	Tick (t_s)	438.0	286.0	443.0	437.0	294.0	444.0	481.0	305.0	488.0
End (t_4)	Day (d)	31.0	27.0	33.0	38.0	32.0	37.0	42.0	37.0	40.0
	Time (t_e)	16:30	08:30	11:00	07:30	07:30	11:00	12:00	14:30	09:30
	Tick (t_s)	1,457.0	1,249.0	1,542.0	1,775.0	1,486.0	1,734.0	1,976.0	1,741.0	1,875.0
Durations (ticks)		1,019.0	963.0	1,099.0	1,338.0	1,192.0	1,290.0	1,495.0	1,436.0	1,387.0
Operational disruption (units) (OD_{post})		37,271.8	28,552.4	35,907.5	42,505.8	36,762.0	40,689.9	45,966.1	43,672.9	43,671.4
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		21.3	16.3	20.5	24.3	21.0	23.3	26.3	25.0	25.0
Overall operational disruption (units) ($OD_{overall}$)		67,437.5	43,518.6	66,572.4	73,300.0	53,255.9	72,184.1	81,020.6	61,127.2	79,426.3
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		38.6	24.9	38.1	41.9	30.5	41.3	46.4	35.0	45.4

Table D.4: Insurance coverage and financial status results

As shown in Table D.4, the manufacturing SMEs simulated in S1 (A) achieved the greatest $OD_{ABS}^{overall}$ values of 38.6%, 41.9%, and 46.4% for the lightly, moderately, and severely flooded manufacturing SMEs, respectively. This is due to the insufficient funds available, in which case, these manufacturing SMEs had to wait for compensation from their insurance company (which may take up to 12 days to be released (see Chapter 7, Section 7.2.3)) in order to contact electricians, plumbers, and IT specialists to carry out the necessary repairs as part of their post-flood behaviours. During this potential 12-day period, SMEs could not enact any of the post-flood behaviours including acquiring the necessary cleaning tools in order to clean up their premises. This was because SMEs did not have sufficient funds available and a lack of electricity. On receipt of compensation, a single production employee from each SME was allocated to contact electricians and plumbers to request they attend to carry out the necessary repairs. Furthermore, once the electricians and plumbers arrived at the flood-affected premises, one production employee from each SME was allocated to supervise these repairs. Also, a proportion of production employees were allocated to acquire the necessary cleaning equipment in order to clean up their premises. With the electricity supply restored, a proportion of production employees were allocated to repair machines and contact IT specialists to perform the necessary repairs before setting-up IT equipment. Finally, SMEs had to contact suppliers and customers to inform them of the resumption of raw material dispatch and product delivery, respectively.

For simulation experiment S1 (B), the manufacturing SMEs simulated in S1 (B) achieved the lowest $OD_{ABS}^{overall}$ values of 24.9%, 30.5%, and 35% (i.e. 13.7%, 11.4%, and 11.4% less than the lightly, moderately, and severely flooded manufacturing SMEs simulated in S1 (A), respectively). This is due to (i) funds being available enabling quick acquisition of services (electricians, plumbers, and IT specialists) without needing to wait for compensation from insurance companies, and (ii) allocating production employees to clean up their respective premises despite having comprehensive insurance, rather than waiting for the insurance company to provide a cleaning service.

In relation to simulation experiment S1 (C), the manufacturing SMEs simulated in S1 (C) also achieved greater $OD_{ABS}^{overall}$ values of 38.1%, 41.3%, and 45.4% (i.e.

13.2%, 10.8%, and 10.4% greater than the lightly, moderately, and severely flooded manufacturing SMEs simulated in S1 (B)), respectively. This is because these SMEs chose to wait for the cleaning service provided by the insurance company to arrive, which was not the case in S1 (B) although they had funds available.

It can be concluded that SMEs with funds available and choosing to allocate their own employees to clean up their premises rather than allocating cleaning service providers yielded lower $OD_{ABS}^{overall}$ values, as discussed in S1 (B).

D.3.2 Mutual Aid Partners

This sub-section discusses mutual aid partner's effect on manufacturing SME's immediate response to and short-term recovery from flood events. As presented in Table D.5, two simulation experiments are presented: (i) simulation experiment S2 (A) in which manufacturing SMEs have a pre-defined mutual aid partner, and (ii) simulation experiment S2 (B) in which manufacturing SMEs do not have a mutual aid partnership. Table D.5 shows that the lightly, moderately, and severely flooded manufacturing SMEs simulated in S2 (A) achieved lower $OD_{ABS}^{overall}$ values of 20.3%, 24.1%, and 27.7%, respectively.

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		SME-Related Organisations Simulation Experiments					
		Lightly Flooded SMEs		Moderately Flooded SMEs		Severely Flooded SMEs	
		S2 (A)	S2 (B)	S2 (A)	S2 (B)	S2 (A)	S2 (B)
Post-flood ($t_1 - t_2$)							
Start (t_1)	Day (d)	3.0	3.0	3.0	3.0	3.0	3.0
	Time (t_c)	17:00	17:00	16:30	16:30	15:30	15:30
	Tick (t_s)	114.0	114.0	113.0	113.0	111.0	111.0
End (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	10:30	10:30	10:00	10:00	09:30	09:30
	Tick (t_s)	149.0	149.0	148.0	148.0	147.0	147.0
Durations (ticks)		36.0	36.0	36.0	36.0	37.0	37.0
Pre-flood operational disruption (units) (OD_{pre})		1,264.8	1,265.5	1,894.6	1,893.9	1,654.6	1,654.5
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		0.7	0.7	1.1	1.1	0.9	0.9
Non-operation ($t_2 - t_3$)							
Start (t_2)	Day (d)	4.0	4.0	4.0	4.0	4.0	4.0
	Time (t_c)	10:30	10:30	10:00	10:00	09:30	09:30
	Tick (t_s)	149.0	149.0	148.0	148.0	147.0	147.0
End (t_3)	Day (d)	4.0	7.0	5.0	7.0	5.0	7.0
	Time (t_c)	12:00	09:00	07:00	11:00	08:00	14:30
	Tick (t_s)	152.0	290.0	190.0	294.0	192.0	301.0
Durations (ticks)		3.0	141.0	42.0	146.0	45.0	154.0
Non-operation operational disruption (units) (OD_{none})		300.0	14,100.0	4,200.0	14,600.0	4,500.0	15,400.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		0.2	8.1	2.4	8.4	2.6	8.8
Post-flood ($t_3 - t_4$)							
Start (t_3)	Day (d)	4.0	7.0	5.0	7.0	5.0	7.0
	Time (t_c)	12:00	09:00	07:00	11:00	08:00	14:30
	Tick (t_s)	152.0	290.0	190.0	294.0	192.0	301.0
End (t_4)	Day (d)	19.0	26.0	22.0	31.0	25.0	37.0
	Time (t_c)	09:00	14:30	15:30	14:00	11:00	09:30
	Tick (t_s)	866.0	1,213.0	1,023.0	1,452.0	1,158.0	1,731.0
Durations (ticks)		714.0	923.0	833.0	1,158.0	966.0	1,430.0
Operational disruption (units) (OD_{post})		33,921.9	28,510.9	36,020.4	36,086.9	42,230.0	43,050.1
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		19.4	16.3	20.6	20.6	24.2	24.6
Overall operational disruption (units) ($OD_{overall}$)		35,486.8	43,876.5	42,115.0	52,580.8	48,384.6	60,104.6
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		20.3	25.1	24.1	30.1	27.7	34.4

Table D.5: Manufacturing SME and mutual aid partner results

For the lightly, moderately and severely flooded manufacturing SMEs simulated in experiment S2 (A), a proportion of production employees were allocated to contact electricians in order to repair the power supply and the damaged electrical sockets. Simultaneously or sequentially, another proportion of production employees were allocated to contact their mutual aid partners in order to send the appropriate number of production employees to work on the allocated machines at the mutual aid partner's site. This subsequently enabled SMEs simulated in S2 (A) to restore their production level on the first day after the flood receded from SMEs' premises. Following this, SMEs enacted the remainder of the post-flood behaviours, such as contacting plumbers and IT specialists to carry out the necessary repairs. Further, these employees were also allocated to acquire the necessary cleaning equipment to clean up the premises. With the electricity restored, a proportion of production employees were then assigned to repair machines, which would, in turn, enable them to return to work on production. As shown in Table D.5, the lightly flooded manufacturing SMEs simulated in S2 (A) were able to resume production on the same day (day 4), whereas the moderately and severely flooded manufacturing SMEs were only able to resume production on the following day (day 5).

In relation to simulation experiment S2 (B), production employees were allocated to carry out the same post-flood behaviours (such as contacting electrical, plumbing, and IT service providers, acquiring cleaning equipment to clean-up their premises) as those carried out by the manufacturing SMEs simulated in S2 (A) except for contacting and working at the mutual aid partners' location. Subsequently, as shown in Table D.5, the manufacturing SMEs simulated in S2 (B) achieved greater $OD_{ABS}^{overall}$ values of 25.1%, 30.1%, and 34.4% (i.e. 4.8%, 6%, and 6.7% greater than the manufacturing SMEs simulated in S2 (A)), respectively. This difference allowed the manufacturing SMEs to maintain production during a period in which they would otherwise remain non-operational.

D.3.3 Refurbishment Company

To investigate retail SME's immediate response to and short-term recovery from flooding, the lightly, moderately and severely flooded retails SMEs were simulated with and without a refurbishment company being called to attend their flood-affected premises. In particular, as presented in Table D.6, two simulation experiments are defined: (i) simulation experiment S3 (A) in which retail SMEs chose to allocate their own employees to refurbish their flood-affected premises; and (ii) simulation experiment S3 (B) in which retail SMEs employed companies specializing in refurbishing premises.

Appendix D. Results and Discussion for Retail SMEs and Related Organisation

		SME-Related Organisations Simulation Experiments					
		Lightly Flooded SMEs		Moderately Flooded SMEs		Severely Flooded SMEs	
		S3 (A)	S3 (B)	S3 (A)	S3 (B)	S3 (A)	S3 (B)
Pre-flood (t₁ to t₂)							
Start (t ₁)	Day (d)	3.0	3.0	3.0	3.0	4.0	4.0
	Time (t _c)	19:00	19:00	16:30	16:30	05:00	05:00
	Tick (t _s)	118.0	118.0	113.0	113.0	138.0	138.0
End (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	12.0
	Time (t _c)	08:00	08:00	06:30	06:30	08:00	10:00
	Tick (t _s)	144.0	144.0	141.0	141.0	144.0	532.0
Durations (ticks)		27.0	27.0	29.0	29.0	7.0	395.0
Pre-flood operational disruption (units) (OD_{pre})		875.0	875.0	1,200.0	1,200.0	325.0	39,097.5
Pre-flood absolute operational disruption (%) (OD_{ABS}^{pre})		0.5	0.5	0.7	0.7	0.2	22.4
Non-operation (t₂ to t₃)							
Start (t ₂)	Day (d)	4.0	4.0	4.0	4.0	4.0	12.0
	Time (t _c)	08:00	08:00	06:30	06:30	08:00	10:00
	Tick (t _s)	144.0	144.0	141.0	141.0	144.0	532.0
End (t ₃)	Day (d)	7.0	8.0	8.0	9.0	10.0	12.0
	Time (t _c)	12:00	16:00	07:30	10:00	08:30	15:30
	Tick (t _s)	296.0	352.0	335.0	388.0	433.0	543.0
Durations (ticks)		152.0	208.0	194.0	247.0	289.0	11.0
Non-operation operational disruption (units) (OD_{none})		15,200.0	20,800.0	19,400.0	24,700.0	28,900.0	1,100.0
Non-operation absolute operational disruption (%) (OD_{ABS}^{none})		8.7	11.9	11.1	14.1	16.5	0.6
Post-flood (t₃ to t₄)							
Start (t ₃)	Day (d)	7.0	8.0	8.0	9.0	10.0	12.0
	Time (t _c)	12:00	16:00	07:30	10:00	08:30	15:30
	Tick (t _s)	296.0	352.0	335.0	388.0	433.0	543.0
End (t ₄)	Day (d)	18.0	24.0	20.0	27.0	21.0	28.0
	Time (t _c)	07:00	08:30	07:00	15:30	08:30	07:00
	Tick (t _s)	814.0	1,105.0	910.0	1,263.0	961.0	1,294.0
Durations (ticks)		518.0	753.0	575.0	875.0	528.0	751.0
Operational disruption (units) (OD_{post})		20,095.0	28,925.0	22,298.0	30,698.0	25,525.0	29,370.0
Post-flood absolute operational disruption (%) (OD_{ABS}^{post})		11.5	16.5	12.8	17.6	14.6	16.8
Overall operational disruption (units) ($OD_{overall}$)		36,170.0	50,600.0	42,898.0	56,598.0	54,750.0	69,567.5
Overall absolute operational disruption (%) ($OD_{ABS}^{overall}$)		20.7	28.9	24.5	32.4	31.3	39.8

Table D.6: Results for retail SMEs and companies specializing in refurbishing premises

In relation to simulation experiment S3 (A), the $OD_{ABS}^{overall}$ values of the lightly, moderately and severely flooded retail SMEs are 20.7%, 24.5%, and 31.3%, respectively (see Table D.6). This is because a proportion of employees of the lightly, moderately, and severely flooded retail SMEs were allocated to contact electricians and plumbers to request they attend their premises to carry out the necessary repairs. Furthermore, once electricians and plumbers had arrived at the flood-affected premises, a proportion of the employees were allocated to supervise these repairs. Simultaneously, a proportion of employees were allocated to acquire the necessary cleaning equipment to carry out premises cleaning and refurbishment rather than allocating a refurbishment company.

For the retail SMEs simulated in S3 (B), the lightly, moderately, and severely flooded retail SMEs achieved higher $OD_{ABS}^{overall}$ values at 28.9%, 32.4%, and 39.8 (i.e. 8.2%, 7.9%, and 8.5%, respectively, which were greater than those achieved by the retail SMEs simulated in S3 (A)). This difference is due to the processes undertaken by the lightly, moderately, and severely flooded retail SME simulated in S3 (B), i.e. contacting a refurbishment company and waiting for them to arrive at the SME's premises (as opposed to assigning their own employees, if able, to carry out refurbishment) (see Chapter 7, Section 7.2.5). This difference motivates retail SMEs to allocate employees to refurbish premises, if possible, although it is understandable that not all SMEs' employees are skilled or capable of post-flood refurbishment.

Appendix E

Graphical Representations

E.1 MANUFACTURING SMES LOCATED IN SHEFFIELD GEOGRAPHICAL AREA

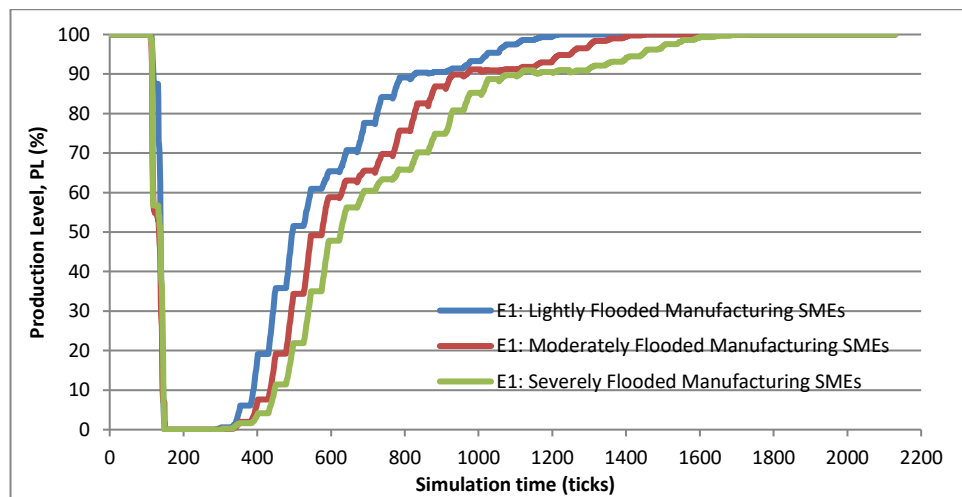


Figure E.1: Simulation experiment E1- manufacturing SMEs located in Sheffield

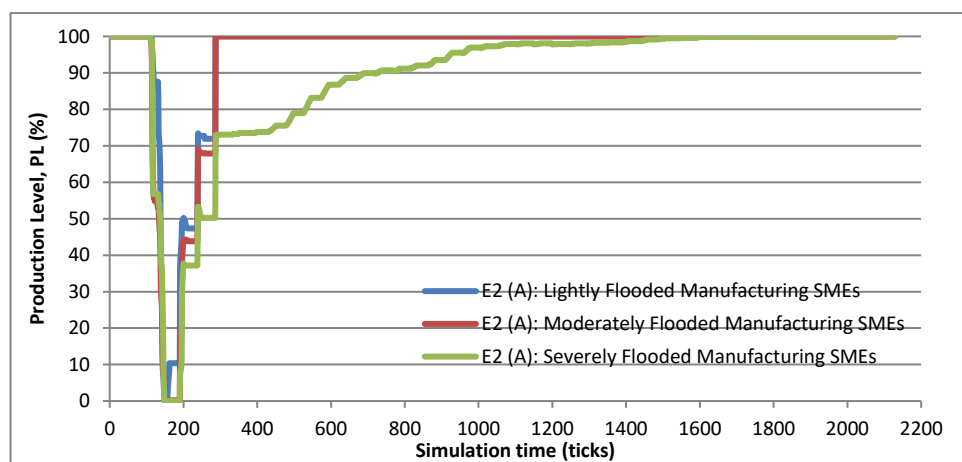


Figure E.2: Simulation experiment E2 (A): manufacturing SMEs located in Sheffield

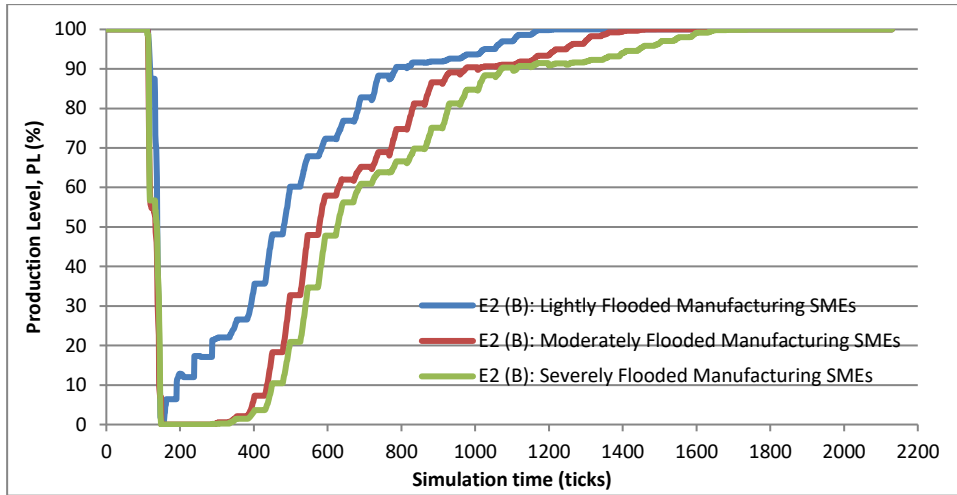


Figure E.3: Simulation experiment E2 (B): manufacturing SMEs located in Sheffield

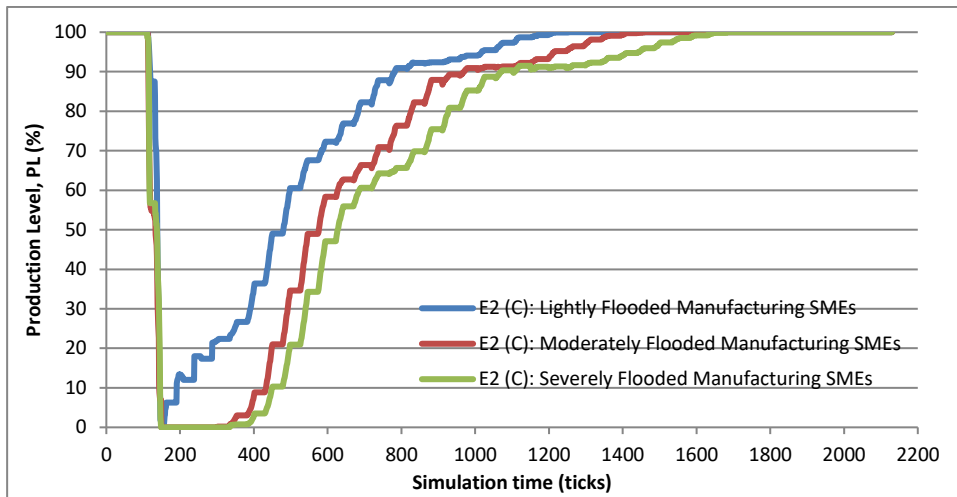


Figure E.4: Simulation experiment E2 (C): manufacturing SMEs located in Sheffield

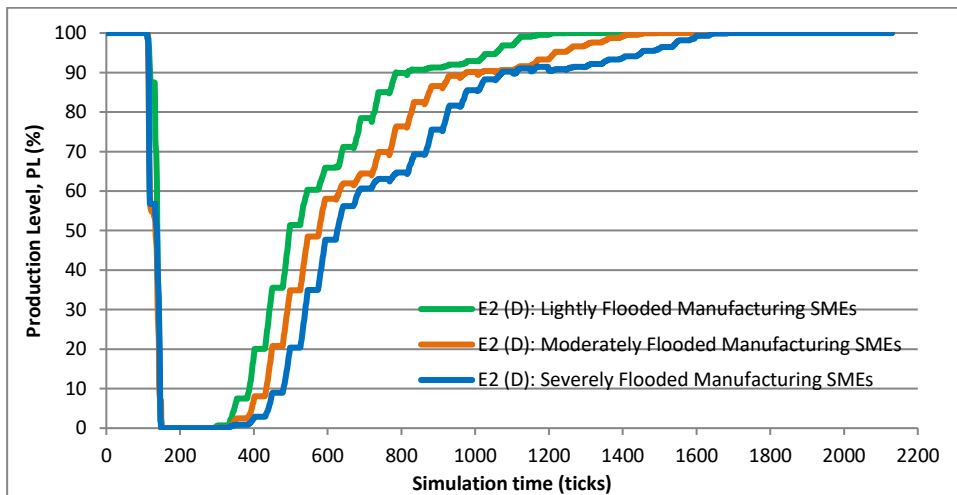


Figure E.5: Simulation experiment E2 (D): manufacturing SMEs located in Sheffield

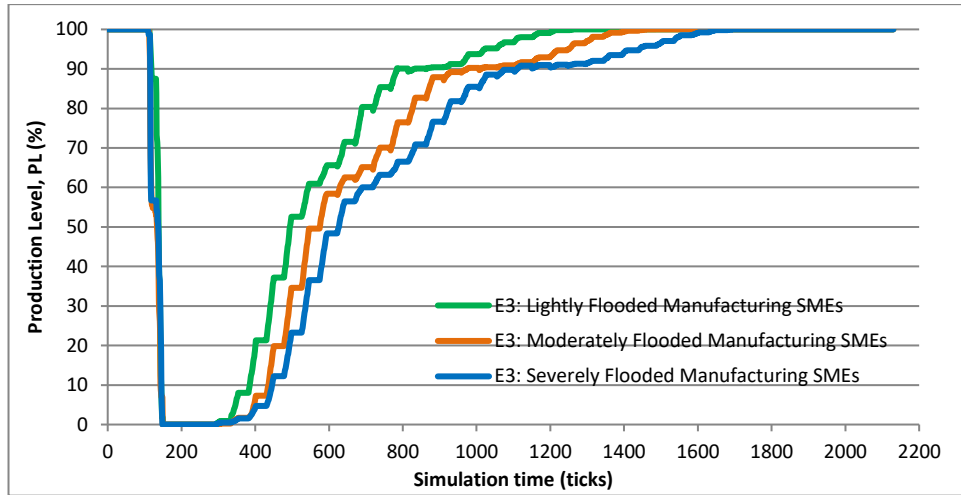


Figure E.6: Simulation experiment E3: manufacturing SMEs located in Sheffield

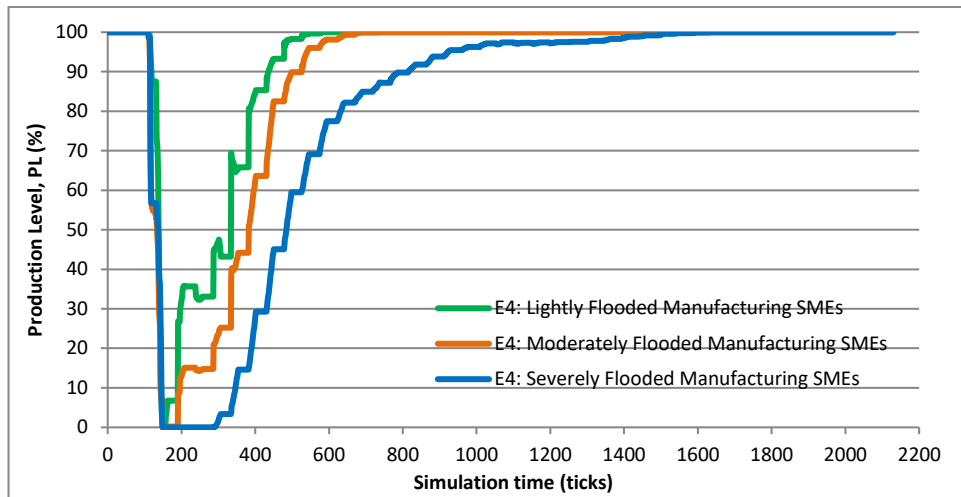


Figure E.7: Simulation experiment E4: manufacturing SMEs located in Sheffield

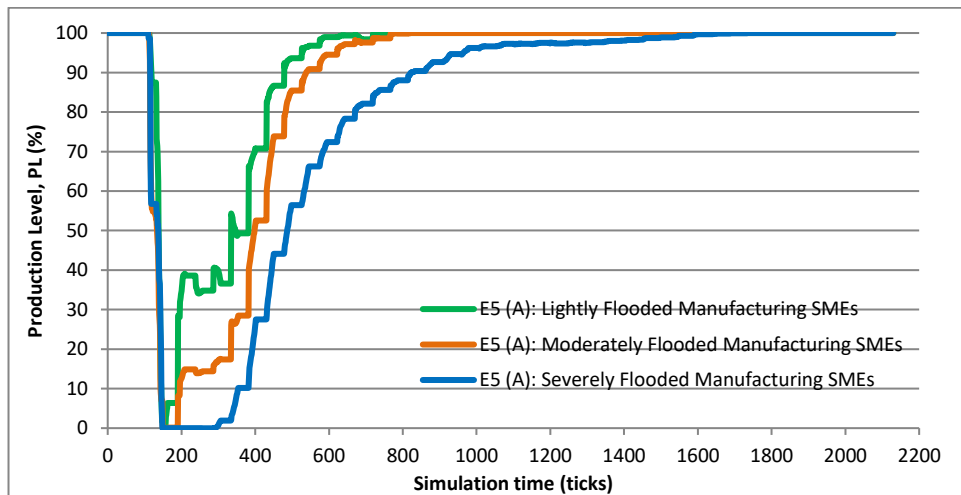


Figure E.8: Simulation experiment E5 (A): manufacturing SMEs located in Sheffield

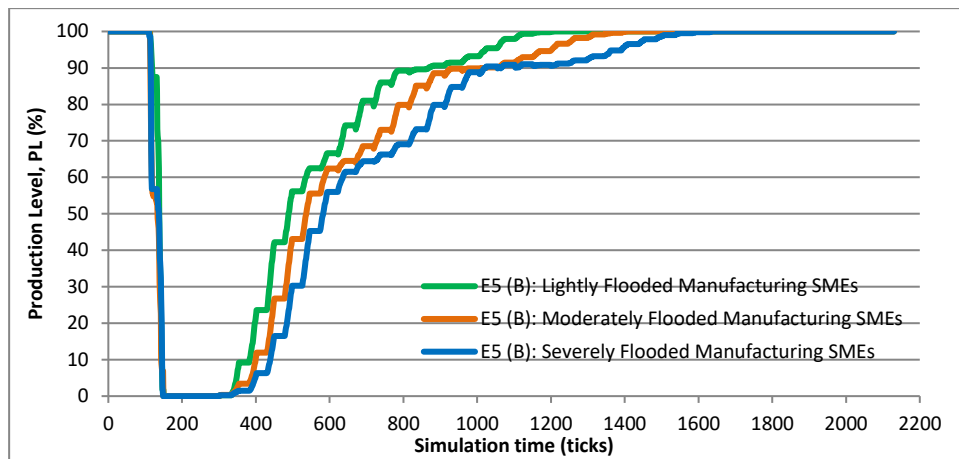


Figure E.9: Simulation experiment E5 (B): manufacturing SMEs located in Sheffield

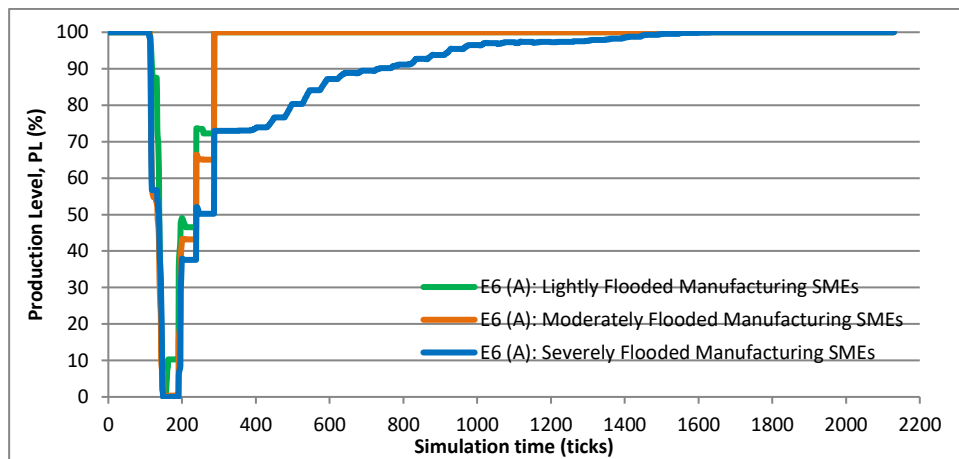


Figure E.10: Simulation experiment E6 (A): manufacturing SMEs located in Sheffield

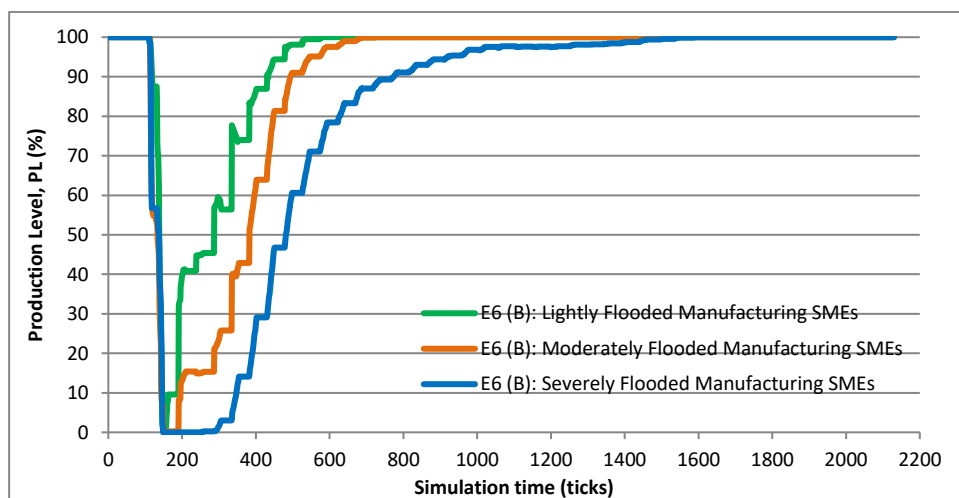


Figure E.11: Simulation experiment E6 (B) : manufacturing SMEs located in Sheffield

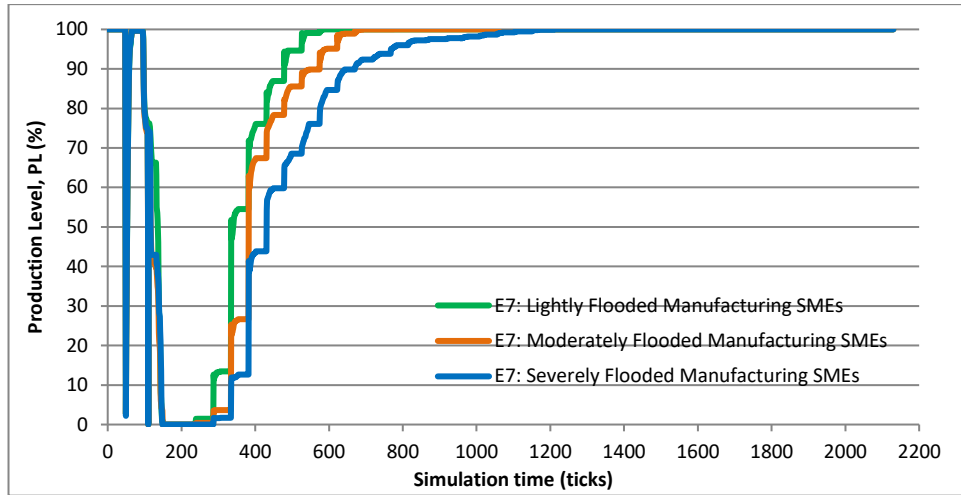


Figure E.12: Simulation experiment E7: manufacturing SMEs located in Sheffield

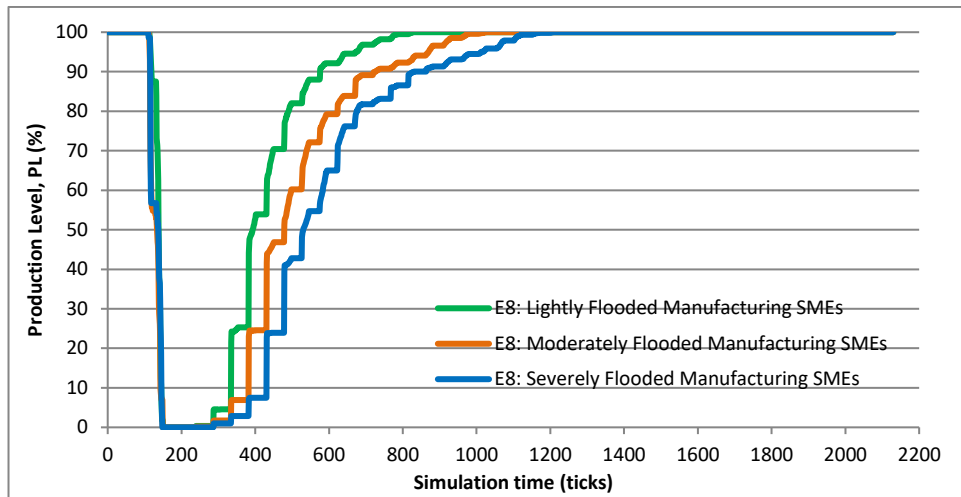


Figure E.13: Simulation experiment E8: manufacturing SMEs located in Sheffield

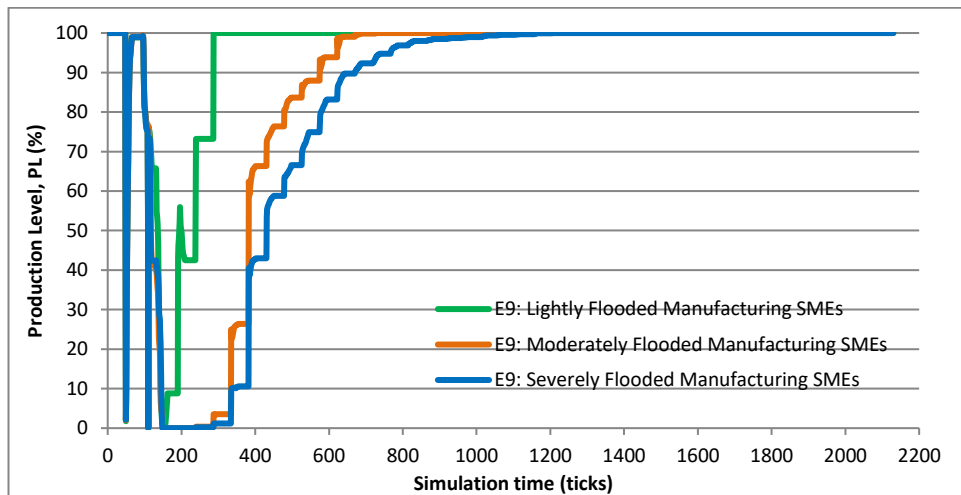


Figure E.14: Simulation experiment E9: manufacturing SMEs located in Sheffield

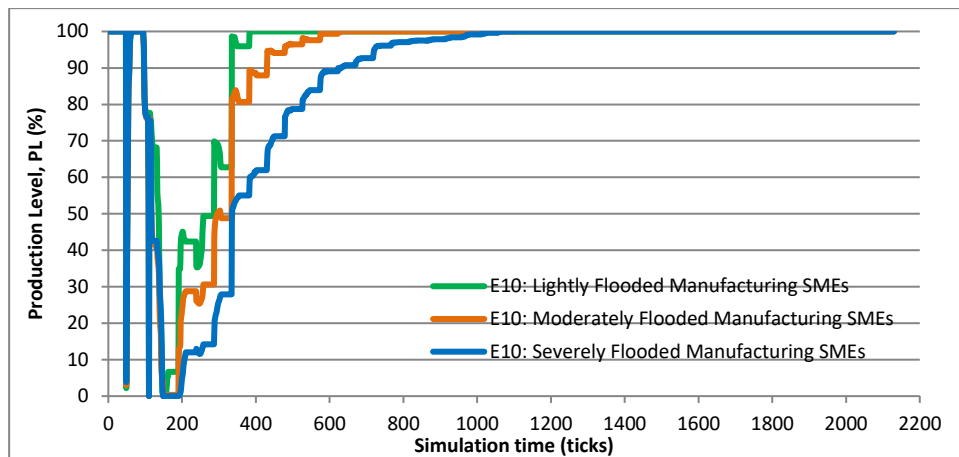


Figure E.15: Simulation experiment E10: manufacturing SMEs located in Sheffield

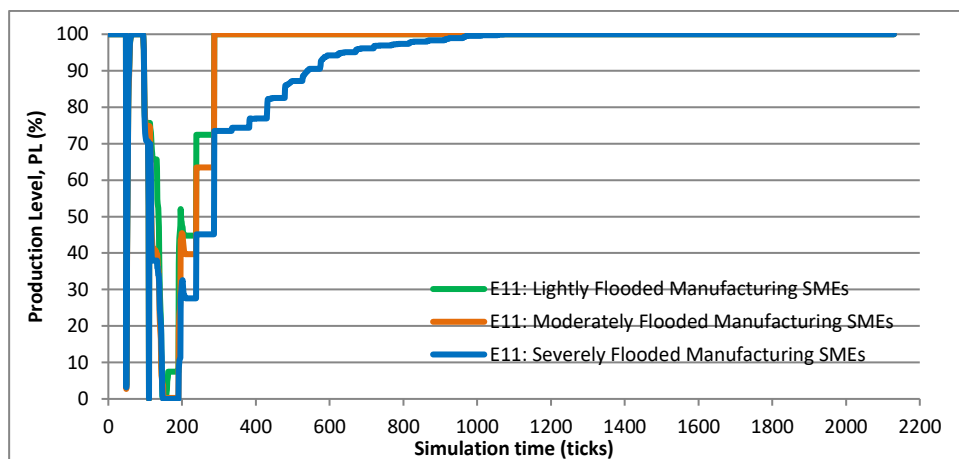


Figure E.16: Simulation experiment E11: manufacturing SMEs located in Sheffield

E.2 RETAIL SMES LOCATED IN SHEFFIELD GEOGRAPHICAL AREA

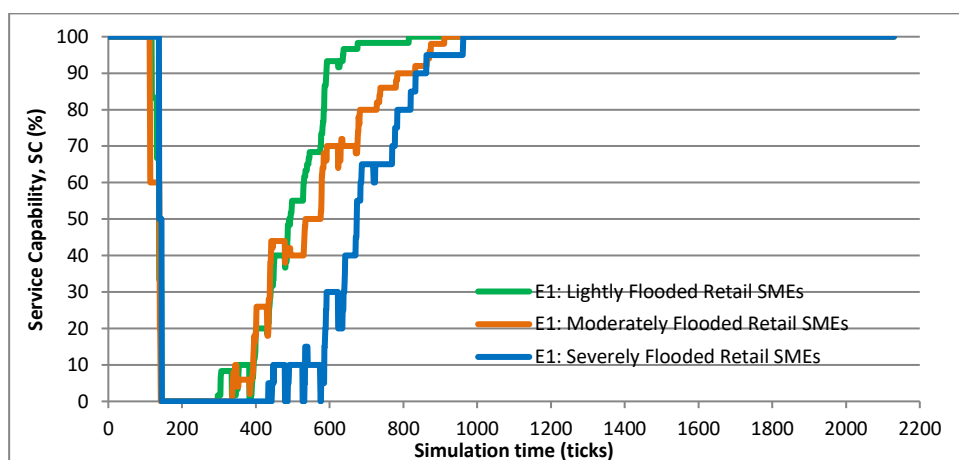


Figure E.17: Simulation experiment E1: retail SMEs located in Sheffield

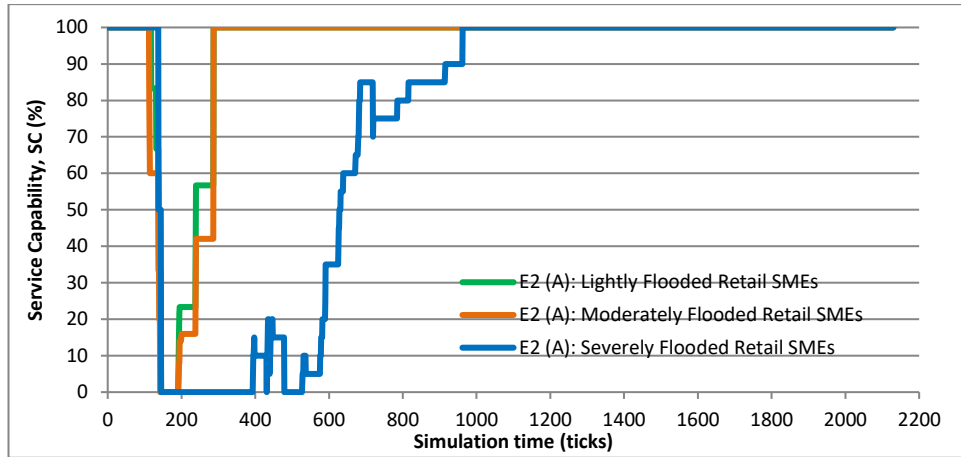


Figure E.18: Simulation experiment E2 (A): retail SMEs located in Sheffield

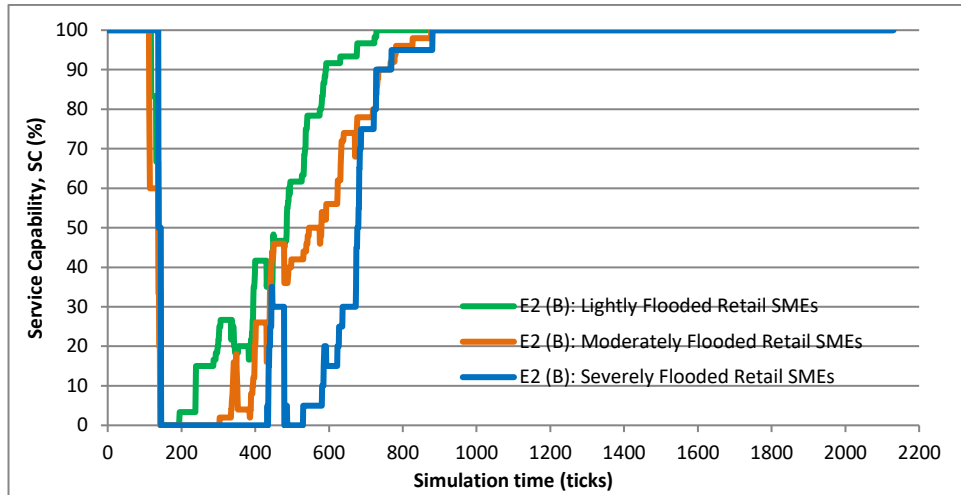


Figure E.19: Simulation experiment E2 (B): retail SMEs located in Sheffield

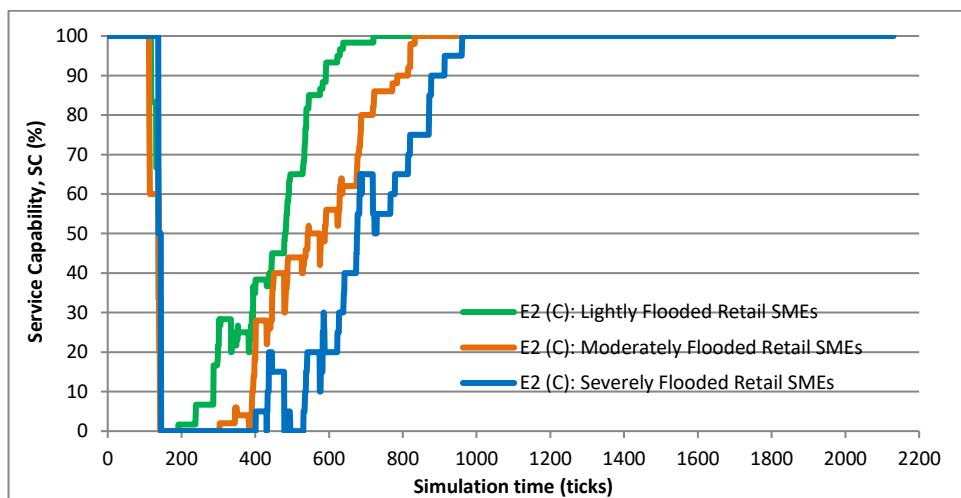


Figure E.20: Simulation experiment E2 (C): retail SMEs located in Sheffield

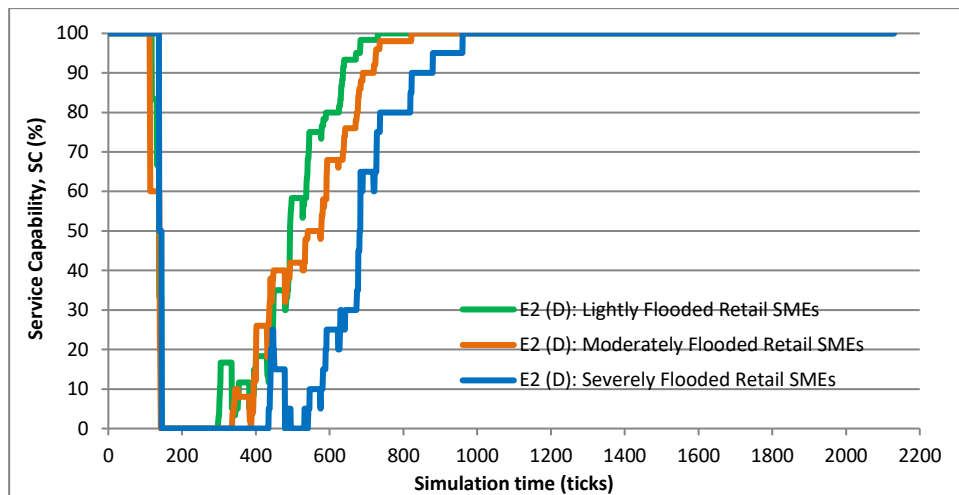


Figure E.21: Simulation experiment E2 (D): retail SMEs located in Sheffield

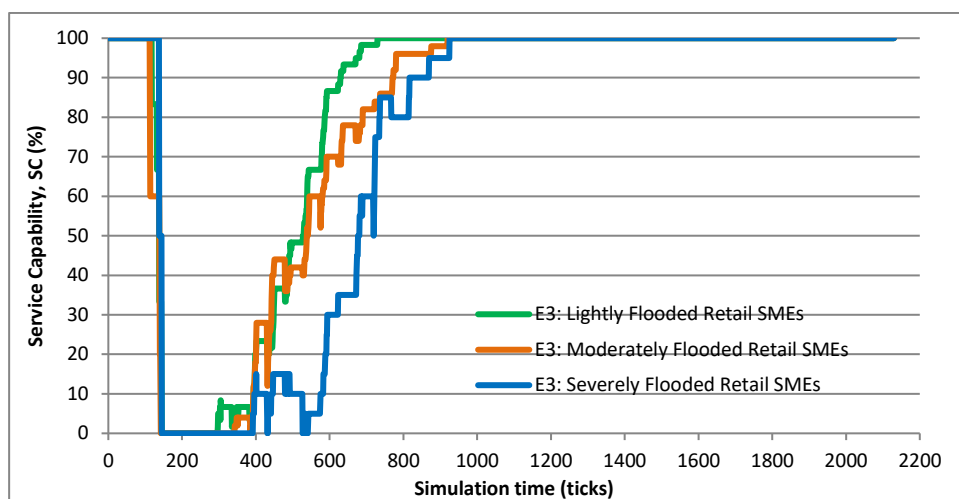


Figure E.22: Simulation experiment E3: retail SMEs located in Sheffield

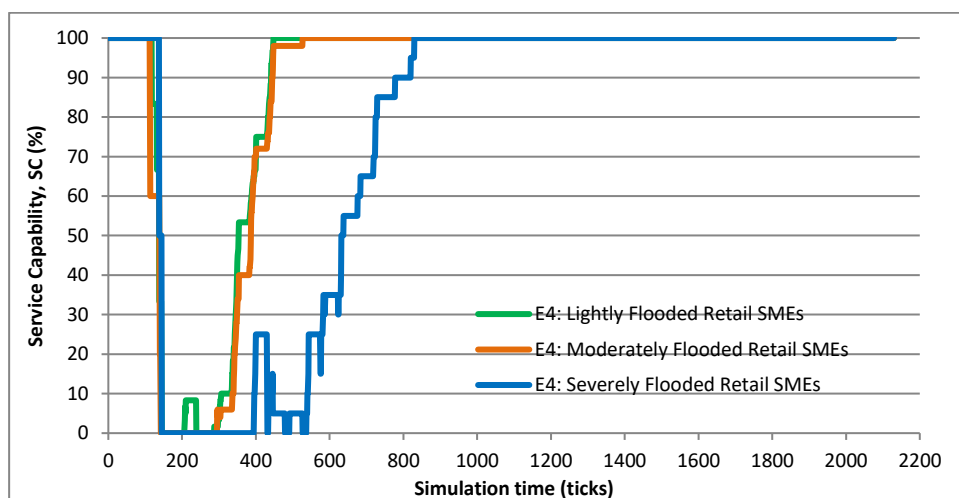


Figure E.23: Simulation experiment E4: retail SMEs located in Sheffield

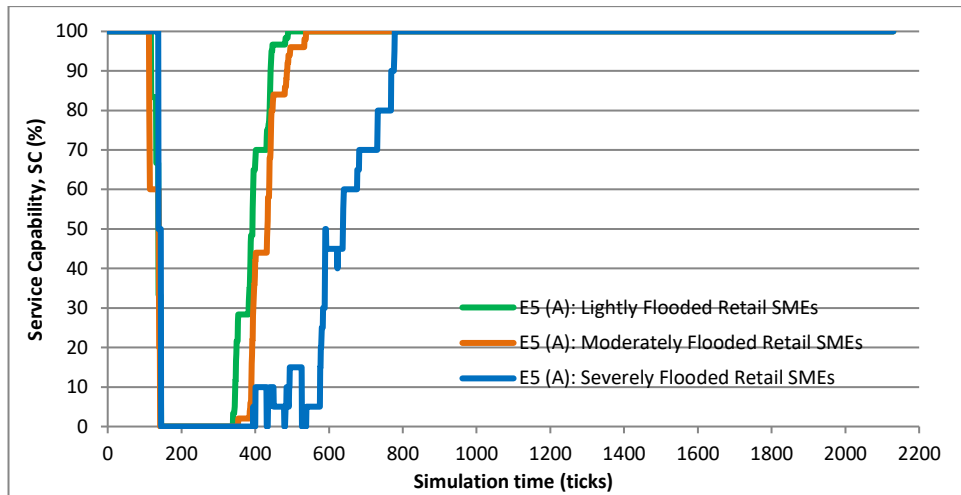


Figure E.24: Simulation experiment E5 (A): retail SMEs located in Sheffield

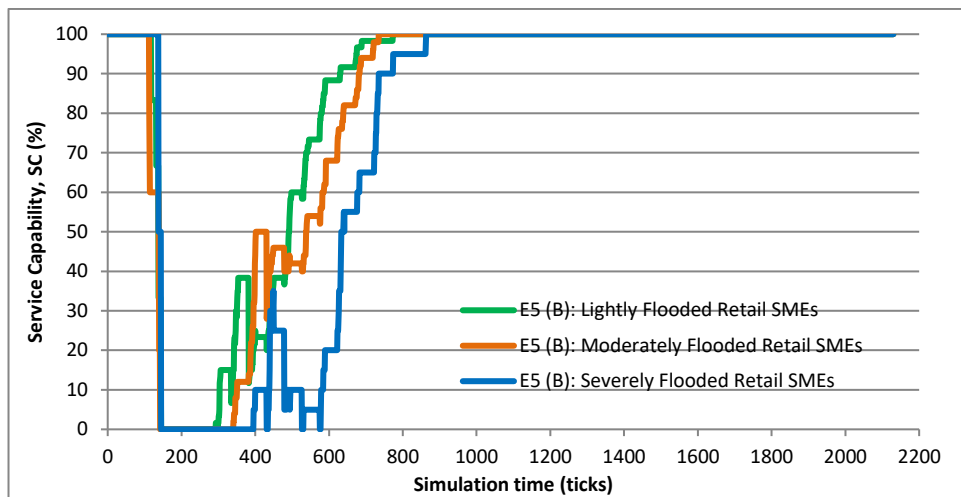


Figure E.25: Simulation experiment E5 (B): retail SMEs located in Sheffield

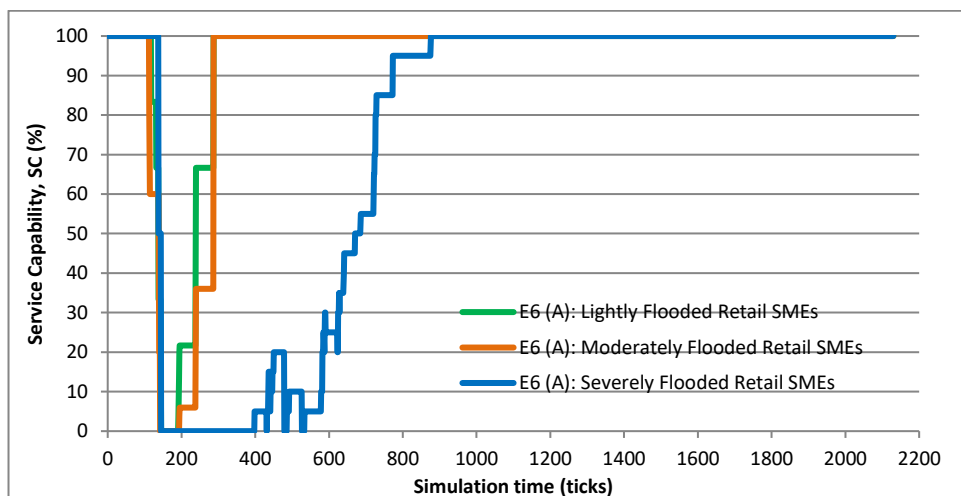


Figure E.26: Simulation experiment E6 (A): retail SMEs located in Sheffield

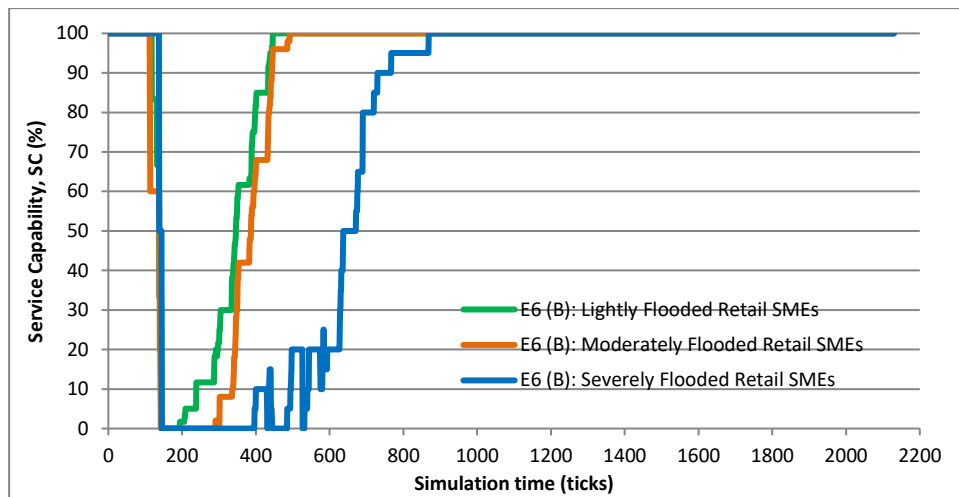


Figure E.27: Simulation experiment E6 (B): retail SMEs located in Sheffield

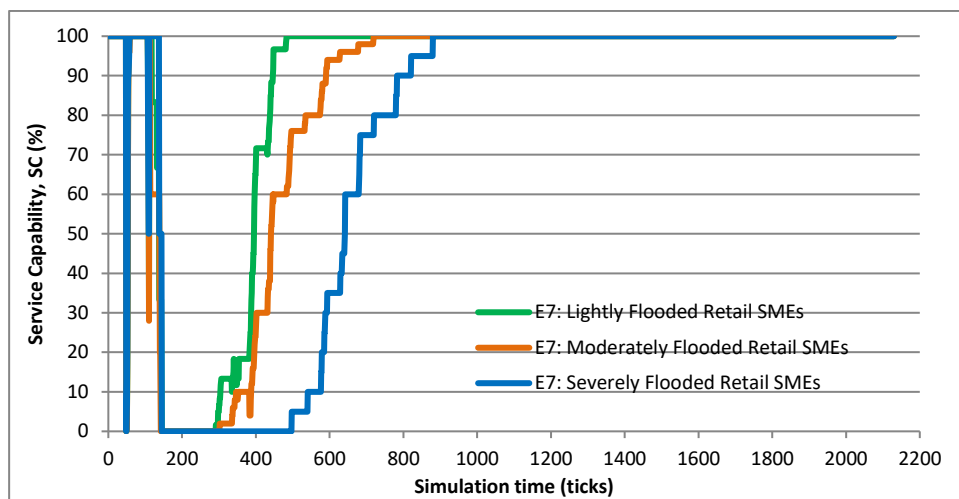


Figure E.28: Simulation experiment E7: retail SMEs located in Sheffield

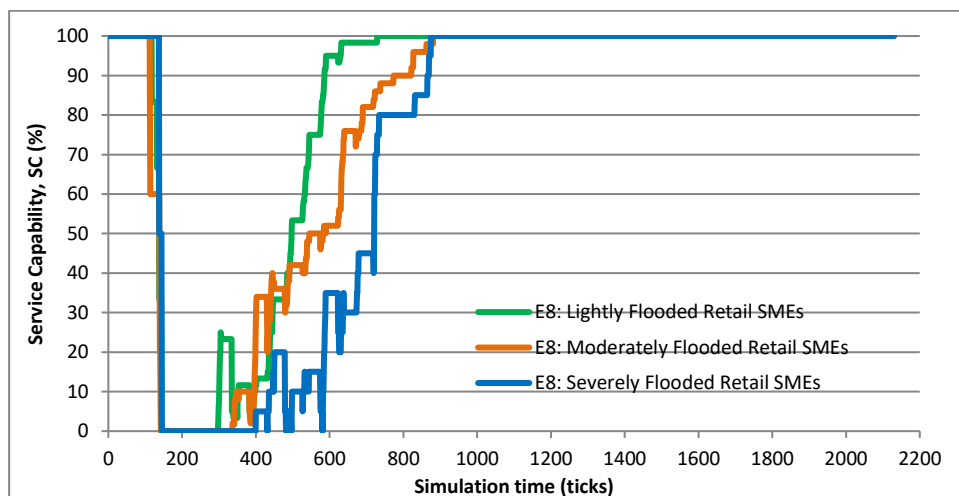


Figure E.29: Simulation experiment E8: retail SMEs located in Sheffield

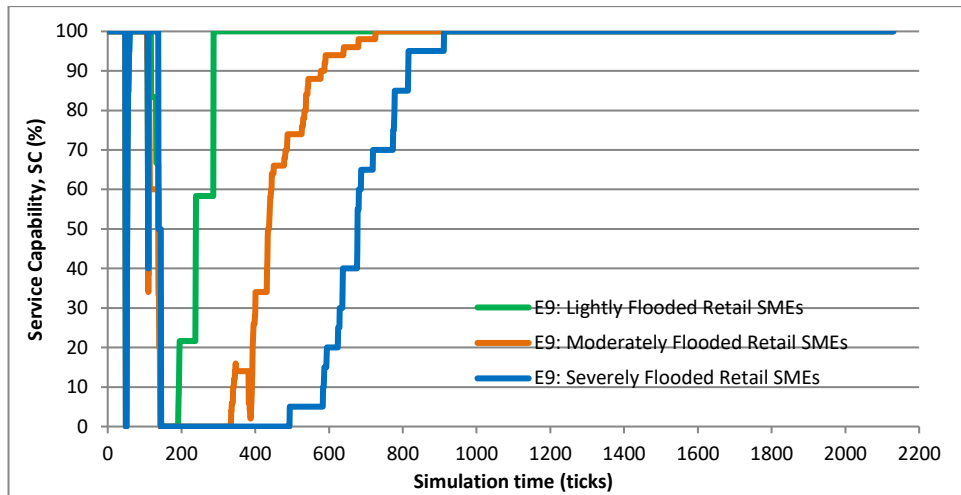


Figure E.30: Simulation experiment E9: retail SMEs located in Sheffield

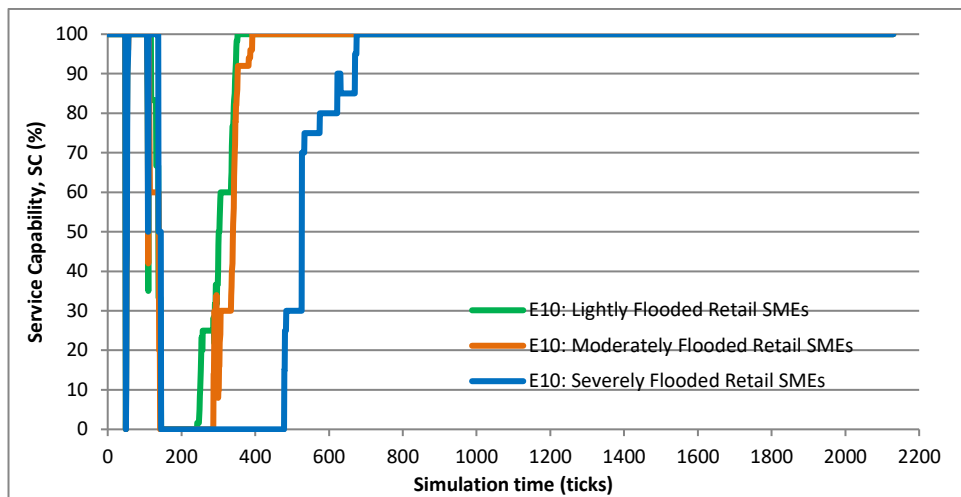


Figure E.31: Simulation experiment E10: retail SMEs located in Sheffield

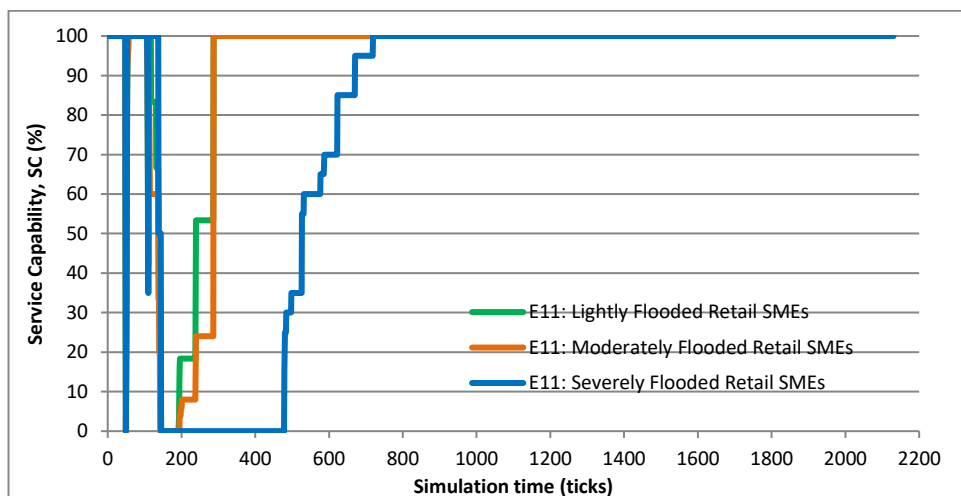


Figure E.32: Simulation experiment E11: retail SMEs located in Sheffield

E.3 SME-RELATED ORGANISATIONS

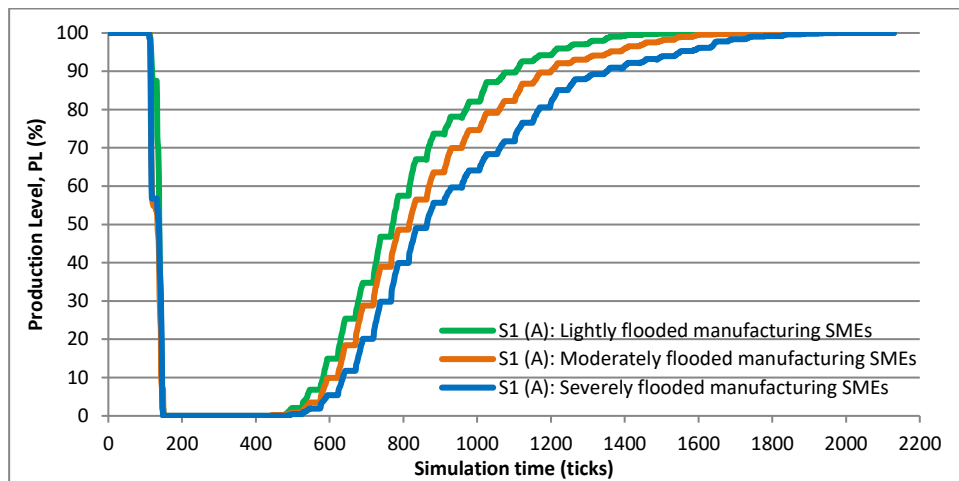


Figure E.33: Simulation experiment S1 (A): manufacturing SMEs with basic insurance and without funds available

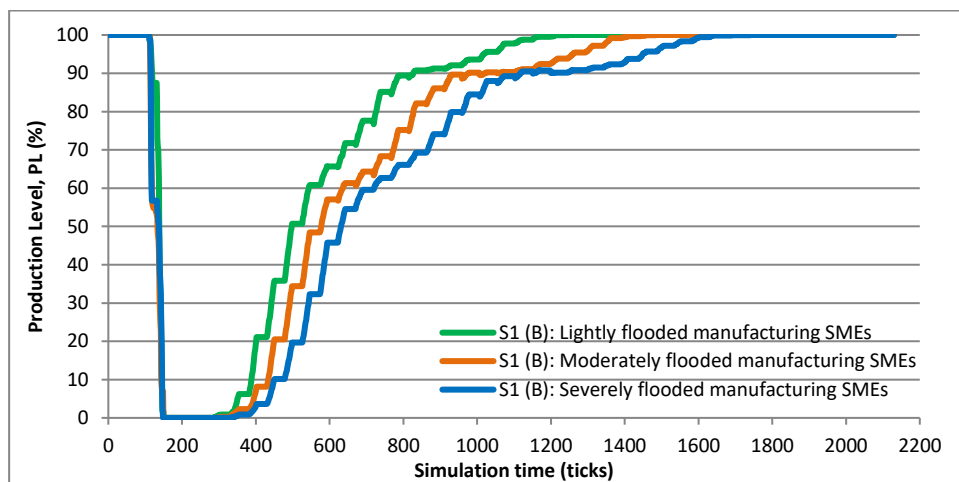


Figure E.34: Simulation experiment S1 (B): manufacturing SMEs with comprehensive insurance and funds available and choosing to allocate cleaning service provided by the insurance company to clean-up their premises

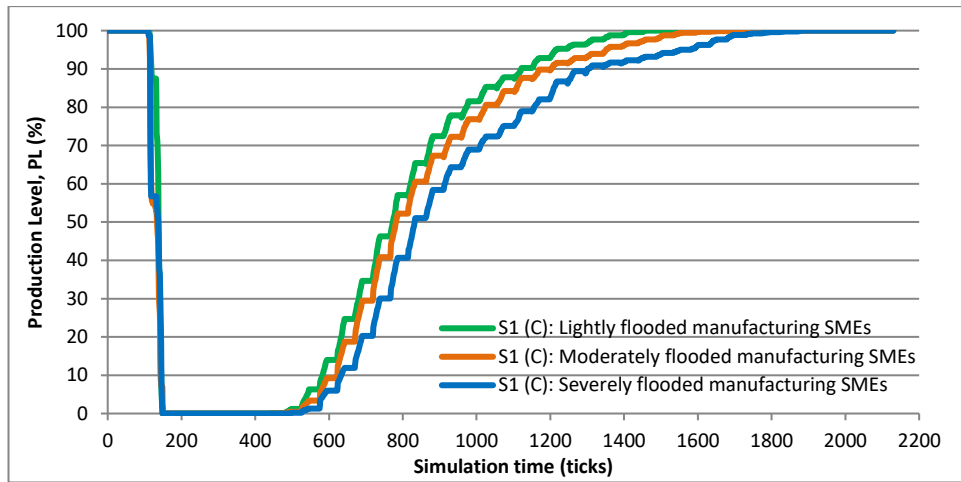


Figure E.35: Simulation experiment S1 (C): manufacturing SMEs with comprehensive insurance and funds available, but choose to allocate their own employees to clean-up

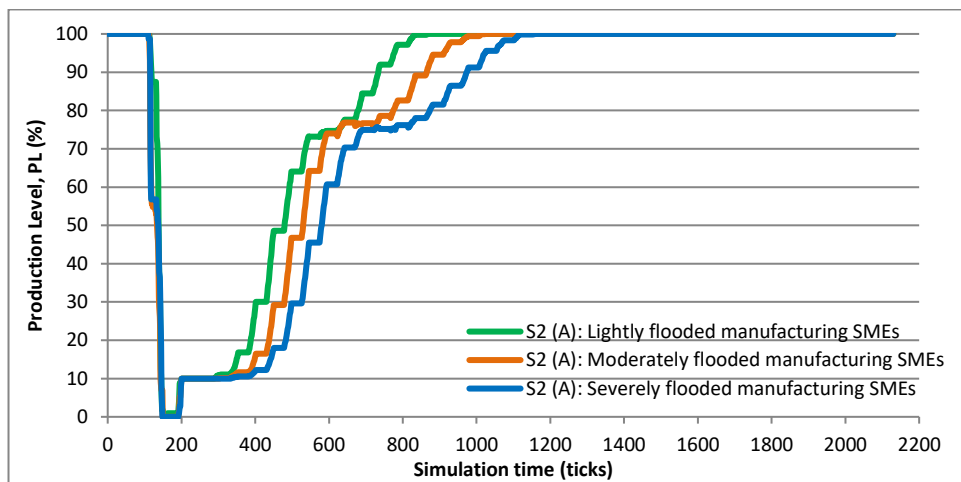


Figure E.36: Simulation experiment S2 (A): manufacturing SMEs with a pre-defined mutual aid partner

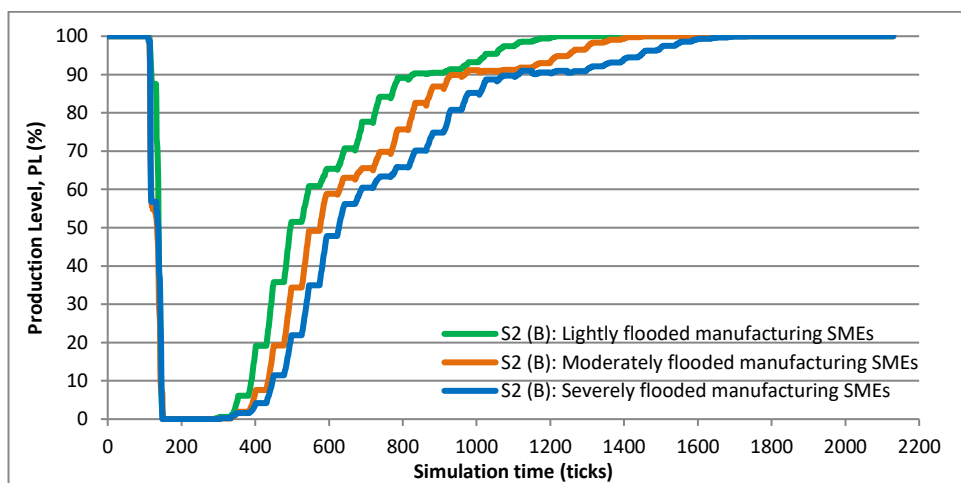


Figure E.37: Simulation experiment S2 (B): manufacturing SMEs without a pre-defined mutual aid partner

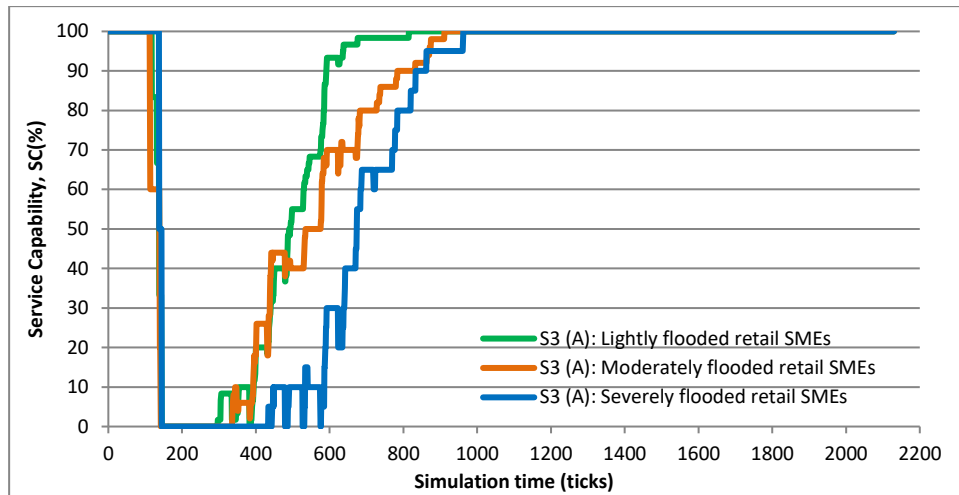


Figure E.38: Simulation experiment S3 (A): retail SMEs employed companies specializing in refurbishment premises

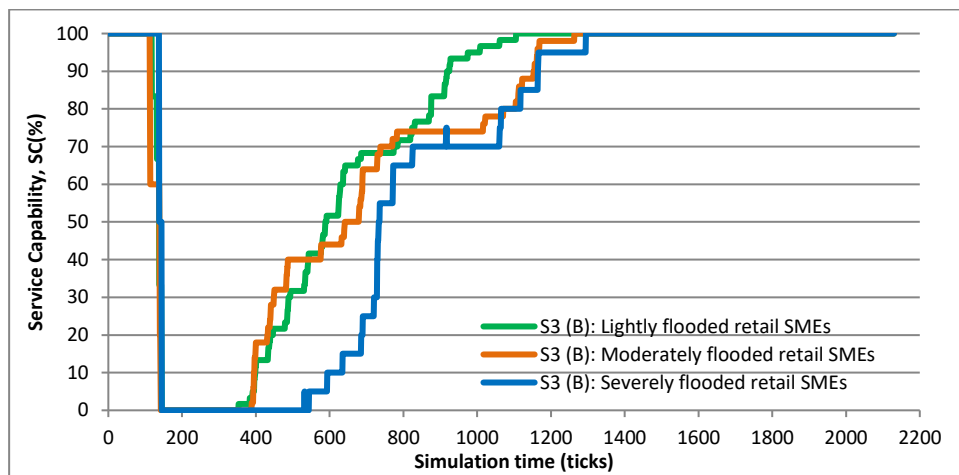


Figure E.39: Simulation experiment S3 (B): retail SMEs choose to allocate their own employees to refurbish their premises

E.4 MANUFACTURING SMES LOCATED IN TEWKESBURY GEOGRAPHICAL AREA

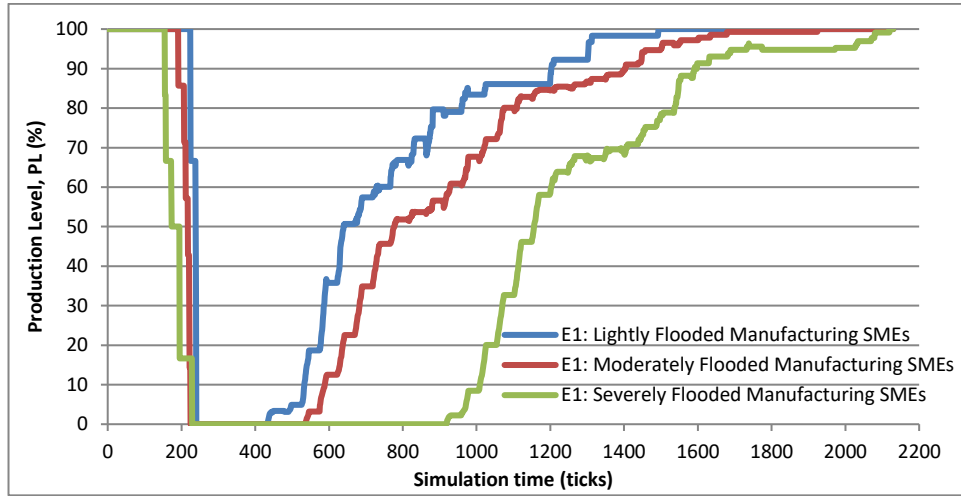


Figure E.40: Simulation experiment E1: manufacturing SMEs located in Tewkesbury

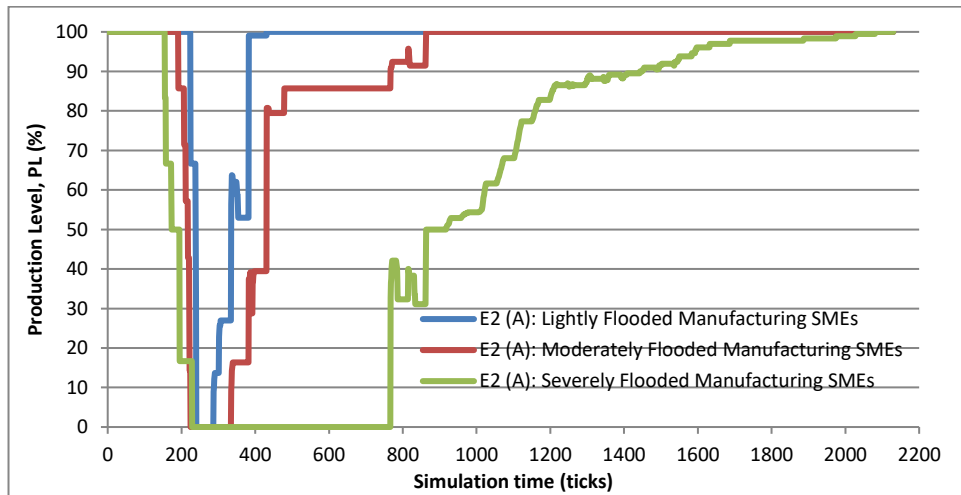


Figure E.41: Simulation experiment E2 (A): manufacturing SMEs located in Tewkesbury

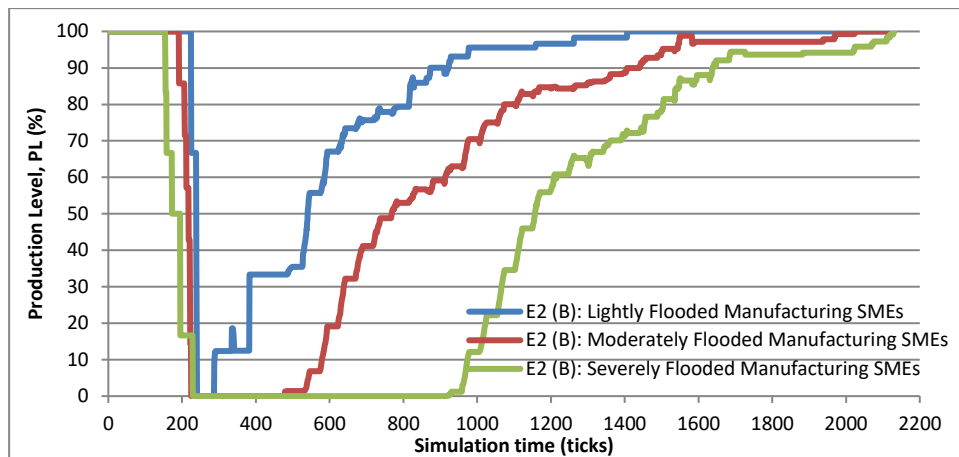


Figure E.42: Simulation experiment E2 (B): manufacturing SMEs located in Tewkesbury

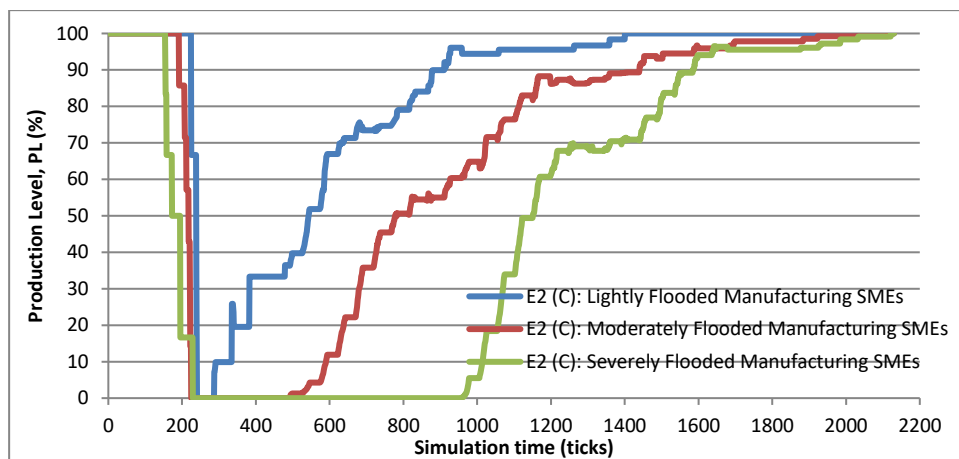


Figure E.43: Simulation experiment E2 (C): manufacturing SMEs located in Tewkesbury

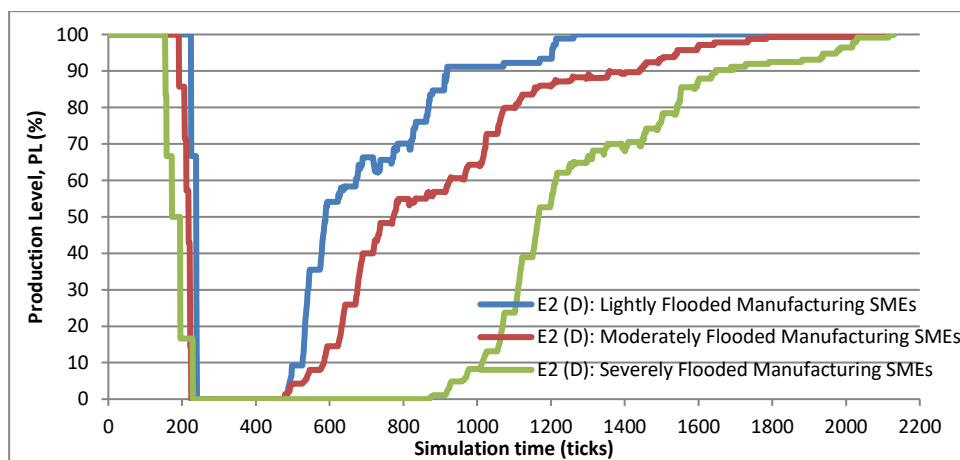


Figure E.44: Simulation experiment E2 (D): manufacturing SMEs located in Tewkesbury

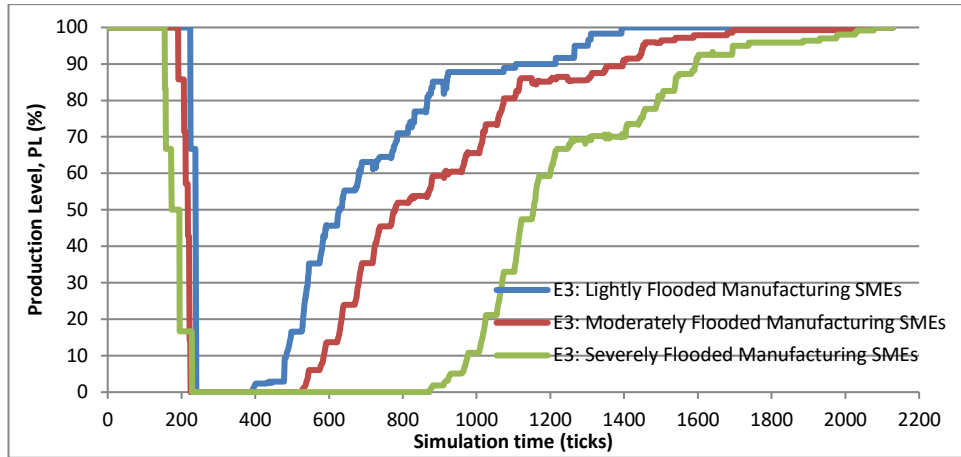


Figure E.45: Simulation experiment E3: manufacturing SMEs located in Tewkesbury

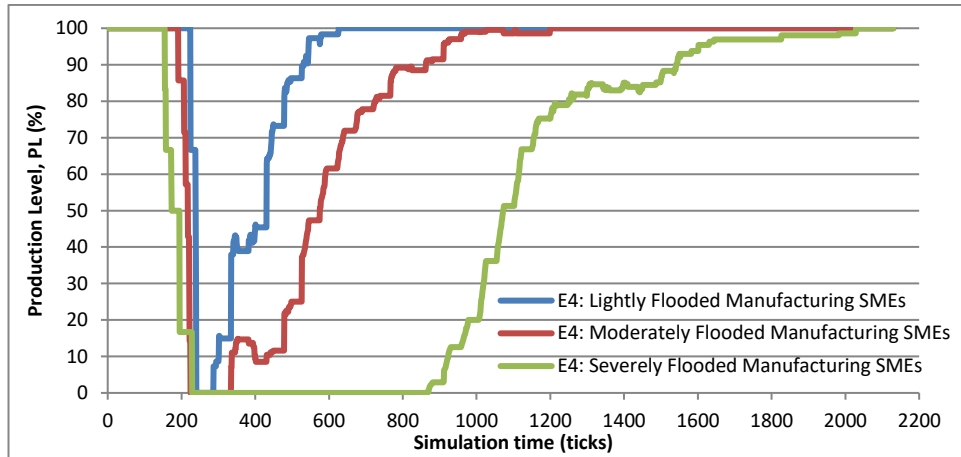


Figure E.46: Simulation experiment E4: manufacturing SMEs located in Tewkesbury

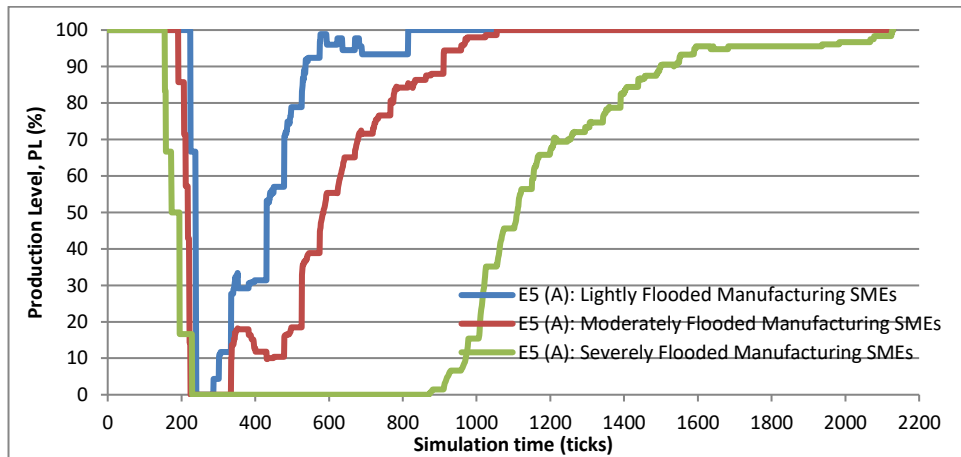


Figure E.47: Simulation experiment E5 (A): manufacturing SMEs located in Tewkesbury

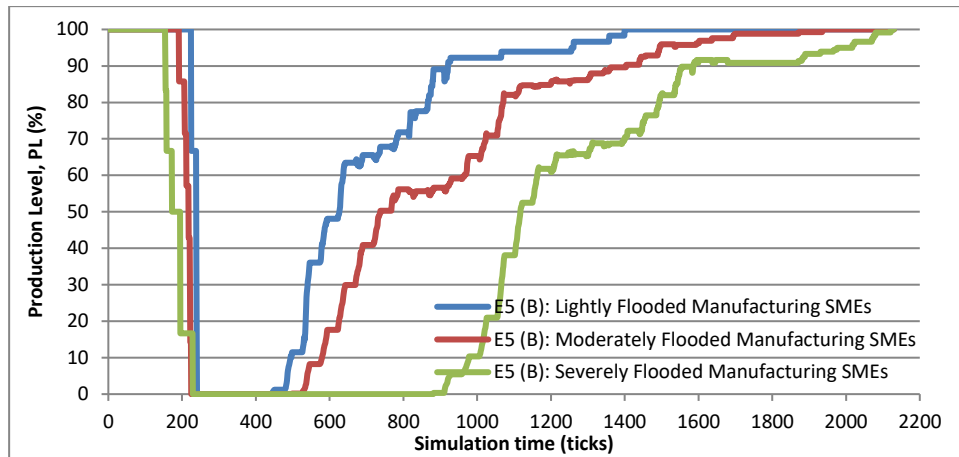


Figure E.48: Simulation experiment E5 (B): manufacturing SMEs located in Tewkesbury

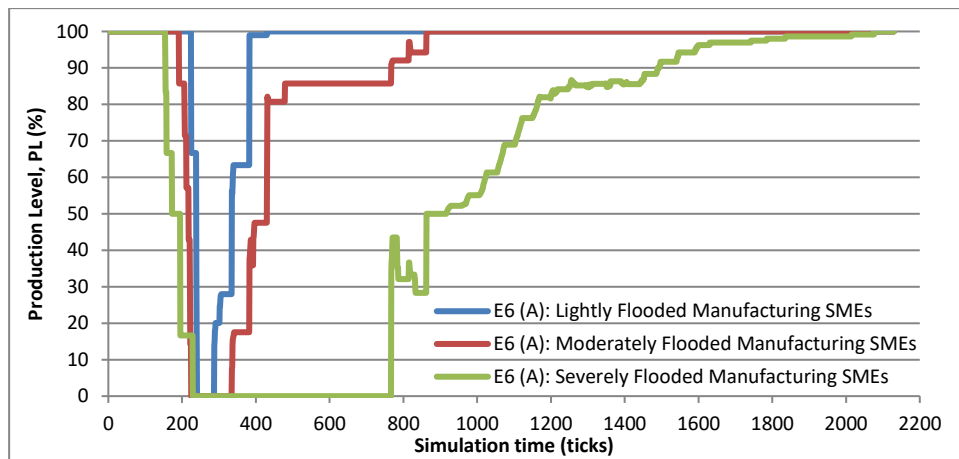


Figure E.49: Simulation experiment E6 (A): manufacturing SMEs located in Tewkesbury

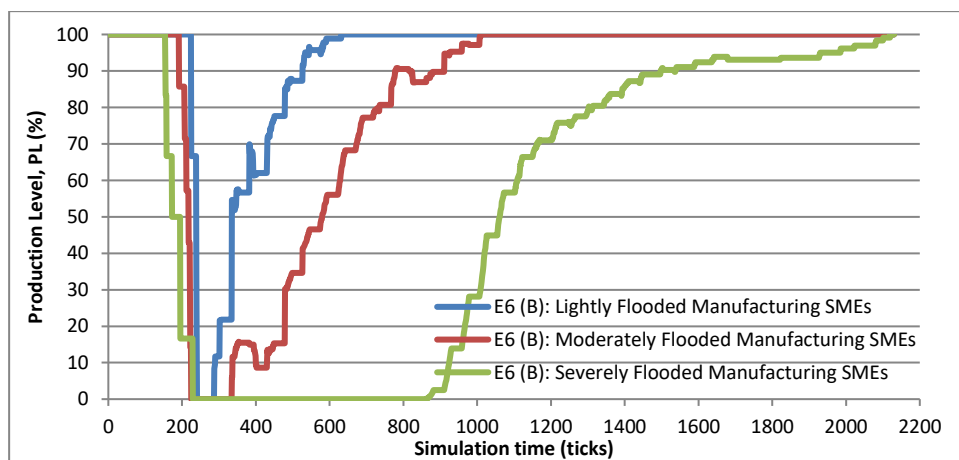


Figure E.50: Simulation experiment E6 (B): manufacturing SMEs located in Tewkesbury

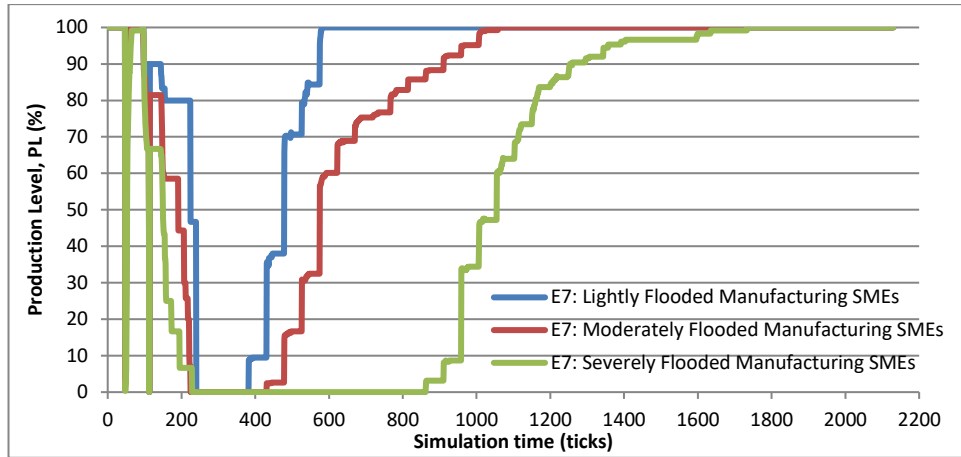


Figure E.51: Simulation experiment E7: manufacturing SMEs located in Tewkesbury

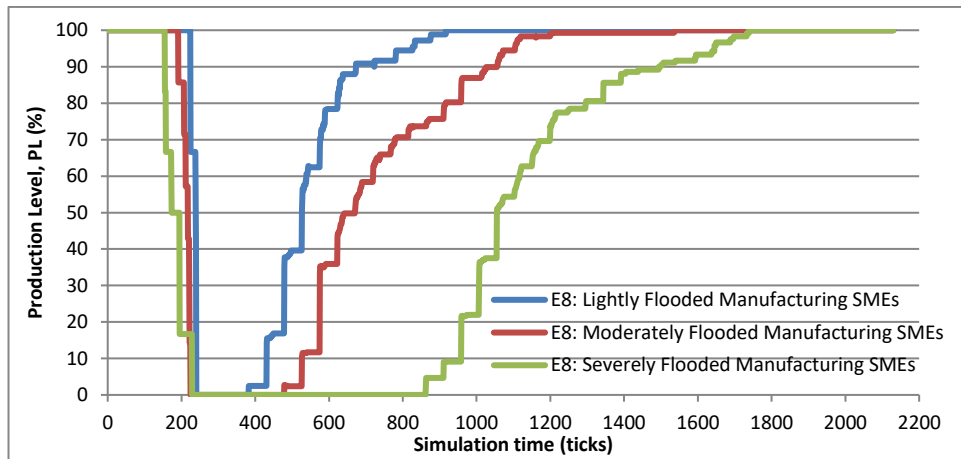


Figure E.52: Simulation experiment E8: manufacturing SMEs located in Tewkesbury

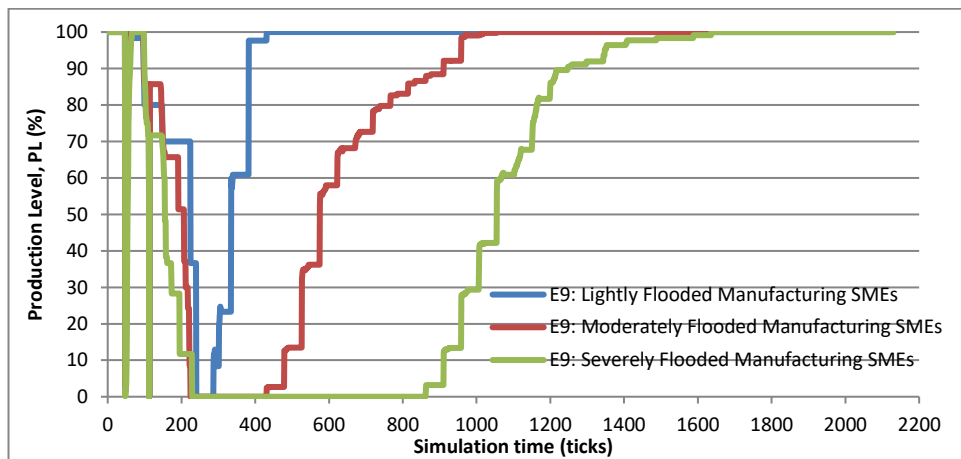


Figure E.53: Simulation experiment E9: manufacturing SMEs located in Tewkesbury

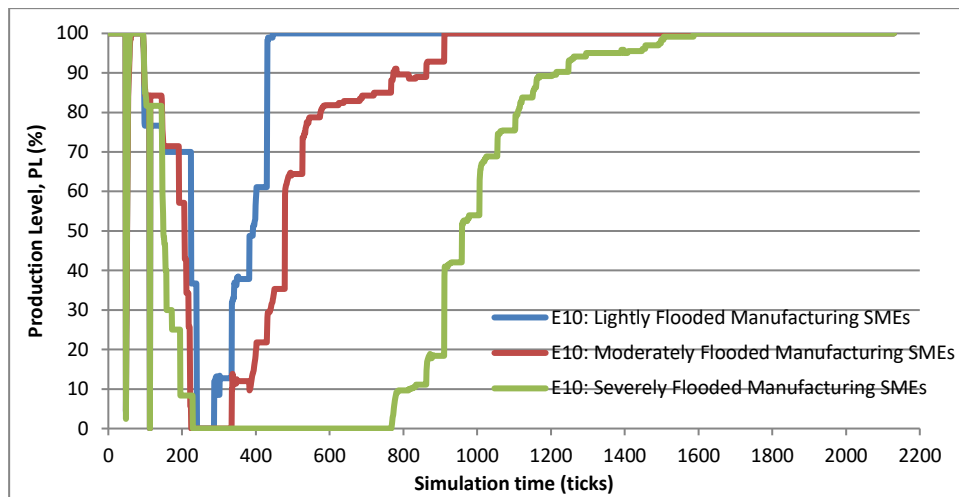


Figure E.54: Simulation experiment E10: manufacturing SMEs located in Tewkesbury

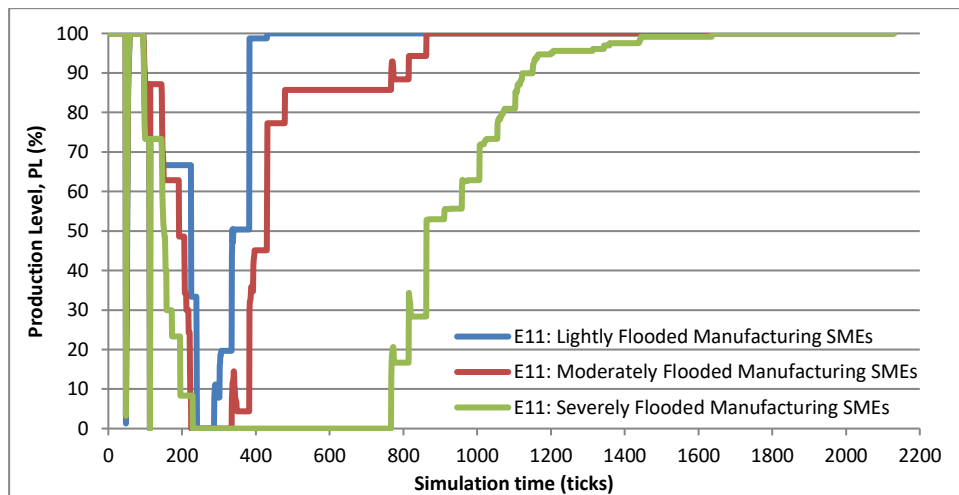


Figure E.55: Simulation experiment E11: manufacturing SMEs located in Tewkesbury

E.5 RETAIL SMES LOCATED IN TEWKESBURY
GEOGRAPHICAL AREA

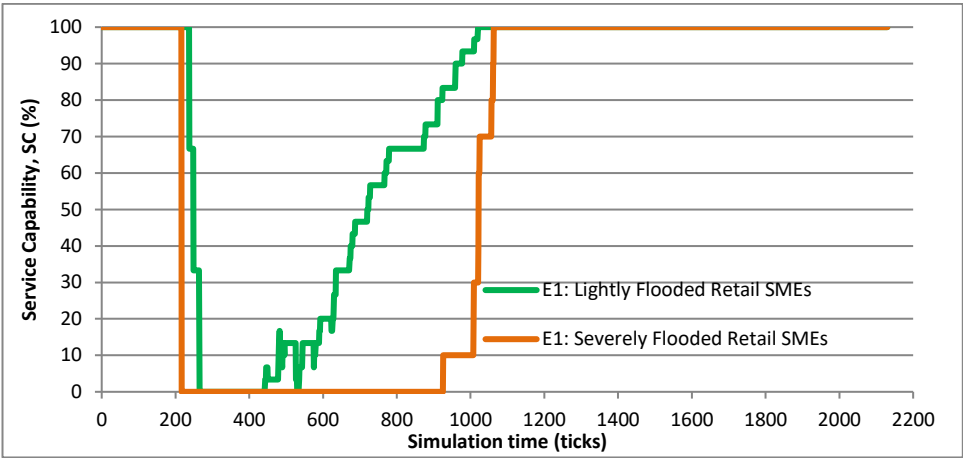


Figure E.56: Simulation experiment E1: retail SMEs located in Tewkesbury

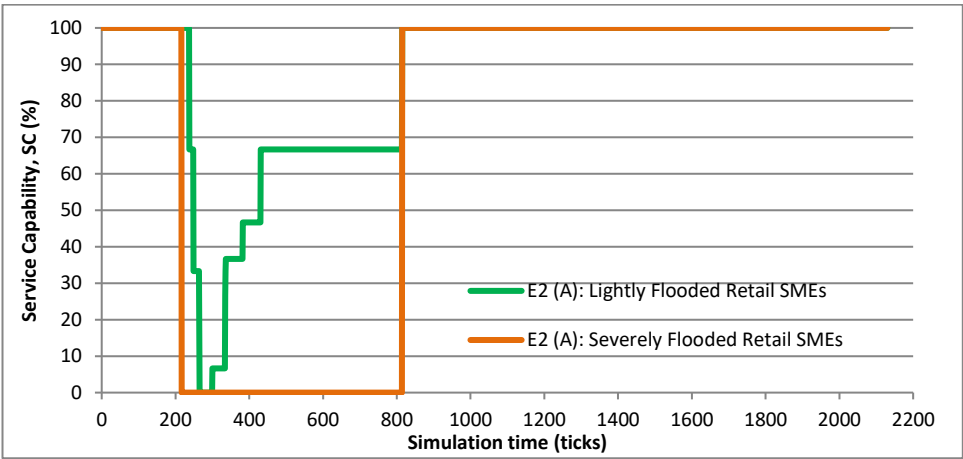


Figure E.57: Simulation experiment E2 (A): retail SMEs located in Tewkesbury

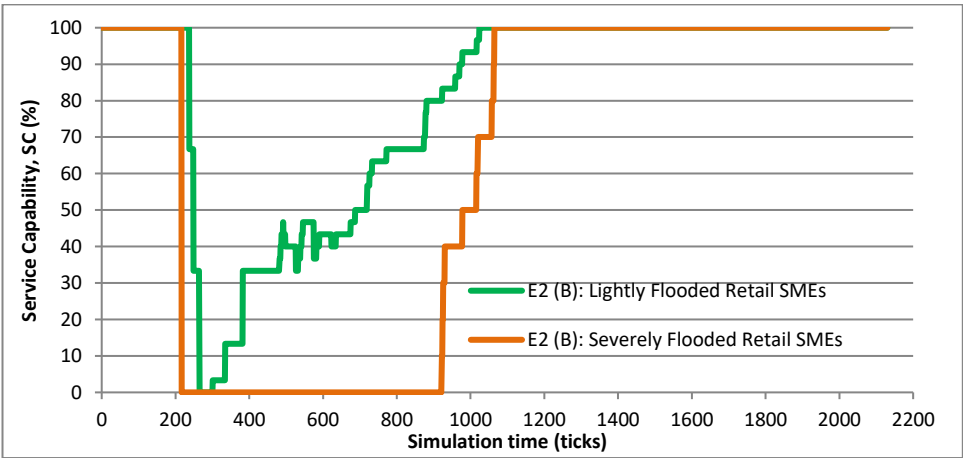


Figure E.58: Simulation experiment E2 (B): retail SMEs located in Tewkesbury

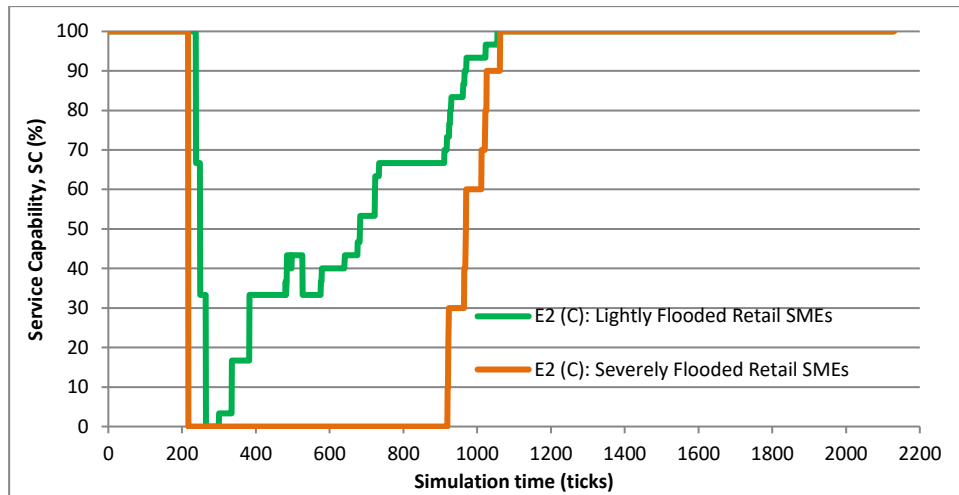


Figure E.59: Simulation experiment E2 (C): retail SMEs located in Tewkesbury

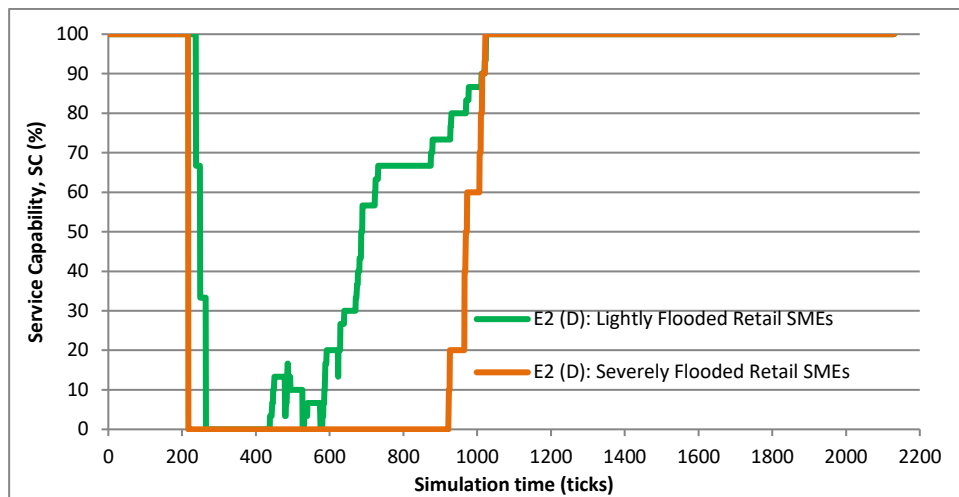


Figure E.60: Simulation experiment E2 (D): retail SMEs located in Tewkesbury

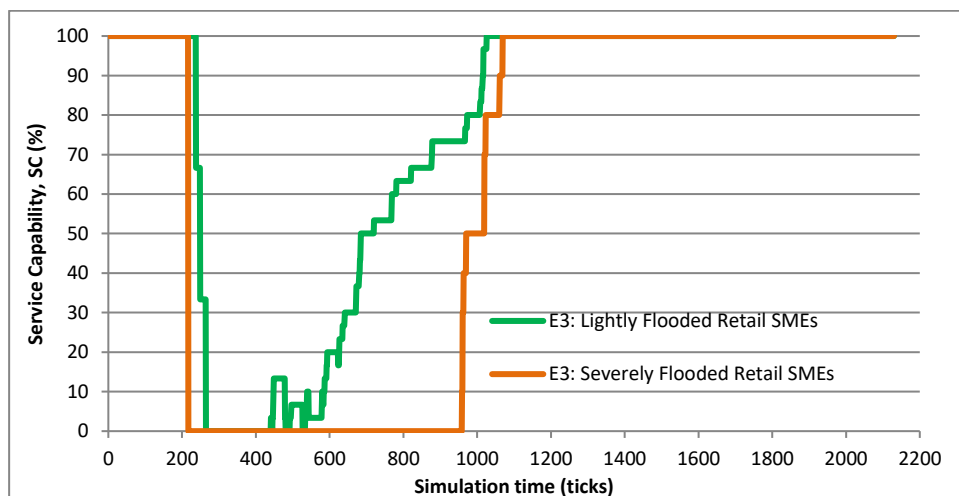


Figure E.61: Simulation experiment E3: retail SMEs located in Tewkesbury

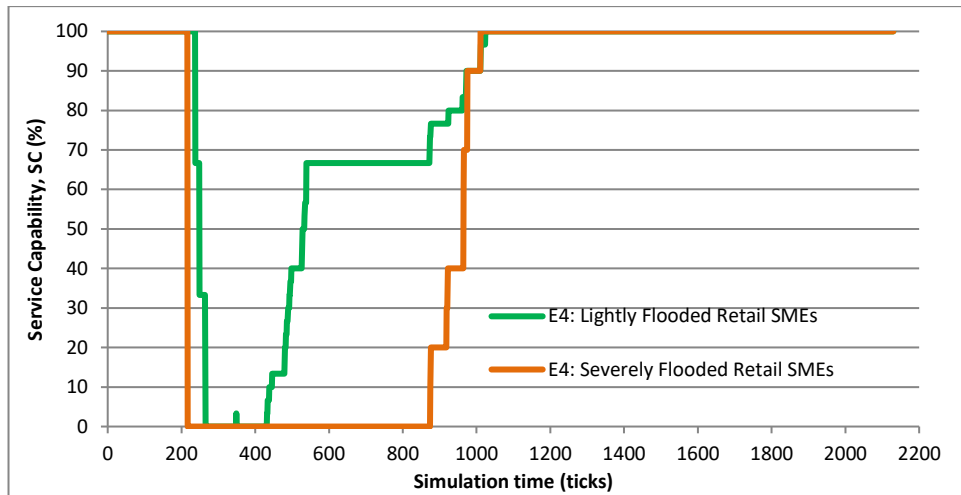


Figure E.62: Simulation experiment E4: retail SMEs located in Tewkesbury

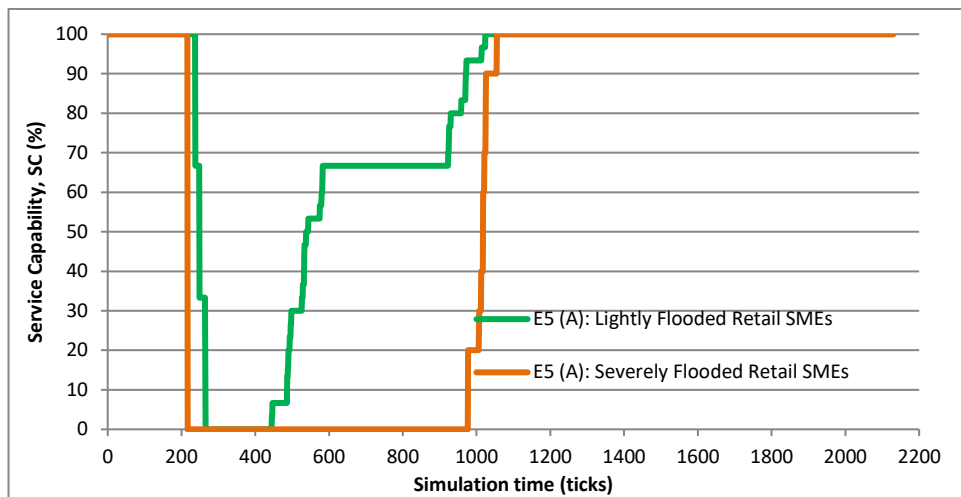


Figure E.63: Simulation experiment E5 (A): retail SMEs located in Tewkesbury

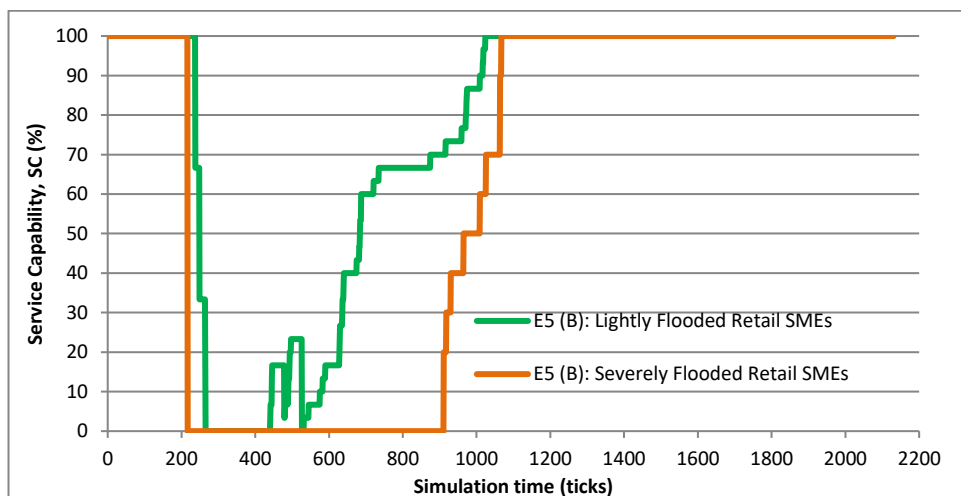


Figure E.64: Simulation experiment E5 (B): retail SMEs located in Tewkesbury

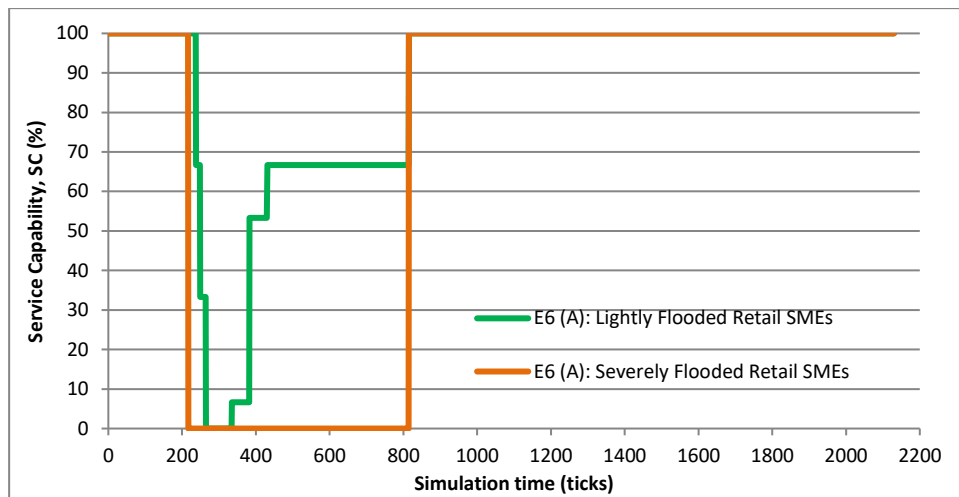


Figure E.65: Simulation experiment E6 (A): retail SMEs located in Tewkesbury

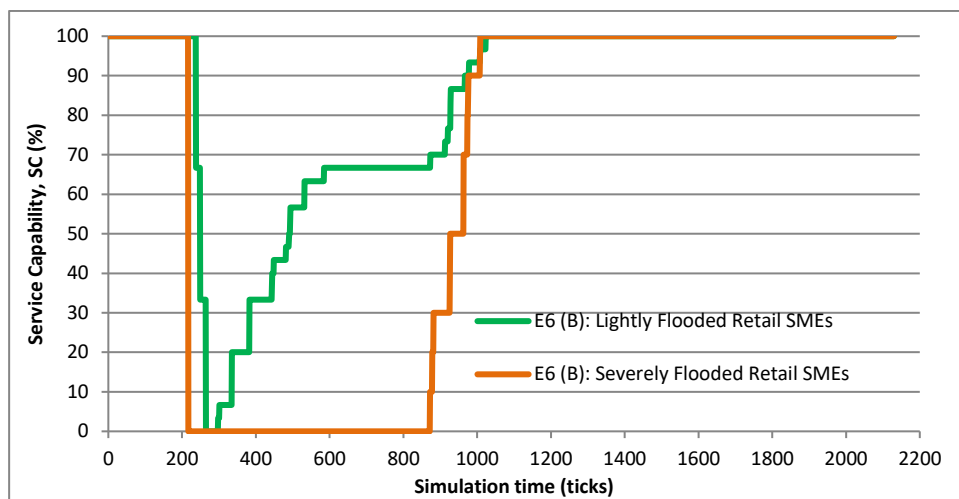


Figure E.66: Simulation experiment E6 (B): retail SMEs located in Tewkesbury

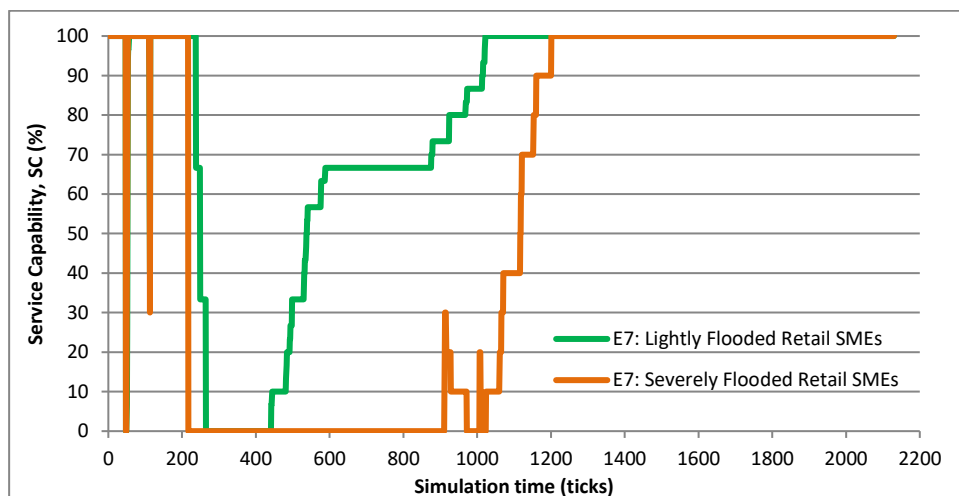


Figure E.67: Simulation experiment E7: retail SMEs located in Tewkesbury

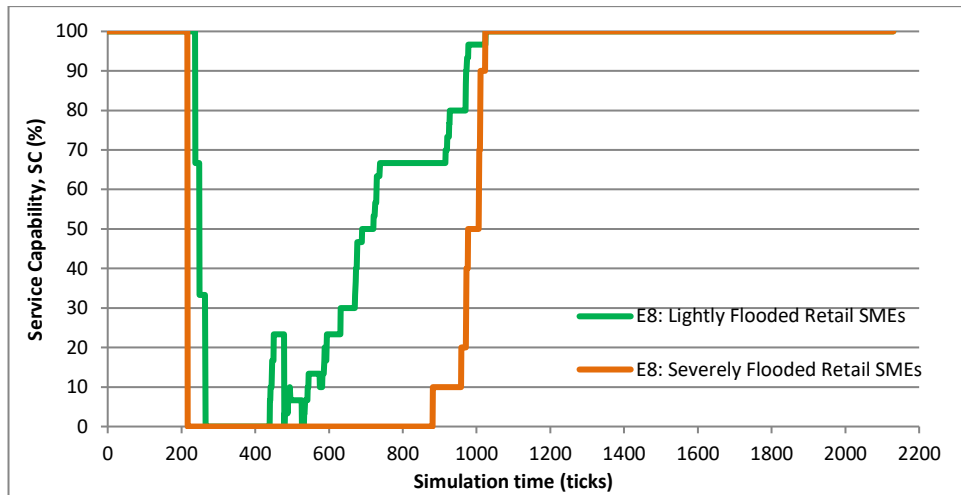


Figure E.68: Simulation experiment E8: retail SMEs located in Tewkesbury

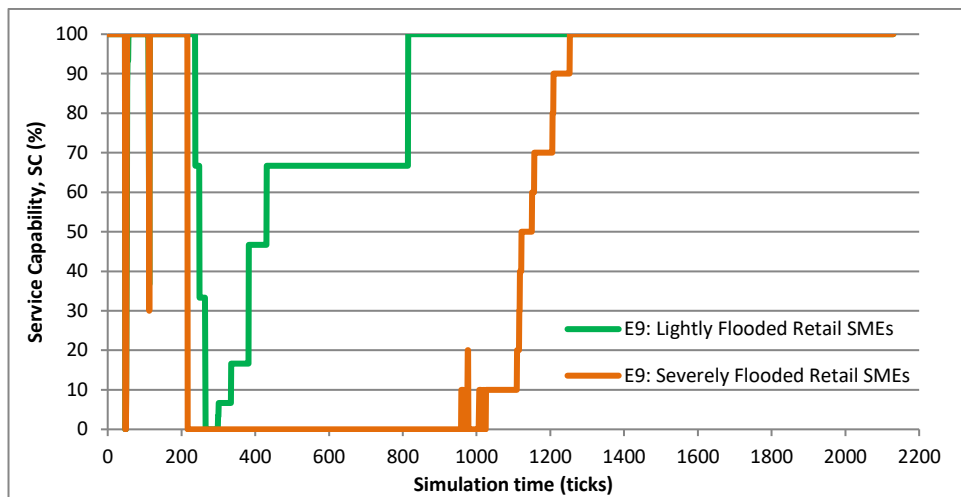


Figure E.69: Simulation experiment E9: retail SMEs located in Tewkesbury

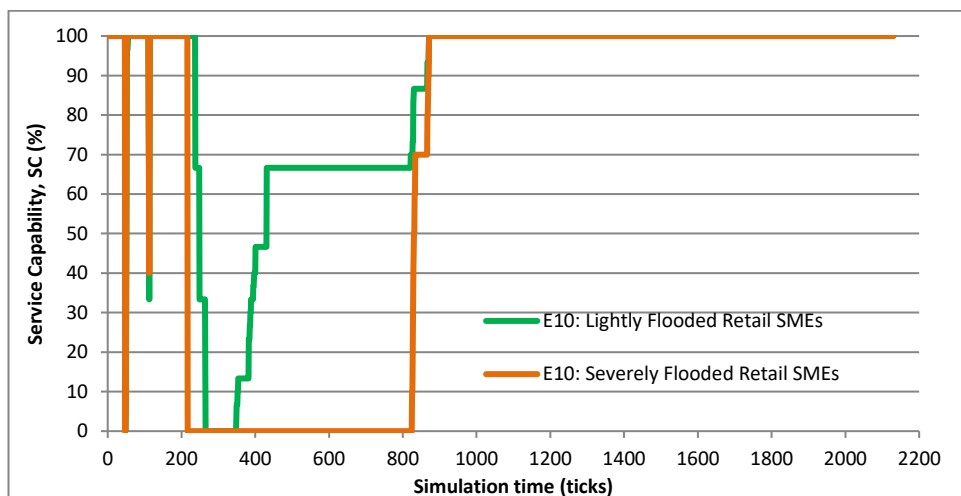


Figure E.70: Simulation experiment E10: retail SMEs located in Tewkesbury

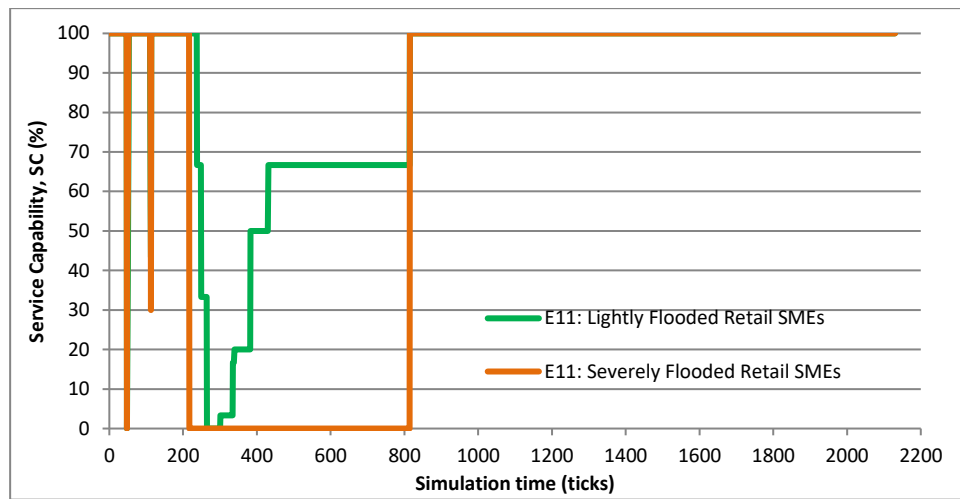


Figure E.71: Simulation experiment E11: retail SMEs located in Tewkesbury