Modeling to Support Acceleration of Restoration of a Residential Building System in Southeastern B.C. due to Riverine Flooding

by

Afia Siddika Ivy
B.Sc., Military Institute of Science and Technology, 2017

A Thesis Submitted in Partial Fulfillment
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Abstract

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Floods are among some of the most damaging natural disasters. They can cause major interruptions to buildings and infrastructure and can have lasting impacts. In the case of flood damage estimation to buildings, structural and non-structural damages are of interest to most flood risk research. Very few studies, conversely analyze the impact of the recovery timeline on losses. Doing so requires consideration of specific types of building, and what the parts of the building depend upon for restoration.

There is a challenge to clearly understand the cause of failures within an interconnected system such as a building, and the requirements for accelerating restoration to overcome the adverse results of flood in the most convenient way possible.

This work seeks to map the various components involved in functional failures of flood damaged buildings to understand their recovery. A novel model of a residential building is constructed using the Graph Model for Operational Resilience (GMOR) to model the complex interaction among dependencies in building systems to understand the cascade of failure of restoration. This is enabled by integrating models of operational and restoration dependencies with hazard damage relationships and repair times to assess where functions fail and how and when they are restored.

A case study is performed to generate recovery model to simulate the restoration of a single residential building in a flood prone neighborhood of Surrey, BC, Canada. It involves synthesis of available data on residential building’s component level dependencies and depth-damage functions to estimate damage. The depth-damage functions, along with construction and repair guides, are used to identify restoration dependencies and to formulate a unique sequence of flood recovery steps for several possible flood depths.

This study demonstrates how restoration can be delayed and probable solutions to improve the resilience of the city through recovery planning of flooded buildings. The results provide insights that should be useful to help emergency managers and other decision makers to develop and implement resilience thinking while revealing the economic benefits associated with increased flood risk management. In future, the custom flood model can be adapted to other locations.

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Chapter 1: Introduction

Among the most frequent natural hazards that occur in Canada, extreme flooding is the single most damaging in terms of economic and social losses since the commencement of the twentieth century (Nastev and Todorov, 2013). Furthermore, floods continue to hold the number one position among the most frequent and costliest type of natural hazard event around the globe (Deniz et al., 2017). Flooding often leads to inundation of large numbers of buildings. Recovery of flooded building is a complex process (Kammouh and Cimellaro, 2017). It requires a number of expert workers with specific knowledge for dealing with flood damaged properties to work together. In addition, an inaccurate recovery plan can prolong the recovery process, increasing secondary water damage.

This work deals with building recovery after a long-term riverine flood (2 - 3 days) hazard. Recovery modeling is performed for a representative building in the Bridgeview area of Surrey, BC. This area lies within the floodplain of Fraser River, one of the major rivers in Canada. It is prone to flooding that results in massive damage to lives and property almost every year (Northwest Hydraulic Consultant Ltd., 2015).

The purpose of this research is to increase understanding surrounding building recovery from flooding. Also, a second objective is to increase the accuracy of restoration planning and design. The approach combines a process to simulate the impact of the relationship between the steps of restoration. These relationships create dependencies of two types: activity dependencies (whereby some steps need to precede others) and workforce dependencies (whereby some steps require specific types of specialized labour). The intricacies are captured in a novel model of flood restoration of buildings. A computational recovery assessment engine called the Graph Model for Operational Resilience (GMOR) is used to simulate the recovery model that can assess component-by-component recovery over time. A detailed case study related to a residential building at the functional and component level illustrates recovery time assessments subject to varying Damage States (DS's) caused by flooding.

Shortly, the research provides a computational recovery methodology that accounts for complex dependencies within the recovery process and has the capability to help inform wider risk analyses for disaster risk reduction and may help to optimize the recovery based on workforce availability constraints.

1.2 Objective

The aim of the thesis is to analyze recovery of single detached homes that experience flood damage to determine a strategic solution of bringing back the building systems to their initial functional capacity in the shortest possible time to reduce further losses. The primary objectives consist of developing data inventory related to infrastructure component restorations; establish a simulation method that explicate the complex recovery process; find a technique for optimizing the recovery timeline using GMOR and generate and analyze a community level recovery planning using a geographic information system.

Here, only the post-flood disaster recovery after a long-term riverine flood (2 - 3 days) (Gulf Engineering and Consultants, 1997) is focused on this research. The theme of making infrastructures flood ready before disaster has not been considered within the research scope. The idea of flood ready concept is a recent addition to the disaster management aspect. It is implemented through construction of new buildings maintaining flood management regulations and by flood proofing the existing buildings. However, flood hazard is an inevitable event that occurs within the Canadian regions almost every year along with large amount of uncertainties (i.e., depth, velocity, and debris) associated to these events (T. Lyle, 2017). As a result, planning and designing recovery process of infrastructure systems focusing complete possible damaged states are taken as the research objective.

1.3 Thesis structure

This thesis lays the baseline of a recovery model approach of system recovery at the component level. This approach considers all the logical component restoration inter-dependencies within the recovery process.

Chapter 2 includes background information that gives an overview of flood hazard risk associated with the study area that is southeastern British Columbia; targeted infrastructure information and classification schemes in the context of Canada; flood damage specific to the selected infrastructure and existing literatures related to recovery modeling.

Chapter 3 presents a case study of a single building. Recovery modeling is performed for a representative single family detached residential building in Surrey BC. A description of the background (i.e., case study region and overview of the GMOR computational engine) is provided. Implementation of the recovery methodology appropriate to the case study components are described. That includes: inventory development for component restoration times, complex recovery modeling using GMOR and simulation of recovery pathways for all the potential damage conditions. Result analysis, discussion, conclusion, and recommendations for future recovery planning related to the case study are also illustrated in this chapter.

Finally, Chapter 4 presents the conclusion and recommendations of the future works.

1.3 Author Contributions

The core of this thesis is composed of a chapter that will be submitted as a peer-reviewed manuscript. Below the preliminary author list, title and author contributions are clarified:

Siddika, A., Bristow, D. A flood restoration model of single detached homes in British Columbia, Canada.

- A.S. developed the methodology, performed the analysis and wrote the manuscript.
- D.B. supervised and contributed to methodology, results and revisions in a supervisory fashion.

Chapter 2: Background

2.1 Overview

The present investigation concerns flood hazard impact on building systems and determines the recovery pathway using viable restoration tactics. Necessary background on hazard characteristics, building specifications, damage conditions, building recovery and recovery model development studies are provided.

2.2 Flood hazard and risk analysis

Thousands of Canadian residents have suffered from devastating effects of flooding in the past few years. The trend of flood events is steadily on increase, notably after 1970's. About 287 major flood events from 1900 to 2015 occurred in Canada (Figure 1).

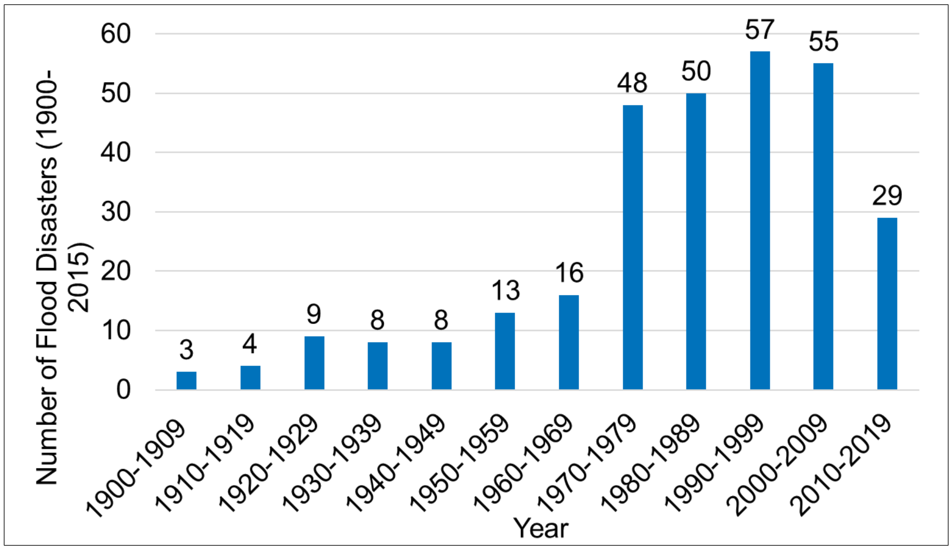


Figure 1 Frequency of flood disasters in Canadian context. (Nastev and Todorov, 2013; T. Lyle, 2017)

Most of these events occurred mainly in four provinces, these are: Ontario (53 events), Quebec (34), New Brunswick (34) and Manitoba (56). Things such as climate change, rapid growth of population, and development in the floodplain can be held responsible for this trend. Moreover, increased precision in flood mapping contributes to a heightened identification of risks in finer resolution (Nastev and Todorov, 2013).

As an example of flood risk in Canada, consider the Fraser River. This river (drainage of 233,000 km^2) is the largest river in British Columbia (BC), Canada, flowing from the Rocky Mountains down to the Pacific Ocean. At Hope the river exits from a confined canyon and flows across the Lower Fraser Valley which is about 180 km from the ocean (Northwest Hydraulic Consultant Ltd., 2016). According to the Fraser Basin Council (2016), the BC Lower Mainland is vulnerable to major, catastrophic floods from the Fraser River. Especially riverine freshet flooding during spring season and coastal flooding during the winter.

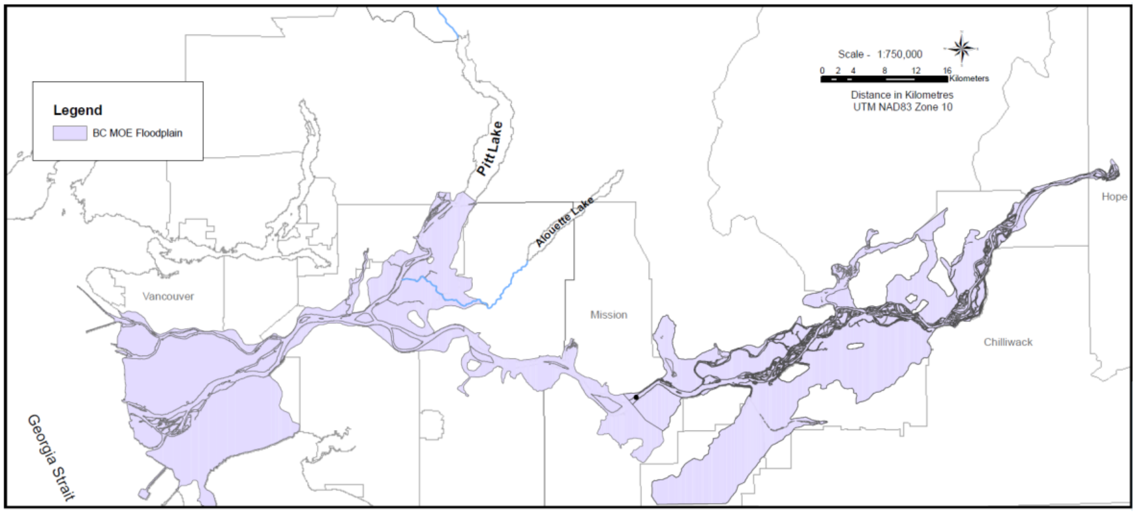


Figure 2 Lower Fraser Valley floodplain (Northwest Hydraulic Consultant Ltd., 2016).

According to Northwest Hydraulic Consultant Ltd., over 300,000 people currently live on the floodplain of the valley. Several major flood events associated with the Fraser River has been recorded ever since flow monitoring commenced. However, the 1948 flood is regarded as the most damaging event. Table 1 below summarises causes and impacts of recent significant flow events in the Fraser River.

Table 1 Fraser river flood history (AECOM Canada Ltd., 2015)

Year	Peak level (m)	Cause and impact
1894	7.9 m at Mission, BC	• The lower Fraser Valley was sparsely populated, and the impact were limited • Level adopted as the 200 ye flood plain level
1948	7.6 m at Mission	• Breached diking systems • Evacuation of 16,000 people • Damage to or complete destruction of 2300 homes • 1500 residents left homeless • 150 million-dollar (2007) flood recovery cost
1972	7.1 m at Hope	• Caused by a frontal rainstorm • 10 million-dollar (1972) damage, predominantly in Surrey, Prince George and Kamloops
2007	6.1 m in Mission 2.4 m at New Westminster	• Caused by abnormally warm spring weather in the interior and a large snow pack volume • Led to an enactment of emergency measures and review of existing flood protection system along Fraser River on a municipal, provincial and federal level
2012	6.7 m at Mission 3.1 m at New Westminster	• Forced several riverside communities and campgrounds to evacuate

Flood risk assessment is important in the natural hazard risk reduction process and also to the emergency management planning cycle in Canada (Nastev and Todorov, 2013). A great amount of computerized flood databases and estimation models are being employed, largely in Europe and America. However, in Canada Quantitative Risk Assessment (QRA) tools are also being developed gradually (Natural Resources Canada and Public Safety Canada, 2017). According to Nastev and Tordov, the accuracy of risk analyses computed by any risk analysis software, (e.g., Hazus 4.2 software) relies profoundly on the quality of the input data. Multitude of input data, such as: property listing, depth-damage functions and flood depth grids are required for flood risk estimation. Also, the quality of these data impacts the precision of the results.

2.3 Flood management in Canada

In short, flood management typically consists of the following topics: mapping and risk assessment to identify the flood prone region, forecasting and flood warning systems, and flood management structures (e.g., reservoir and dams). Over time, each province of Canada seems to encounter an event that changes its flood management practice. For Ontario, it was Hurricane Hazel in 1954. For Manitoba, it was the Red River floods of 1950 and 1997. In the case of Alberta, it was probably the Southern Alberta flood of 2013. Table 2 presents the evolution of flood management approaches in Canada.

Table 2 Evolution of flood management approach in Canada

Source	Year	Flood management approach
(Sandink, Kovacs, Oulahen, & McGillivray, 2010)	1953-1970	Flood control structure (i.e., dyke, dam)
	1955-present	Flood map generation in some provinces (including Ontario, BC, Alberta) based on land use
	1970- present	Funding approval for non-structural measures
	1972-present	Non-structural management of floodplains in BC, (In Alberta since 1960)
	1975-1996	Co-ordinated national flood map generation
	1980-present	Emergency Preparedness Program (JEPP)
	2008-present	National Disaster Mitigation Strategy (NDMS)
(Nadarajah, 2016), (Government of Canada, 2016)	2016-present	1. Updated Flood mapping 2. Adoption of catastrophic modeling 3. Overland flood insurance for homeowners.

According to Sandink et al., (2010), flood control structures were initially taken as the key flood solution by the federal government of Canada. A coordinated reliance on these structures was in place from approximately 1953 and 1970. This effort was supported by the Canada Water Conservation Act. Disaster Financial Assistance Arrangements (DFAA), the Joint Emergency Preparedness Program (JEPP) and the Flood Damage Reduction Program (FDRP) were the national level instruments for these initiatives. However, these structures were in use without a coordinated national flood mapping program until 1975. During that time, flood mapping and flood management through land use planning began in several provinces, including Ontario, British Columbia and Alberta, but the maps were not easily available. These flood maps were distributed to the municipality level after several hazards (such as hurricane Hazel). Creation of regulations informed by the maps began by passing several bylaws in 1955 and thereafter. These laws prohibited construction within the identified flood zone. After a devastating Fraser River flood in 1972, the province of British Columbia began flood management by non-structural means (i.e., floodplains management). The non structural measures included: delineation of a 1 in 200 year design flood on flood maps, flood proofing of buildings and management of development in floodplains. They implemented these measures through zoning by-laws.

However, there are several challenges associated with the flood mapping in Canada. Mainly, due to the inconsistency related to flood return periods and age (Sandink et al., 2010). Another important issue is the difficult accessibility of maps. All these reasons make catastrophic modeling for probable hazard risk analysis difficult. It is to be mentioned that flood hazard is a location specific localized hazard. Using the flood map and catastrophic model, estimation of future losses and risk analysis can be performed. Catastrophic models are efficient in risk analysis as they provide a more realistic approach using decades of historical data. This data is used to estimate probability distributions of event characteristics to simulate potential future events (Obersteadt, 2018).

This situation is changing recently. After the massive flood hazard situation in Southern Alberta floods in 2013, the damage and its economic costs for Canadian taxpayers caught the political attention. 75,000 people evacuated, 4 people died and economic loss was estimated to be over $2.25 billion. After this situation, in 2016, the federal government along with IBC and other insurance company agreed to collaborate in updated flood mapping, risk analysis and loss and damage estimation (Government of Canada, 2016).

As of February 2016, the IBC has been coordinating the generation of flood maps and assessment of the flood risks right down to the residential level for fluvial flooding. This effort revealed some important results, such as 20% of Canadian households could be qualified as high-risk. Also, among these high risk buildings, 10% could be considered very high risk. That’s estimated to be 1.8 million households (Nadarajah, 2016).

2.4 Flood damage to buildings

Damage to residential building caused by flood hazard depends on variable parameters, such as depth of water, velocity of floodwater, duration of flooding, warning time, sediment, and effluent content (Romali et al., 2015). However, most of the historical assessment has focused on only variable depth of flooding (Pistrika et al., 2014). Flood related previous studies undertaken in Canada (IBI Group and Golder Associates, 2015) has also considered building damage as a function of depth of inundation. Furthermore, Natural Resources Canada and Public Safety Canada (2017) suggested the use of depth-damage curves in damage estimations in the Canadian guideline and database of flood vulnerability report.

Sources related to a literature search of depth damage relationships for residential buildings (considering the full range of possible damages) are presented in Table 3. It is to be mentioned that most of the literature sources that are found are U.S. based.

Table 3 Literature sources for a single residential building component's possible damaged conditions due to variable flood heights.

Author	Background Country	Year	Building type
USACE 92 (Davis and Skaggs, 1992)	U.S.	1992	Residential buildings with basement
(Gulf Engineering and Consultants, 1997)	U.S.	1997	Residential buildings with basement
GEC 2006 (United States Army Corps of Engineers, 2006)	New Orleans, U.S.	2006	Residential buildings on slab structure
Hazus 13 (Department of Homeland Security, 2013)	U.S.	2013	Residential buildings with basement
JRC 17 (Huizinga, Meol, and Szewczyk, 2017)	(global) E.U.	2017	One and two storeys with basement
NRCan 17 (Natural Resources Canada and Public Safety Canada, 2017)	Alberta, Canada	2017	Residential buildings with basement
(Deniz et al., 2017)	Colorado, US	2017	One storey with finished basement

Findings of the literature search refine the idea of relationship between flood intensity (i.e., depth of water) and building component failure criteria. The type of flood focused for this study is the long-term riverine flooding (2 - 3 days) the velocity of which can be negligible.

Building damage details that are looked into for the literature search are mostly the permanent members of a building system (i.e., drywall, floor) (Figure 3). Permanent structural and non-structural components of a building are both prone to damage by riverine flooding. These components are responsible for collectively performing different functions of a building. However, in this literature search, the internal contents (e.g., furniture, clothing) that are not a permanent part of a building and exterior attributes (e.g., backyard shed) are excluded. The reason behind excluding the internal contents is, once the building is flooded, all of the internal contents are expected to become waste (Natural Resources Canada and Public Safety Canada 2017).

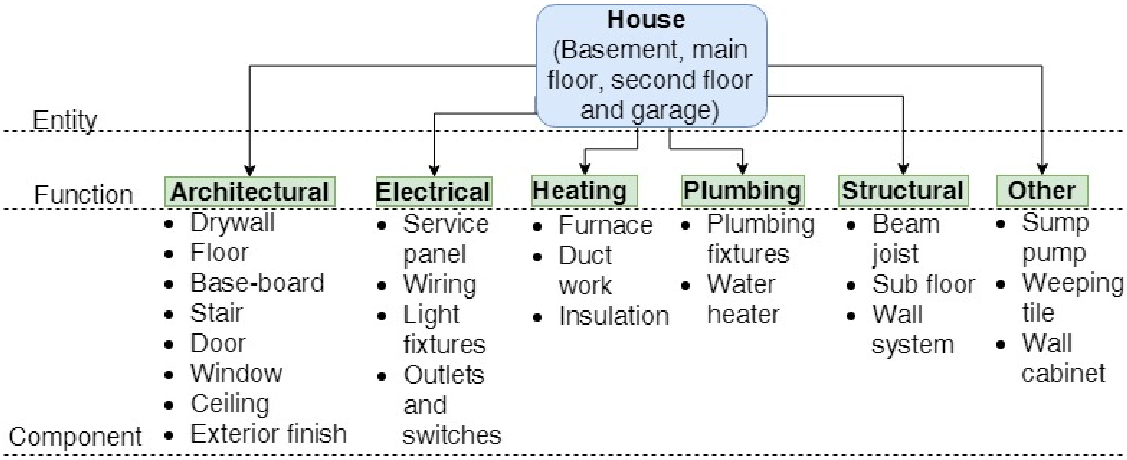


Figure 3 Residential building system overview (a single-family dwelling unit).

It is to be noted that the depth-damage relation described mostly for the water height inside a structure which was measured from the main floor level. As a result, a means of correspondence needed to be identified to relate the depth of water inside a structure with the actual flood height in the study area.

As per City of Surrey (2019b)'s flood proofing regulations, for the portion of the Fraser river floodplain lying in Bridgeview area, the minimum main floor elevation needs to be equal or more than 0.3 metres above the adjacent street or natural ground elevation. Following Figure 4 illustrates the relations among flood elevation, main floor height, and the depth inside a building.

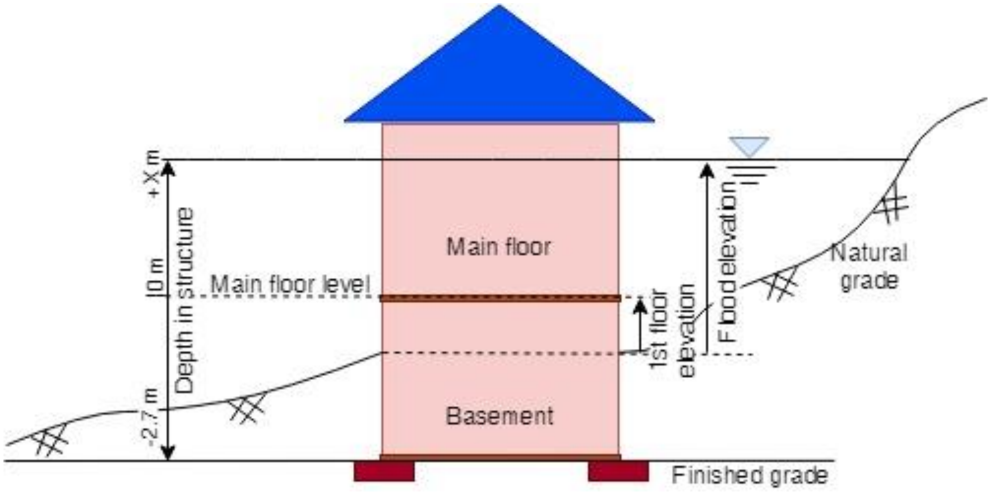
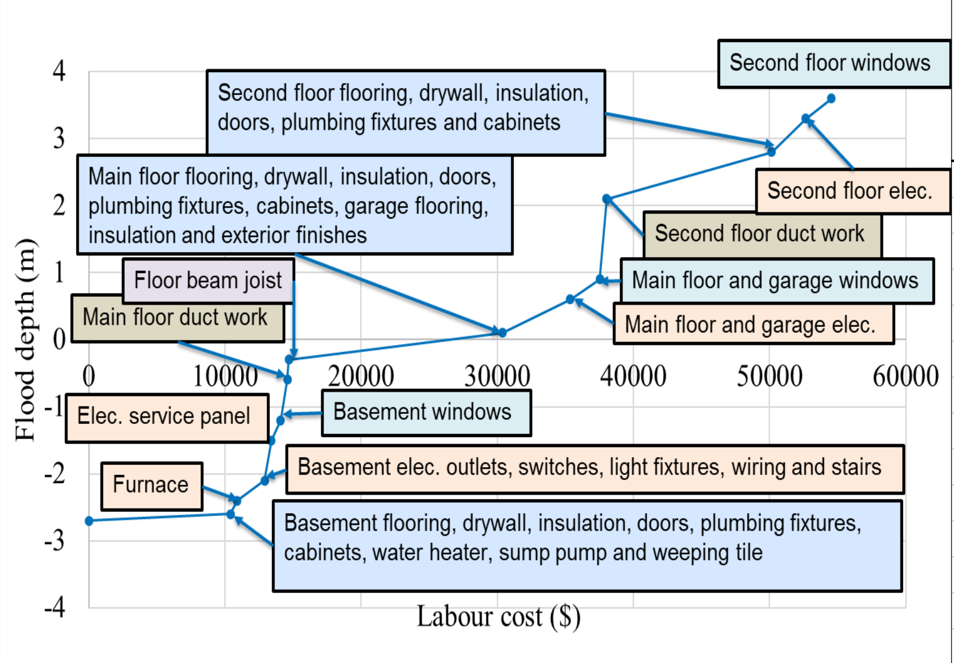


Figure 4 Depth in structure determination from the main floor elevation and flood elevation data. Here, depth of water in structure (measured from main floor level) = Depth of flood above ground – Main floor level.

An estimate of the relationship between flood depth and costs from a synthesis of the literature is shown in Figure 5. Here, the water height is considered to extend positively upward from the main floor level to a range of 2.7 m to 3.6 m depending on the number of storeys present and negatively downward to of -2.7 m (which is a typical basement depth in North America) (Department of Homeland Security, 2013 and Natural Resources Canada and Public Safety Canada, 2017). Damage information was collected for each 0.3 m increment of water depth which is also a standard as observed in most of these studies. Figure 5 represents the findings related to component failures of a building with respect to depth of water inside a building. At any depth of flood, components presented within boxes at and below that height need to be restored.



Damage States (DS)	Flood depth (m) inside the structure
DS-A	-2.6
DS-B	-2.4
DS-C	-2.1
DS-D	-1.5
DS-E	-1.2
DS-F	-0.6
DS-G	-0.3
DS-H	0.1
DS-I	0.6
DS-J	0.9
DS-K	2.1
DS-L	2.8
DS-M	3.3
DS-N	3.6

Figure 5 Possible damaged conditions of a two storey with basement single detached residential building for full range of possible flood heights inside the structure (with cumulative labour cost for restoration). Depths of water are depicted with associated Damage States (DS).

In total, fourteen flood depth intervals were identified for which significant information on component failure is gathered from the literature. These fourteen intervals are termed as Damage States (DS's) and presented as DS A up to DS N. Seven DSs for basement level, four DSs that also include the main floor level, and three DSs that also include the second floor are noted. Furthermore, critical DS's that mark 0.1 m water depth above the floor of all three levels (of a two story with basement building) are: -2.6 (above basement floor), +0.1 (above main floor) and +2.8 (above second floor) are significant as large increases in damage occur as soon as water passes above another floor. The building finishes and materials such as interior finishes, interior wall and ceiling, doors and windows are found to be prone to water damage before most other components (Natural Resources Canada and Public Safety Canada, 2017). Next, water damage prone components are the electrical system components (i.e., service panels, meters, switches, and outlets). Electrical system components require complete replacements in most of the cases even if they are inundated even for short periods of time (U.S Department of Homeland Security, 2005). Some other building systems components such as, mechanical (plumbing, heating, ventilating and cooling), and security system (fire alarm) require replacement after inundation reaches at certain heights (United States Army Corps of Engineers, 2006).

Another significant aspect of flood water damage is mold contamination which is considered as secondary damage. This situation is severe and occurs due to several reasons, such as, lack of immediate recovery response, wicking of moisture upward by the semi-permeable building material by contaminated flood water, and lack of proper de-humidification during the clean up-phase. This situation may occur regardless of building component exposure to direct flooding (Natural Resources Canada and Public Safety Canada, 2017). As a result, quick response and complete recovery become crucial.

2.5 Development of building recovery models

The following literature search confirms the difficulties that reside in accelerating or optimizing recovery and reviews potential solutions. This literature is mostly related to natural disaster damage and post-disaster recovery of various infrastructures (i.e., building, lifeline, and community).

Prior to infrastructure recovery modeling, one of the key principles is to acquire proper understanding of damage conditions. Deniz et al. (2017) explain that most of the available damage estimation models are location specific. Available models mostly focus in the European region (i.e., Germany) and Japan with scarce coverage of North America. Multi-hazard software Hazus is one of the few in North America and most commonly used in the

USA. However, it provides loss estimation based on assessed building value rather than actual replacement costs. To overcome this shortcoming, Deniz et at. (2017) developed a model using building architectural layouts and inventories of building components in a 2013 Colorado flood and then assessed actual loss. The actual loss to 3,000 buildings were estimated upon the repair cost of unit prices that considered the construction and material costs in Boulder in 2013. The findings of these papers are valuable damage literature for recovery modeling.

Another valuable finding is the recovery timeline provided by NiyamIT Inc., (2017). This Hazus tsunami model technical report provides building recovery timeline against three types of repair requirements. This report explores both the riverine damage and flow velocity damage to the building and correlates recovery to the economic loss calculation. It classifies the recovery requirement in three categories, namely, moderate repair (associated with 5% - 25% monetary loss), extensive repair (associated with 25% - 100 % monetary loss) and complete repair (associated with 100% monetary loss). However, this report does not provide any recovery model for time estimation rather a series of default value of building recovery time to further assist the repair and replacement costs. The similar case is observed in Hazus flood technical manual (Department of Homeland Security, 2013). In that work, a group of experts made assumptions on possible depths of flooding and associated building recovery steps (i.e., clean-up, physical restoration, and political delays). Their physical restoration timeline of buildings is generated following the pattern of Hazus 2013 earthquake model. The remaining recovery steps were included as add-ons (i.e., a constant value for any damage state) to further assist the building repair and replacement cost estimation. Although these expert judgements works as reference, they do not contribute to the optimized recovery simulation.

Among the recovery related challenges, the complex nature of recovery process is the most important one. This is because recovery time estimation consists of several factors, such as the structure characteristics, hazard intensities, and the amount of workforce (Kammouh and Cimellaro, 2017). Another reason is that, there lies interdependencies among the components of a system which needs to be identified during recovery modeling. He and Cha (2018) identified the importance of understanding the interdependence among civil infrastructure network as the key to post-disaster recovery planning for. Very few recovery related studies, however can address the interdependencies resided in a system in a quantitative manner. He and Cha are one of the few and estimated timeline for recovery in their lifeline recovery model. They considered electric power, telecommunications and water supply as components of a system and used the national and regional commodity-transaction data to create a dynamic input output model. However, the model developed is a hypothetical infrastructure network model and the damage consideration was based on generic assumptions. Damage states for systems were sub-divided as classes, such as minor, moderate, medium, and severe and counted as percentage of complete damage (5, 30, 60 and 100 percentage respectively) with a view to suggesting recovery modeling for each class**.** Another opportunity for improvement of this model was found to be the usage of coefficients in the recovery time formulas that have not been adequately assessed. Kammouh and Cimellaro (2017) also tried to address the complex nature of recovery modeling. They propose an empirical probabilistic model of restoring lifelines (power, water, gas and telecom) post an earthquake event. They derived fragility restoration functions based on datasets collected from a wide range of literature focusing on earthquake recovery over the past century. The aim was to introduce a simplified recovery time estimation method. However, the historic database model lacks the ability to create optimized recovery that is sensitive to differing resource constraints. Furthermore, natural disaster damage being a location specific factor, implementing such functions in different hazard locations may be difficult.

Another aspect of interdependency and complexity between various infrastructure systems is that hazards can initiate a cascading effect on all the components of the system. This reason makes it important for the damaged system to recover quickly and limit additional failures. As a result implementing recovery strategies (such as: the efficient use of time, cost or other resource constrains) to determine the optimized pathway is important (Afrin and Yodo, 2019).

For recovery optimization, Afrin and Yodo (2019) proposed three recovery pathway archetypes considering a lattice network system framework inspired by a water distribution network case study. These recovery strategies, namely, preferential recovery based on nodal weight (PRNW), periphery recovery (PR), and localized recovery (LR) were assessed based on time and cost constraints. Among these three strategies localized recovery (LR) was found to be the most efficient one by this research. However, a random root node was selected in this strategy for initiating recovery after a localized disruption. Furthermore, the lattice pattern is difficult to use for modeling most of the interdependencies that lies within a system as they are usually complex. Another study by Lubashevskiy et al., (2013) presented a solution for optimization focusing on resource prioritization for recovery of several cities after a natural hazard. They proposed an algorithm for the redistribution of vital resources (pure water, food, medical drugs, fuel, etc.) as a part of short-term recovery. At first, a semi-optimal plan for the desired redistribution was created based on the cooperative interactions among these cities. Ordering the cities according to their priority in resource delivery were generated using the proposed algorithm. However, there was no interdependency consideration among these cities except for the demand and capacity of resource delivery. Also, the algorithm presented was specific to the scenario (vital resource distribution).

This literature investigates recovery models after a natural hazard and identified some of the key gaps existing in previous studies. First and foremost, there is a scarcity of empirical restoration data related to flood hazards in the Canadian context. Other gaps are: holistic recovery modeling defining complex dependencies among components and strategic optimization of the recovery pathways.

2.6 Building classification scheme in the context of Canada

Building classifications are important for understanding the flood risk to building stocks. Accurate building classification include crucial characteristics such as material, construction techniques, and dimension and occupancy type in a particular.

In Canada, the first building classification scheme was developed and used for the Acres Study (1968). In that flood damage estimation study, the residential structures were mainly categorized based on the building materials, such as: wood or brick, then further divided into three sub-categories based on structural frame pattern (such as solid wooden structure, double wall frame and rough frame structure).

The Ontario Department of Municipal Affairs developed a building classification scheme based on the Acres study scheme which was published in a handbook with the detailed descriptions and cross sections of building types. This classification was employed in subsequent studies such as Fort McMurray (1982) and Paragon Engineering Study of Ontario (1985). Fort McMurray (1982), implemented a modified classification scheme in their study based on Acres classification data to align with the variation existing in its study area (Natural Resources Canada and Public Safety Canada, 2017). This classification was further employed by the consultant team in various studies within Canada. In 2015, the Fort McMurray building classification scheme was refined for the Alberta Provincial Flood Damage Assessment Study (IBI Group and Golder Associates, 2015). The residential buildings were classified according to their construction techniques, size, quality, and the number of stories. Details of this classification scheme are provided in Table 4.

Table 4 General information of the residential classification Scheme for Alberta municipality (Natural Resources Canada and Public Safety Canada, 2017), (IBI Group & Golder Associates, 2015).

Class	Floor Area (sq. m)	General descriptions
AA-1; AA-2	456	Typically, custom construction with superior architecture and premium quality construction materials and finishes.
A-1; A-2	266	High end homes typically featuring moderately high-quality construction materials and finishes.
B-1; B-2	163	Generally, most numerous types of single dwelling units in Alberta municipalities with average quality units, conventional design and medium quality materials and finishes.
C-1; C-2	88	These houses are constructed in newer suburban with average to below average quality in terms of design, construction materials and finishes.
D	128	These are mobile homes without basements, located on temporary basements and reflects lower range of real estate values.
MA	93	These are high rise units which are in more than five storey structure typically of concrete and light steel frame.
MW	65	These are high rise units which are in less than five storey structure typically of wood construction.

2.7 Conclusion

This chapter presents necessary background related to flood hazard risk, existing flood management practices, and building classification schemes in the Canadian context. It also presents detailed literatures on building damage associated to the hazard, and existing recovery models of infrastructures (i.e., critical infrastructures, buildings, and communities) after a natural hazard. Recovery is an understudied piece of flood risk that is needed to refine understanding of indirect damages. In reviewing the literatures related to recovery modeling, it is important to be familiar with not only the context and steps of analysis, but also many assumptions made while performing the analysis. Different definitions of damages and the characterization of recovery are important assumptions that vary between different studies. These variables establish the background for the development of more detailed recovery models specific to southeastern BC.

Chapter 3 Case study: Single building restoration

3.1 Introduction

The Fraser River runs through Metro Vancouver and experiences periodic flooding. Fraser River dikes located in several parts of the Metro Vancouver area are built to design criteria developed by the Fraser River Flood Control Program in the 1960’s and 1970’s. More recent dike-confined hydraulic modeling of flood flows found that the present design flood levels would be up to a metre higher in some areas (Northwest Hydraulic Consultant Ltd., 2015). Furthermore, current provincial standards are not being met by the dikes in general and neither of them fully meet or exceed the standards. The reasons are two-fold: increased accuracy in numerical flood modeling that resulted in higher design flood levels, and design criteria for structural and geotechnical aspects of infrastructure that have become more stringent over time.

Partly in response to such findings, the Fraser Basin Council recently set out to provide the Lower Mainland region an assessment of vulnerabilities and flood consequences for design flood scenarios with a 1 in 500-year annual exceedance probability. Indications of inadequate protection against the present Fraser River flood scenarios was evident for the majority of diking systems in the Lower Mainland (Northwest Hydraulic Consultant Ltd., 2016). For instance, the concrete flood walls and earth dikes in the low-lying area of Bridgeview are laid at a level of 4.8 m geodetic (with 0.6m of freeboard) above 1 in 200-year river flood (AECOM Canada Ltd., 2015). There is, hence, expectation that areas like Bridgeview may experience inundation events in the coming years unless the dikes are upgraded or formal retreat. In lieu of such actions recovering from flood quickly may be important to the health and vitality of such areas.

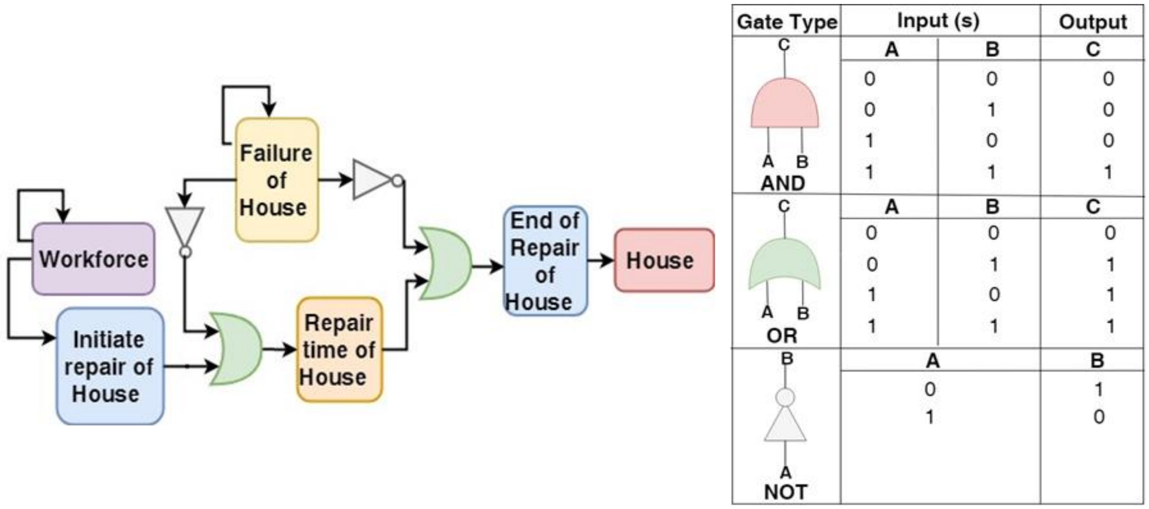
The Scope of this chapter is the detailed recovery modeling of a specific single-family residential buildings' system in the Bridgeview area of Surrey, BC due to flood damages with the objective of estimating the recovery timeline for the full range of possible damages caused by the full range of possible flood heights. The recovery modeling described herein is developed using a systems methodology inspired by (Bristow and Hay, 2017) that includes the use of the computational engine GMOR (Graph Model for Operational Resilience) to simulate recovery of a single building during a post-flood disaster situation.

3.2 Graph Model for Operational Resilience (GMOR)

Bristow and Hay's Graph Model for Operational Resilience (GMOR) is a computational recovery assessment engine that aims to reduce uncertainty of recovery time following disasters. This framework models disaster recovery pathways with respect to the system interdependencies and provides expected recovery timelines. GMOR focuses on the recovery of individual system components which collectively maintain each function. Interactions and relations among components are focused and modeled for recovery assessment instead of using aggregated component recovery data that has been a common practice for most of the previous recovery studies (Bristow and Hay, 2017).

A simple example model is represented in

Figure 6 to illustrate the graph model definition and its supporting data. The basic graph model consists of four different types of entities. These are: functions (pink), resources (purple), events (yellow), and activity times (orange).



Gate Type	Input (s)		Output
	A	B	C
AND	0	0	0
	0	1	0
	1	0	0
	1	1	1
	A	B	C
OR	0	0	0
	0	1	1
	1	0	1
	1	1	1
	A		B
NOT	0		1
	1		0

Figure 6 Basic graph demonstration model. The model consists of four different types of entities: functions (pink), resources (purple), events (yellow), and activity times (orange and blue) and logic gates and symbols. Here, A and B denote the input entity states to a gate and C denotes the resultant output state.

The house, workforce, failure of house and repair time represents the function, resource, event and activity time entity respectively. Two more entities are added to the basic model to elucidate the beginning and end of restoration, they are “Initiate repair” and “End of repair” (blue). These entities help to track the state of repair work and the reservation period of the workforce engaging in a specific repair task in instances where a resource must do multiple repairs. Here, the essential attribute of each entity is its state, a 0 (non-functional) or a 1 (functional), which is computed based on the state of the entity’s dependencies. These dependency relationships are denoted by the logic gates and symbols, these are: AND gate, OR gate and NOT gate. The output value of these types of gates given different input values are shown in

Figure 6. Also, connections of entities by arrows defines their dependency relationships. For example, an entity residing at the nodes (vertices) of the graph are dependant on the entities connected by the edges. There is a possible inclusion of a delay time, τ_i that

signifies the time required to change the realized state (i.e., initiate repair, end repair) from 0 (non-functional) to 1 (functional) once the entity's dependencies permit such a transition. Entities that are self-dependent (failure and workforce) are required for the model to run by triggering an initial positive state value that other entities in turn depend on.

Assessment of the individual state of entities and the system's overall state vector depends upon the computation of interactions among the entities after a shock and probable entity disruption. For instance, the value of the self-dependencies of the failure entity is an initial condition that can be determined based on the height of a component versus the local flood height. GMOR relates the restoration requirements with the damage and computes when each component recovers. This attribute makes the use of GMOR manageable for credibly sized, and data-driven assessments. Therefore, it is feasible to perform rapid model creation for recovery time assessment of multi-damage state spatial infrastructure systems. These models consist of the dependencies required for recovery and are capable of informing the impact of the order or recovery on slowing or accelerating overall recovery of the system of interest (Bristow, 2019).

3.3 Methodology

A building is composed of sets of components that underlie the functioning of the building. Informed decision-making during damage recovery after a disastrous situation requires understanding of the damage itself and the impacts of probable restorations of the components over the system. The objective, therefore, is to develop a systems methodology using GMOR that can enable the computation of complex relationships among component repairs and resource requirements which can be further assessed based on time constraint to determine an optimized pathway.

The approach combines, location specific damage restoration time estimation method which is identified as a key to recovery design (Deniz et al., 2017), a means to simulate the complex recovery of a residential building (discussed elaborately in upcoming sections), a computational engine to calculate the recovery time line (for which GMOR has already been selected considering its absolute suitability to the research purposes) and finally an aid for the optimization technique to determine the shortest possible time for recovery (amalgamation of event tree analysis and GMOR was used for this purpose).

Here, the GMOR computational engine serves as the center of all these processes. Complex recovery simulation and estimated restoration times of each component of a system serves as the entity specifications of a GMOR model (Figure 7). Six kinds of entity specifications are taken as input by the model among which the “restoration activity”, “restoration dependency”, “resource requirement” and “realized state” are illustrated in 3.3.3 GMOR Sequence model for building recovery section.

For this specific case study, “event dependency” is defined as per the Damage States (DS’s) that are already discussed in the background section and is further discussed in 3.3.4 Restoration scheme section. The recovery calculation serves as deterministic to DS’s and are calculated for each of the fourteen DS’s. All these DS’s serves to cover the large spectrum of probable damage conditions from different flood depths specific to the building.

Restoration times are specific to each component and governed by each Damage State. These are calculated using RSMean data (further discussed in detail in 3.3.4.1 Restoration dependency section). Considering availability of limited resource for building recovery, all the possible resource ordering was assessed using event tree analysis. The purpose was to prioritize restoration works to observe the impacts on recovery timeline and determine the optimized timeline.

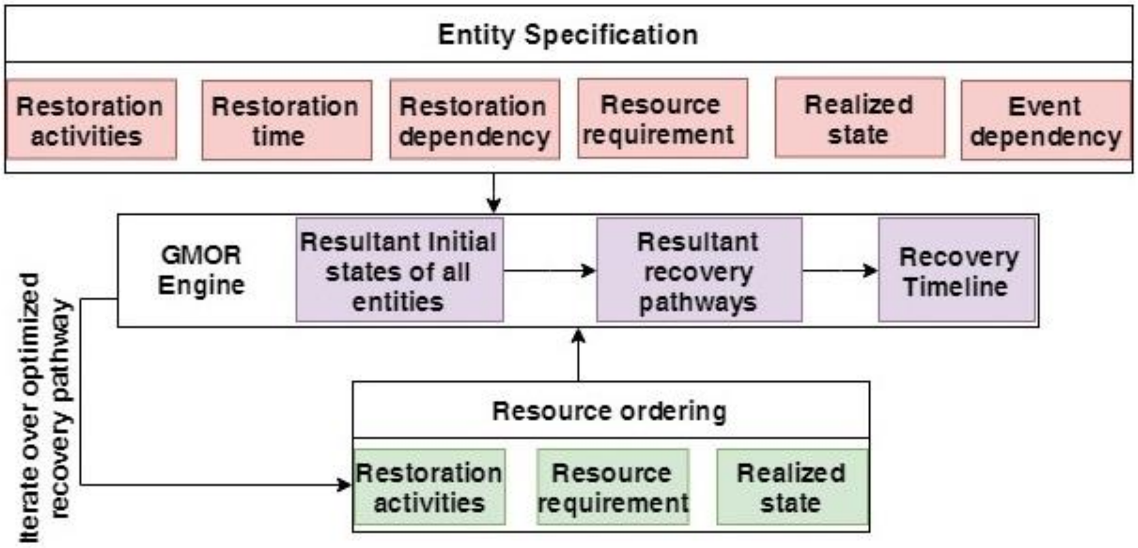
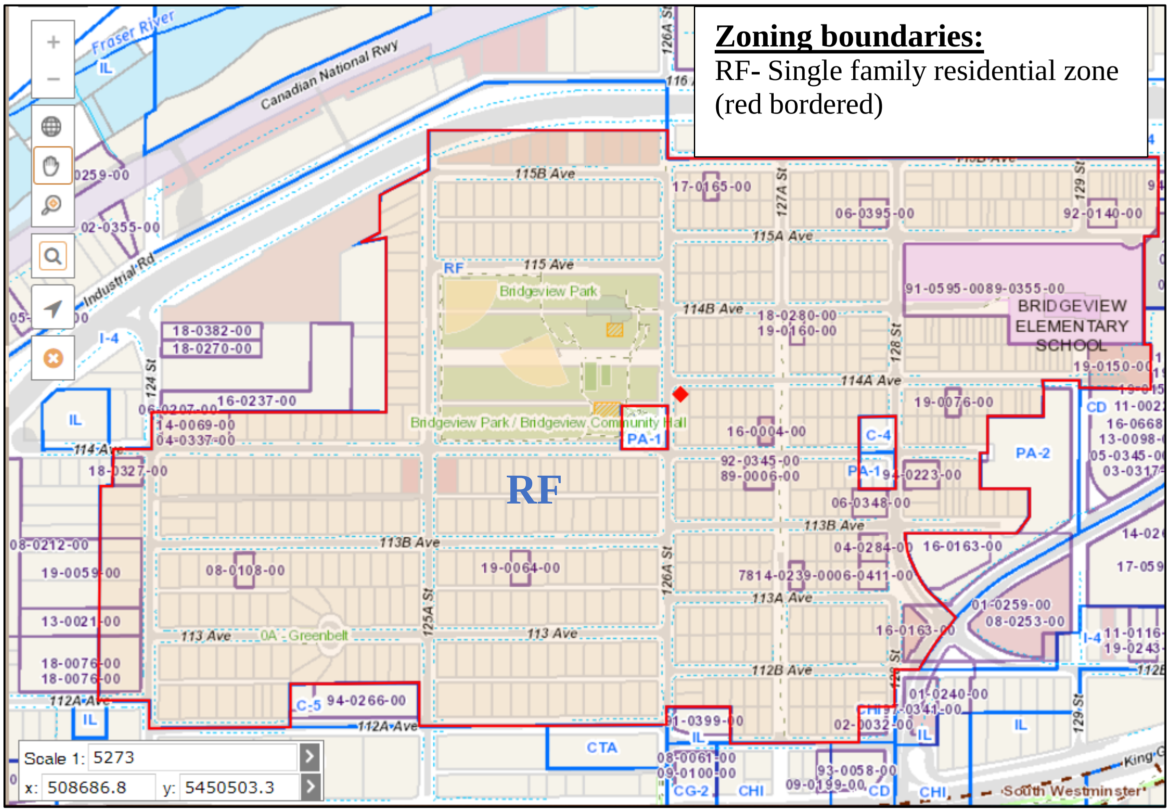


Figure 7 **Schematic depiction for determining recovery time of a single building using GMOR.**

3.3.1 Study area selection

The Bridgeview area with a population of 1,895 (2005). This area of 124 ha lies within the Fraser River low lands (Figure 8). The elevation of most of this area rests below four metres and the lowest point is at two metres and slopes towards the Fraser River from south to north. This area lies within the 200-year Fraser River flood plain of which, 178 ha from Pattullo Bridge until west of 132 streets is protected by dikes. Rest of the area is unprotected. The Bridgeview area climate is governed by the inter-coastal Pacific-Northwest with warm summers and winters with heavy rainfall lasting until the spring (AECOM Canada Ltd., 2015). The Bridgeview area falls within the planning jurisdiction of both Metro Vancouver and the City of Surrey. Metro Vancouver regulates the land-use planning on a regional scale, whereas the City of Surrey looks into municipal planning (City of Surrey, 2012).


Zoning boundaries:
RF- Single family residential zone (red bordered)

Scale 1: 5273
x: 508686.8 y: 5450503.3

Figure 8 Bridgeview street map. Purple bordered zones are area under development application. Some of the blue bordered zones are: PA-1 and 2 (Assembly hall 1 and 2), C-4 and 5 (Local and neighbourhood commercial), IL (Light impact industrial), CD (comprehensive development), CG-2 (Combined service gasoline station), CHI (Highway commercial Industrial), I-4 (Special Industrial) and CTA (Tourist accommodation zone). (City of Surrey Mapping Online System (COSMOS), 2019).

Flooding is an important issue in this area since residential homes and businesses are present. Incidents of frequent flooding within this area have been observed by the City Engineering Operations and Maintenance staff. In particular, 112A Avenue west of 124 Street has been marked as the worst area and during almost every rain event water levels reach up to residential front yards, and a significant amount of complaints from residents regarding inaccessibility and nuisance due to the floods occur (AECOM Canada Ltd., 2015).

3.3.2 Representative building selection

Building specifications are one of the base information that can be used to interlink the damage extent with the restoration time estimation. It has been already established that building characteristics play an important role in determining flood damages (Natural Resources Canada and Public Safety Canada, (2017), Department of Homeland Security, (2013), United States Army Corps of Engineers, (2006)). This is because building specifications such as material, age, height and presence of basement define the probability of damage to components. Furthermore, the quantified damage information helps to calculate the damaged component's restoration cost and time. As a result, a representative building selection that is specific to the study area is a significant first step for producing a useful model.

A sample set of 30 buildings were selected that located within RF (single family residential) zone in the Bridgeview area of Surrey, BC (Figure A 1). For this research, all the available sources such as BC Assessment, (2019), City of Surrey Mapping Online System (COSMOS), (2019) and several property selling websites were used to investigate the building characteristics in the study area. The selected set of buildings were assessed based on the available information related to building height, material quality, age, property value, number of stories and presence of basement Table A 1).

It was observed that 16 out of these 30 buildings are built after the 1950's and are built following basic building code requirements of the era, and with average quality building materials (BC Assessment, 2019). Most of the buildings have floor area between 1,200 sq.

ft. to 2,400 sq. ft. and a basement or second story is quite common. As per assessment from July 2018, these building's value varies from $600,000 to $730,000 (CAD). Next, comparable building classification schemes in the Canadian context are investigated (detailed in section Appendix A) to determine an equivalent characteristic building class. This procedure was adopted since often property related information is confidential, and in this case, it was unavailable. The best available resource at the time of writing is the Natural Resources Canada and Public Safety Canada (2017) building classification scheme recently used in the Alberta flood damage assessment (IBI Group and Golder Associates, 2015). The Bridgeview investigation findings merged with Building classification "B" of the Alberta study. B type buildings are average quality units with conventional design, and medium quality materials and finishes (Table 6). As a result, a two storey with basement residential building with B type building characteristics is selected as the representative building for the study area for further recovery modeling. The detailed specification of building materials and the component dimensions for the representative building are provided in Table 6 and Table 5.

Table 5 Building component specification for representative building (floor area 166 sq. m.) (Natural Resources Canada and Public Safety Canada, 2017).

Building components	Basement	Main floor	Second floor	Garage
	(Units)			
Drywall (sq. m.)	219	336	336	-
Insulation (sq. m.)	87	87	87	349
Doors (unit)	6	8	8	1
Windows (unit)	5	14	14	2
Flooring (sq. m.)	30	9	9	-
Carpeting (sq. m.)	53	74	74	-
Baseboard (linear m.)	66	106	106	-
Bathroom (unit)	1	2.5	2.5	-

Table 6 Building materials and finishes specification for the representative building (B type building) (Natural Resources Canada and Public Safety Canada, 2017).

Basement	
Floor:	Wood strip, carpet.
Walls:	Wood stud, drywall painted.
Insulation:	6mil poly V.B.
Ceiling:	Drywall painted.
Doors:	Wood, solid core.
Stairs:	Solid stringers, closed riser and plywood tread.
Main floor and Second floor	
Floor:	Carpet, prefinished hardwood.
Walls:	Drywall painted.
Insulation:	6mil poly V.B.
Ceiling:	Drywall stippled.
Doors:	Wood, solid core.
Cabinets:	Plywood body, solid wood doors and drawers, P-Lam counter.
Bathroom:	Tile to ceiling above tub or fibreglass tub enclosure.
Garage	
Walls:	Stucco.
Insulation:	6mil poly V.B. or unfinished.
Windows:	Wood.
Doors:	Painted wood.

3.3.3 Building component restoration

The duration from failure to functioning of a system depends collectively on the restoration times of the system components. The initial challenge encountered for the flood recovery modeling of a residential building is to obtain reliable data sources for components restoration times. From the literature search, one of the significant gaps that was recognised is the lack of historical recovery data specific to the study area. As a result, an alternative reliable method of restoration time estimation has been used in this research, namely construction cost estimation using the RSMean data from Gordian (2019). RSMeans has been the industry standard database since 1942 for construction and repair related data. Contractors, facility owners, architects, engineers or anyone can use this information for localized construction and repair related estimations.

Fundamental of building recovery is the building component restoration. A schedule of building restoration works for each of the Damage States (DS’s) is devised using representative building data and information on restoration from Gordian (2019). The schedule for each DS’s is termed as restoration scheme which is then used for restoration time estimation baseline.

3.3.4 Restoration scheme

The findings from damage literature of buildings are combined into a restoration scheme that is used as the key of recovery design in this research. Theoretically, the overall recovery time of a residential building includes time for damage investigation, clean-up, approval application, and the physical restorations of building components (U.S. Department of Housing and Urban Development, and Office of Lead Hazard Control, 2015). Steps related to application approval have various contextual dependencies that can vary greatly from location to location. As such, for this research, analysis is restricted to building specific inspections (i.e., furnace, beam joist), clean-up and the physical restoration.

Possible Damage State (DS’s) of a residential building due to specific depths of water has been thoroughly explored in the background section (2.4 Flood damage to buildings). Fourteen DS’s are identified that accounts for complete possible building flood damages. Detailed restoration schemes for each DS’s are specified through literature research and recommendations from Gordian (2019).

Table 7 represents the restoration scheme developed for Damage State A (-2.6 m flood inside structure). Restoration works (i.e., demolition, installation, clean, and paint) of the building components are scheduled as per expected damage related to the flood depth.

Table 7 Physical restoration scheme for Damage State A (-2.6 m depth of water inside structure). Depths are measured from main floor.

Activity ID	Abbreviation	Restoration activity
1	D Wood work	Demolition of baseboard of basement
		Demolition of bathroom cabinets of basement
		Demolition of doors, wood casings and door jambs of basement
2	RCD plum	Remove and clean bathroom toilet, sink and tub of basement
		Demolition of hot water heater
3	IS Furnace	Clean and service furnace
4	IS Sump_weep	Inspection and clean sumps and weeping tile
5	D Drywall	Demolition of drywall to walls and ceilings of basement
6	D Vap_ins	Demolition of poly vapour barrier and insulation of basement
7	I Vap_ins	Installation of poly vapour barrier and insulation of basement
8	I Drywall	Installation of drywall to walls and ceilings of basement
9	I Wood work	Installation of baseboard of basement
		Installation of bathroom cabinets of basement
		Installation of doors, wood casings and door jambs of basement
10	I Plum	Installation of bathroom toilet, sink and tub of basement
		Installation of hot water heater
11	D Floor	Demolition of flooring of basement
12	I Floor	Installation of flooring and Carpeting of basement
13	CP Int_comp	Clean and paint interior structural and non-structural components of basement

***D= demolition, RCD= remove, clean and demolition, IS= Inspection and Service, I=Installation and CP= clean and paint.**

Here, similar component restoration works are enlisted in a general restoration activity group for the simplicity of the model. For example, plumbing work includes restoration of water heater and plumbing fixtures. Similarly, wood work includes restoration of baseboard, stairs, doors, windows, and cabinets of kitchen and washroom. The electrical works are divided into two groups, namely, wiring and electrical works. The following one consist of restoration of service panel, furnace, electrical outlets, switches and light fixtures. Restoration scheme related to two of the main floor and second floor flooding scenario (DS-H and DS-N) are presented in Table C 1 and Table C 2. Details on post-disaster phases of residential building recovery, such as inspection, preparation and clean-up are further mentioned in Appendix B.

3.3.3 Time calculation

Once the restoration schemes are understood, using representative building data (i.e., material type and dimension of floor) and the required restoration total labour cost for a specific task (i.e., demolition or installation of total floor area) was estimated. Next, the cost of labour was divided by specific labour (i.e., carpenter, plumber) rate. The overhead and profit rate of labour was used for the restoration time estimation. Following is the method for restoration time calculation where times are back-calculated using RSMeans data (equation (1**)**.

$$\text{Restoration time} = \text{location factor} \cdot \text{component unit} \cdot \text{unit labour cost} \div \text{labour rate} \quad (1)$$

per day

Here, the location factor used for Vancouver region. The component unit is based on the specific component detail from representative building specification (

Table 5). Location factor, unit labour cost and labour rate are obtained from RSMean data. Table 8 above, shows a summary of this back calculation for the representative building in the Bridgeview area. Detailed cleanup phase time calculation for the representative building using Gordian (2019) data are provided below Table 9 along with their respective Damage States (DS).

Table 8 Restoration time back-calculation for the basement components of a two-storey single detached residential building.

Components (unit)	Restoration activity	Unit	Labour cost ($/ unit)	Labour rate with O and P ($/day)	Labour cost ($)	Restoration time (days)
Flooring (sq. m.)	Demolition	30	17.5	464.8 (Carpenter)	525	1.13
	Install		75.2		2256.7	4.86
Bathroom cabinet (unit)	Demolition	1	36		36	0.08
	Install		94		94	0.2
Drywall (sq. m.)	Demolition	219	4.19		917.61	1.97
	Install		17.9		3920.1	8.43
Doors (unit)	Demolition	6	43		258	0.56
	Install		27.5		165	0.35
Windows (unit)	Demolition	5	24.5		122.5	0.26
	Install		110		550	1.18
Bathroom toilet, sink and tub (unit)	Remove	1	85.5	524 (Plumber)	85.5	0.16
	Clean		30		30	0.06
	re-install		277		277	0.53

Table 9 Clean-up process time calculation for representative building basement (83 sq. m or 893 sq. ft. floor area). Similar processes occur for other stories of the building.

Page reference	RSMeans entry	Labour cost per unit ($/sq. ft)	Cost ($)	Rate with O and P ($/hr)	Time (hr)	Time (day)
10	Grey Water (non-solids) Extraction	1.42	1268.8	59.8	21.22	2.65
10	Debris removal (incl. content loss)	1.13	1009.7	59.8	16.88	2.11
10	Muck out	0.69	616.5	59.8	10.31	1.29
10	Deodorize/disinfect	0.42	375.3	59.8	6.28	0.78
246	Carpet demolish	0.09	80.4	59.8	1.34	0.17
278-280	Remove appliances (washer, dryer, refrigerator, oven, freezer and dishwasher) each		204.4	59.8	3.42	0.43
11	Thermal Fog Area	0.55	491.4	59.8	8.22	1.03
11	Dehumidifier				40.00	5.00
147	Plumbing Maintenance Flush out/unclog		262		4.00	0.50
	Utilities back on (power, water, gas)					3.00

*Rate of workforce is considered for Skilled labour considering 8 hours working day.

It is to be noted that, to enable the use of the RSMeans data, more refined specification of building components is required, such as the specification of furnace type, water heater and ductwork dimensions. In such cases, selection is made considering average quality components. The final building material and component specifications including the refined specifications are presented in Table A 2.

3.3.3 GMOR Sequence model for building recovery

The novel model architecture devised here, dubbed a sequenced model, creates the means to simulate a semi-optimal recovery model of a residential building. The purpose of this model is to gain the ability to simulate the complex nature of recovery.

A system recovery plan consists of numerous component restoration tasks. Again, there may exist diverse dependency conditions (i.e. Workforce dependency: availability). The recovery simulation of representative building after a flood hazard includes detailing of the building component's restorations in a logical manner set by their interdependent relationship. Finally, the semi-optimal sequence model and associated restoration times are used by GMOR engine to compute the recovery times for each Damage State (DS-A to DS-N).

Following Figure 9 represents a single building (denoted as House) recovery using a sequence model that allows for jobs to be done in parallel and sequence as dictated by the dependencies. For instance, jobs 1, 2….n can be done in parallel, and job 1.i must be done before 1.ii and 1.iii are the conditions of a recovery process. Furthermore, whether all the jobs that can theoretically be done following the sequence (parallel or series) are done following the series, depends on the type and availability of workforce available (more details on this are in Table 10.

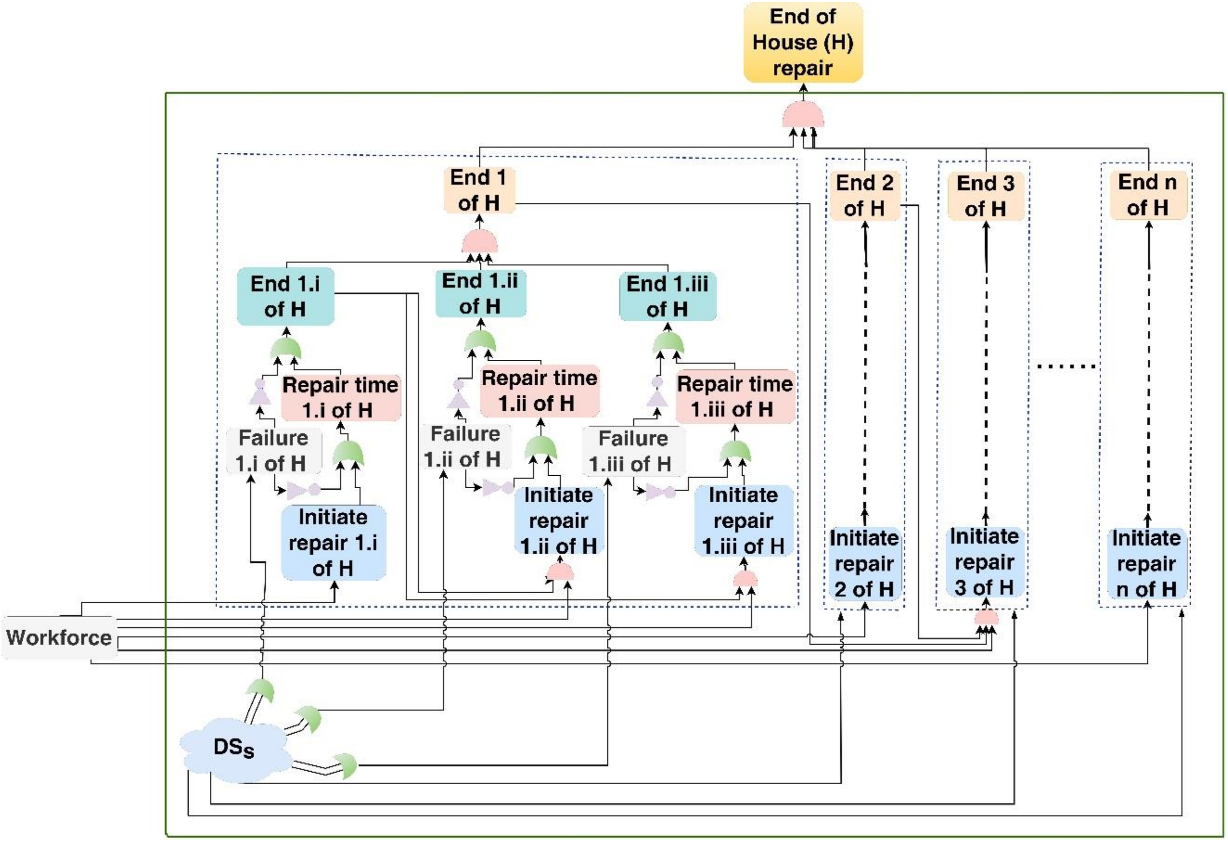


Figure 9 Overview of a generic sequence model (logic diagram) for restoration activity simulation used in GMOR recovery modeling. The sequence contains sub-sequences in parallel and series, for example, 1, 2…n can be done in any order but 1.i must be done before 1.ii and 1.iii but either 1.ii or 1.iii can be completed before the other. As illustrated the set of restorations numbered 1 include a series of sub-restorations. Sub-restorations for stages 2…n are omitted for clarity. The types of workforce required throughout a building recovery is listed with the respective restoration activities in Table 10. The Damage States (DSs) respective to variable depth of flood are enlisted in Table C 1 and Table C 2 with their required restoration activities.

Sets of restoration activities (task 1.i, 1.ii and 1.iii) that may need to be fully completed prior to another set of activities (i.e., task 3) can take place or sets of activities that may be executed together (task 1 and 2), are presented as bounded by dashed borders. The real-life example of such sets of restoration activities can be the replacement of wiring in a kitchen. For wiring replacement to initiate, several activities need to be completed, such as: wood work, plumbing fixtures, and drywall and insulation removal. Again, among these restoration activities, drywall and insulation removal can take place in a series manner as initiation of one of the restorations works requires another work to be completed earlier. Along with restoration dependency, there reside another dependency among these tasks. That is, the workforce dependency as these two tasks rely on same type of workforce such as the carpenter. Another example of restoration is, plumbing fixtures and wood cabinet removal. These two tasks do not co-relate, neither it depends on same type workforce (they depend on plumber and carpenter, respectively). Again, a set of restoration activities may have sub-sequences of restorations. For the wood work restoration example; demolition and installation of baseboard, doors, cabinets, windows, and stairs may be considered as subsequence.

In the model, the solid border in the figure represents the complete set of physical restoration activities of a single building for all possible damage states that the building might encounter. The rounded rectangle shape in the figure represents entities that can be in a state 0 or 1 (functional or non-functional). These entities can refer to many things, such as, phase of an activity (beginning or ending a restoration activity), events (i.e., failures of components) and resources (workforce and time). The state of each entity is important for the dynamics within the model. For example, considering two tasks in a series, the following dependent task’s “initiate” state will remain 0 (non-functional) until the proceeding task’s “End” is 1 (functional). The following task’s “initiate” state will turn 1 (functional) as soon as the proceeding task’s “End” turns to 0. Moreover, the computation of overall status of the House (functional or non-functional) depends on the status of the entities altogether. The AND gate, OR gate, NOT gate, and arrow connections specify the dependency relationships among the entities as previously mentioned in detail at 3.2.3 Graph Model for Operational Resilience (GMOR) section.

The cloud shape in Figure 9 is a simplified representation of multiple Damage States (DS's), whereby each Damage State accords with a different flood depth (mentioned earlier in Figure 5). The model correlates with a single Damage State at a time, which then activates the appropriate restoration steps within the sequence model. Restoration schemes respective to variable DS's are in Appendix C.

The model consists of logical dependency relationships among restoration activities, time and workforces. Hence, the creativity of the sequence model lies in the ability to simulate the restoration activities that need to be performed in parallel or in series for the whole range of relevant flood depths using established construction time estimates.

3.3.4.1 Restoration dependency

As previously discussed, restoration dependencies are the fundamentals of the sequence model. The dependencies are designed based on information about residential building component restorations (i.e., Damage States (DS's), restoration techniques). This information is gathered using several flood damage repair websites, construction reports related to residential building renovations and interviewing a maintenance and repair worker. These are then synthesized into a dependency mapping restoration schemes to each of the Damage State (DS-A to DS-N). As an example, the full system dependency relationship for a 0.1 m flood (DS-H) within a single building is provided below in Figure 10.

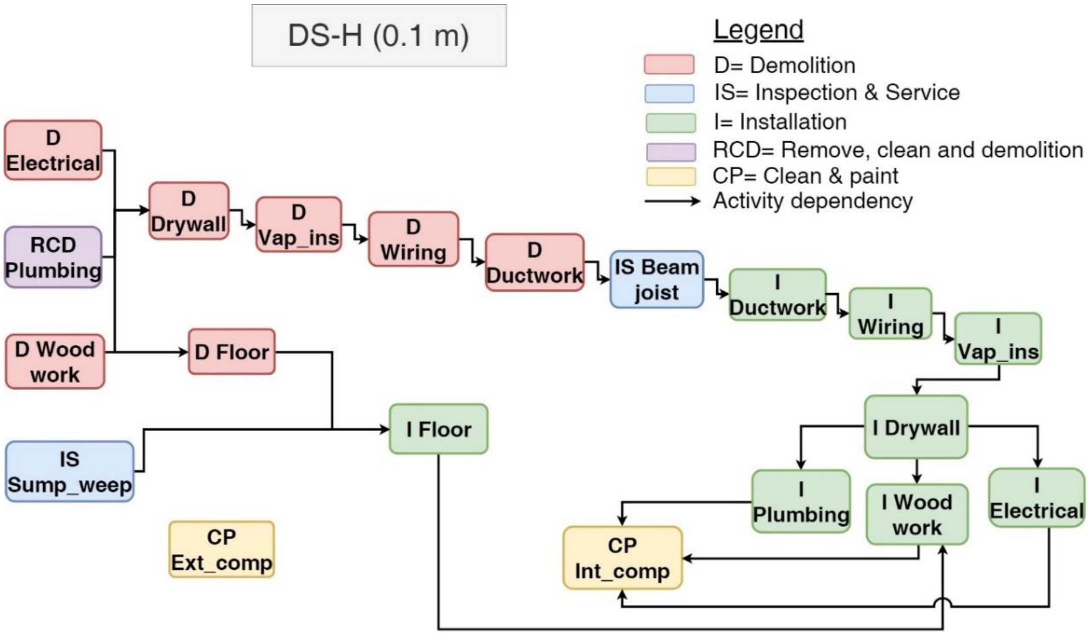


Figure 10 Schematic diagram of dependency among the restoration activities for a single building recovery post-encountering Damage State H (0.1 m depth of flood).

Here, the pink rounded rectangles denote demolition of components and these take place prior to the installation works that are marked by green rounded rectangles. This example includes, inspection and servicing of beam joist and sump pump and weeping tile which need to be performed prior to installation of ductwork and flooring respectively. Here, all the restoration activities are needed to be completed prior to cleaning and painting interior components. Also, cleaning and painting of a building exterior can take place at time within the recovery timeline (CP Ext_comp in the figure).

Restoration dependency maps for the probable minimal damage state A (at -2.6 m depth of water within structure), probable maximum damage state N (at 3.6m depth of water within structure) and some other damage states are presented in Figure D 1 to Figure D 4**.**

3.3.4.2 Workforce dependency

For the representative single-family residential building, recovery resources considered are mostly workforce (i.e., carpenter, electrician, and plumber). The workforce is of great significance, as it is not only a crucial parameter for restoration time calculation, but also plays a great role in prioritizing restoration works due to the assumed limited supply of workforce during a post disaster situation (more details on restoration prioritization is in the next section 3.3.5). From the background study, eight types of specific workforce are identified to be involved throughout the restoration process. These are: carpenter, insulation worker, electrician, plumber, pipe fitter, and skilled labour force.

The workforce types along with their respective restoration works are listed in Table 10. For demonstration purposes, the model is used here with a single group of each type of workforce.

Table 10 Workforce type as per restoration consideration used in recovery modeling.

Workforce	Restoration activity
Carpenter	Demolition and Installation of wood works, drywall, flooring.
Insulation worker	Demolition and installation of vapour barrier and insulation.
Plumber	Remove, clean and install plumbing fixtures and service water heater.
Electrician	Demolition and installation of furnace, electrical works.
Pipe fitter	Demolition and installation of ductwork.
Skilled labour	Clean up prior building restoration activities; inspection and servicing of sump pump and weeping tile.
Wood engineer	Inspection and servicing of beam joist.
Painter	Clean and paint the interior and exterior components.

Recall from Figure 9 that a restoration process only starts to proceed from "initiate" to "end" once the required workforce (i.e., carpenter, plumber etc.) is made available. Once a given restoration requiring a specific type of workforce is complete, then the next restoration activity requiring that workforce can commence. Figure 11 shows the workforce dependencies for damage state H (0.1 m depth of flood inside the structure) as an example.

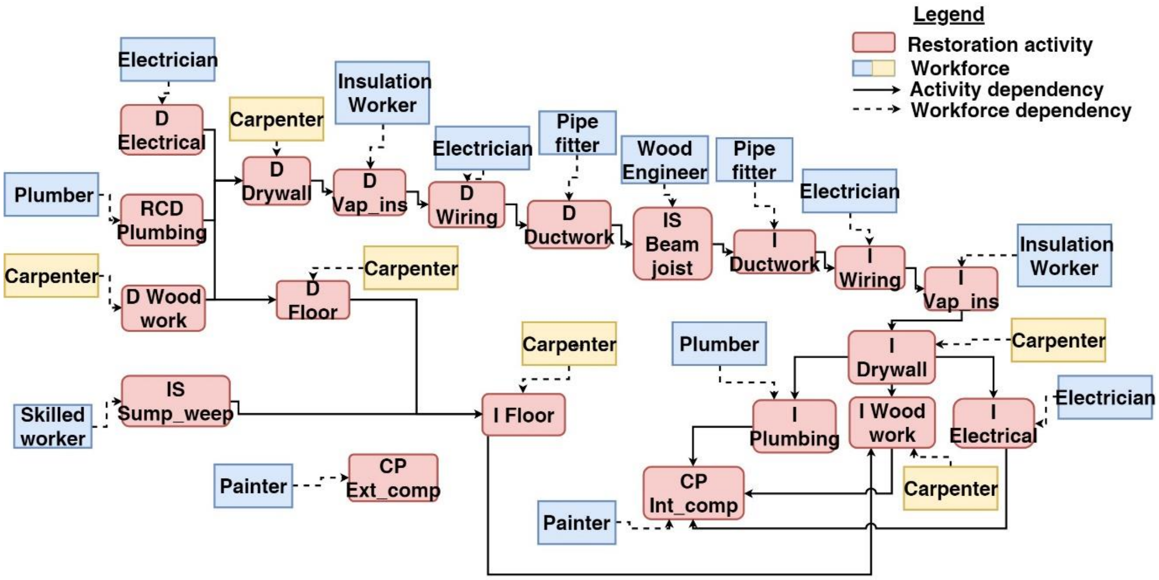


Figure 11 Schematic diagram of workforce dependency for executing the restoration activities for a single building recovery post-encountering Damage State H at (0.1 m depth of water inside structure). Here, *D= demolition, RCD= remove, clean and demolition, IS= Inspection and Service, I=Installation and CP= clean and paint.

From the workforce dependency map alignment, it is found that the carpenter is a critical resource of the recovery model. It is needed by several restoration processes at the same time due to its presence in the parallel restoration pathways. Whereas the rest of the workforce are always required in series manner. For example, an electrician is required for restoring the electrical service panel, outlet, light fixture, furnace and wiring demolition and installation works. But their restoration sequences defined by the restoration dependency follows a series pathway. As a result, Electricians are needed for one work after another, not at the same time (Figure 11). Similarly, the case is for rest of the workforces (i.e., plumber, pipe-fitter etc.) except carpenter. Carpenter can be required for drywall and flooring works at the same time. As a result, proper ordering of this workforce can largely impact the recovery process.

3.3.4 Restoration prioritizing

The prioritization of restoration works is an important factor as during a post disaster situation, supply is always limited, and proper distribution has a great impact on the recovery process. However, the optimal order is not necessarily known, especially during recovery planning and decision making that follows right after a natural disaster (Lubashevskiy et al., 2013).

To solve this problem, Event tree analysis (ETA) is used in this research to determine the total number of possible restoration sequences for each Damage State (DS) of the representative building. The purpose is to use this information to find out the best restoration order possible to develop the optimized recovery pathway for building recovery. ETA is a logical modeling technique for an overall system analysis. It explores possible outcomes from a single initiating event (Rausand and Hoyland, 2003). A previous recovery model in literature, performed resource redistribution (food, medicine etc.) after a natural disaster using a proposed algorithm which was based on resource demand and supply capacity (Lubashevskiy et al., 2013). However, Lubashevskiy et al., method didn’t consider interdependencies among the restoration of components. As a result, ETA is selected as the most suitable method for restoration prioritization as it inherits the ability to consider the interdependencies among the restoration of components.

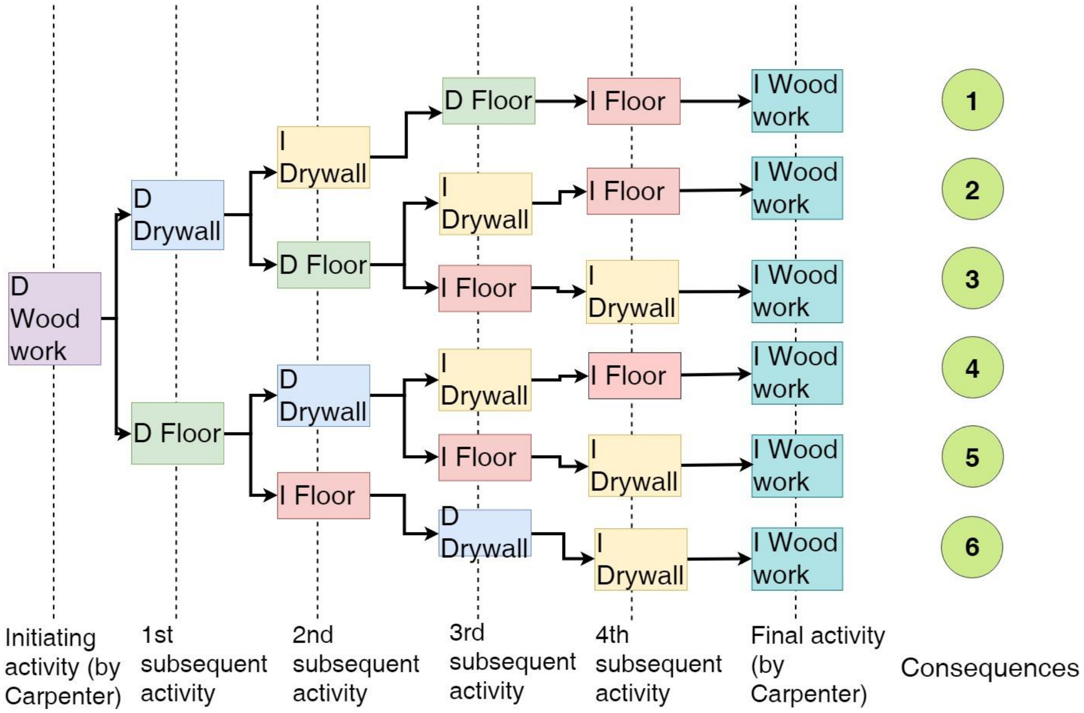


Figure 12 Potential pathways for restoration activity prioritization by Carpenter (event tree analyses). Here, D= demolition and I= Installation.

While performing ETA, the critical workforce carpenter is used as a key to the analysis (Figure 14) because this particular workforce has parallel restoration activities (i.e., drywall and floor restoration works) and these activities are some of the most time consuming activities (as mentioned in previous section). Other factors that are considered during the analysis are: that the demolition of wood work (i.e., baseboard, cabinets, door etc.) needs to be ordered first and its installation must be at the end. Furthermore, the installation of any of the flooring or drywall cannot be performed unless their demolition has already taken place. Performing the ETA analysis reveals a total of six possible permutations (Table 6).

The purpose of ETA is to determine all the possible restoration sequences in order to optimize the building recovery. The specific resources (i.e., workforces) are ordered according to these permutations. Next, the permutations are taken as input to the recovery model. Finally, the overall recovery time is calculated in GMOR for each of the workforce orderings. Finally, the optimal solution for fastest recovery is determined through comparison among all the recovery times.

Table 11 Permutations of restoration works in ascending order for Carpenter. Here, D= demolition and I= Installation.

ID	Sequence of restoration works performed by Carpenter (workforce)
P-1	D Wood – D Drywall – I Drywall – D Floor – I Floor – I Wood work
P-2	D Wood work- D Drywall - D Floor -I Drywall – I Floor – I Wood work
P-3	D Wood work – D Drywall – D Floor – I Floor - I Drywall - I Wood work
P-4	D Wood work – D Floor – D Drywall – I Drywall – I Floor – I Wood work
P-5	D Wood work – D Floor – D Drywall – I Floor – I Drywall - I Wood work
P-6	D Wood work – D Floor – I Floor – D Drywall – I Drywall – I Wood work

3.4 Results and Discussion

The result and discussion section unfold following four segments. These are: (1) comparison of the workforce order permutations, (2) complete recovery times of a single building for each Damage State (DS) following the optimized recovery pathway, (3) building function recovery timeline, and finally, (4) detailed building component restoration timeline.

3.4.1 Optimization of recovery timeline

Recovery time for three basement level water depths (DS-A, C and F), one main floor level water depth (DS-H) and one second floor level water depth (DS-N) are presented in

Table 12 to illustrate a range of results. It shows that recovery times for the highest Damage State (DS-N) (3.6 m depth of water inside structure) tend to require from 167.3 days up to 182.1 days (approx. 6 months). Another finding is the shortest recovery time tends to occur with the third permutation (P-3). This permutation requires the least time for all the DS's except DS-A and DS-B (two of the lowest flood heights). However, the shortest recovery timeline for DS-A and DS-B can be achieved by following P-2 which has a difference of less than a single day with the recovery timeline following P-3. Furthermore, for recovering from DS-N, the improvement of P-3 over half of the permutations (P-1, P-4 and P-6) is as high as nearly 8.2% (or 15 days). As a result, the ordering of P-3 is nominally the best restoration pathway if restricted to choosing a single strategy for all the DSs.

Table 12 Physical restoration time (days) of a single building with respect to flood damage states DS-A, DS-C, DS-F, DS-H and DS-M (depth of flood for these Damage States, DS-A= -2.6 m; DS-C= -2.1 m, DS-F= -0.6 m, DS-H = 0.1 m and DS-N= 3.6 m)

Permutation ID	DS-A	DS-C	DS-F	DS-H	DS-N
P-1	38.9	48.6	55.7	96.7	182.1
P-2	**37.8**	47.5	54.5	95.3	179.4
P-3	38.7	**42.6**	**48.1**	**88.3**	**167.3**
P-4	38.8	48.6	55.7	96.7	182.1
P-5	38.1	42.9	50	88.5	169.1
P-6	39.6	48.6	55.7	96.7	182.1

The overall results of recovery comply with the results of building repair and clean up provided by NiyamIT Inc., (2017). This report provides building recovery timeline against three types of repair requirements. These are, 30 days for moderate repair, 90 days for extensive repair and, 180 days for complete repair. These are similar to recovery timelines for DS-A (-2.6 m depth), DS-H (0.1 m depth) and DS-N (3.6 m depth), respectively.

About the second finding of this section, Figure 13 is presented as an illustration of the workforce ordering for building recovery following P-3 for DS-H (0.1 m of depth of water). Here, the complete recovery process of a building staring from the power inspection and clean up phase is presented. Eight types of workforces are provided with order numbers (as per P-3) throughout the recovery process. For example, the first time an electrician is required is during power investigation in this model. Moreover, after the completion of the clean up phase, the need for an electrician is sequenced among the other workforce requirements to complete the physical restoration of the building.

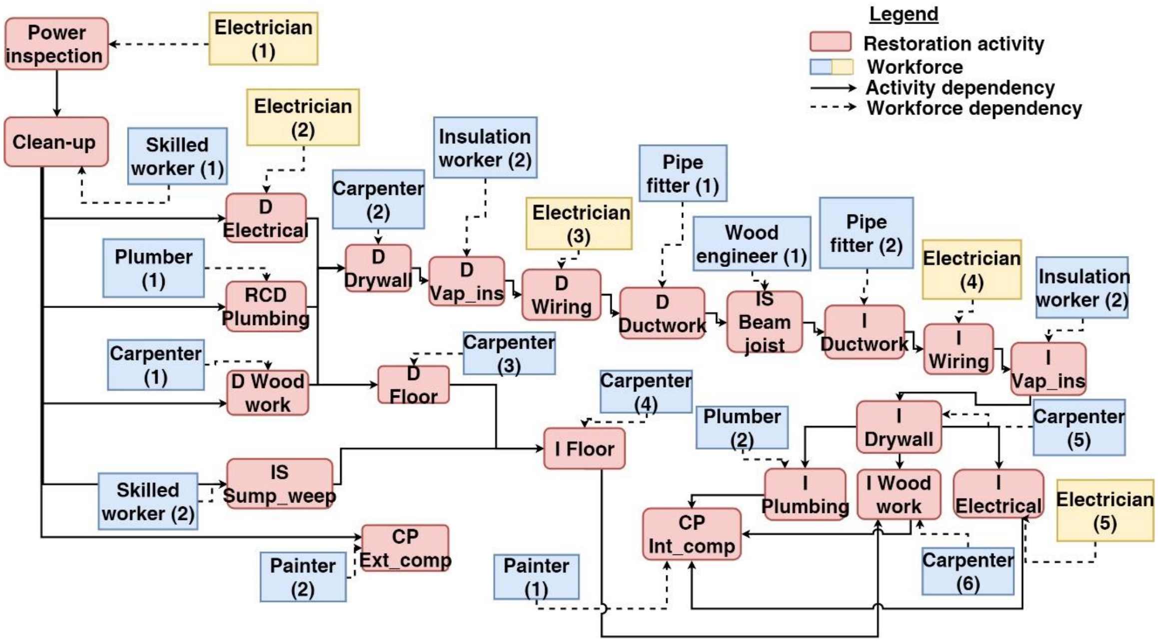


Figure 13 Permutation 3 (P-3) resource ordering for the representative building recovery from damage state H (0.1 m depth of water inside). The number after each workforce name (i.e., (1), (2),..) is its order for prioritizing restoration activity. Here, *D= demolition, RCD= remove, clean and demolition, IS= Inspection and Service, I=Installation and CP= clean and paint.

The inter-relationship among demolishing the damaged electrical works (i.e., outlets, service panel and light fixtures) and dry wall demolition works and other following restoration works can justify the order of all the restoration works and need for prioritizing workforces (except carpenter that has been discussed in previous section).

3.4.2 Building recovery

In Figure 14 compete building recovery is presented for all possible damages for the P-3 permutation. The graph shows the non-linear impacts of flood height increase on the recovery time.

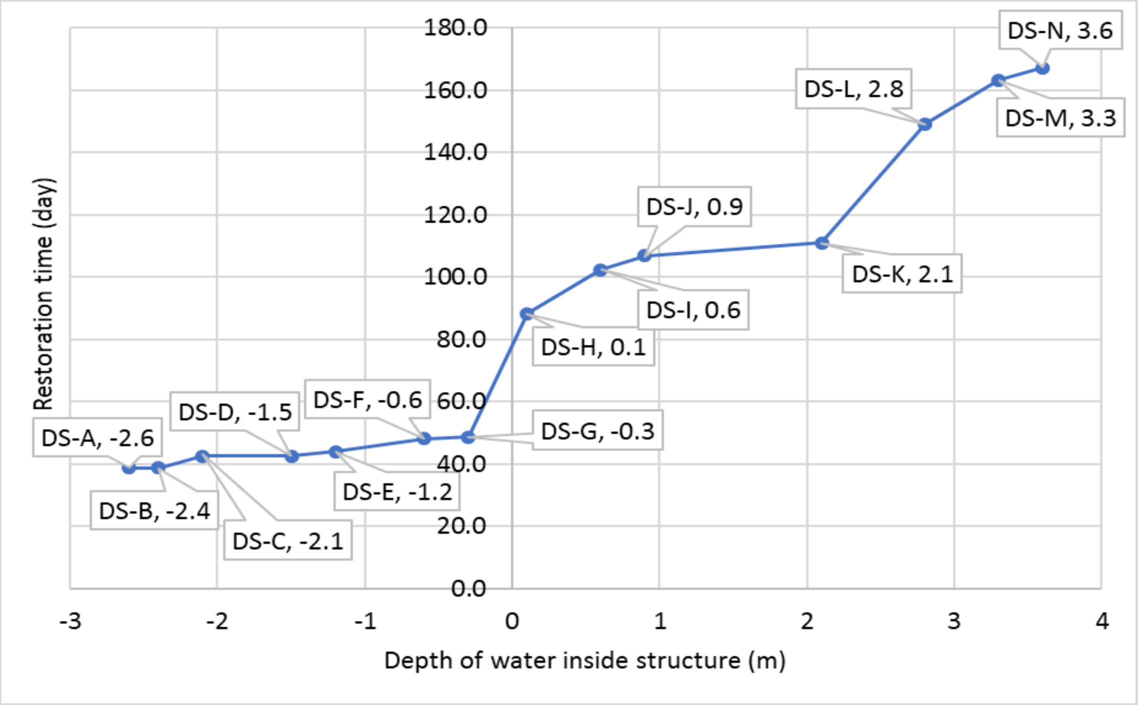


Figure 14 Recovery time of a Single detached two story with basement building for variable flood Damage States (DS-A, -2.6 m depth of water to DS-N, 3.6 m depth of water). These recovery times were determined using Sequence model (Iteration 1).

Here, pronounced increases in recovery time occur once water reaches the main floor level (0.1 m depth of water) and again when water reaches the second floor (2.8 m depth of water). The jumps would have an impact on the viability of successfully recovering a neighbourhood and on the economic prosperity of the region.

In the future, when data becomes available for uncertainty analysis of the model parameters, damage state DS-H and DS-L should be given careful attention because of the large increase in recovery time that occurs at these flood depths. The main floor elevation from ground level (set at a minimum of 0.3 m height from adjacent road mid point by local regulations) would also be an important parameter to include in such an assessment. The main floor elevation may vary for building to building as per City of Surrey, (2010) zoning law. As a result, while considering depth of water inside a structure from an actual flood height, this factor (main floor elevation) may affect the recovery design considerations. Moreover, the accuracy of the recovery time relies on the underlying data accuracy (i.e., building material, dimensions, and local contractors per hour unit costs). All these factors can have a negative impact on the accuracy of final result. This issue needs to be identified and validated in the community level recovery analysis.

3.5.3 Building function recovery

Figure 15 presents the restoration time for building functions by building function category. These are (from Figure 3): architectural, structural, electrical, plumbing, and heating. These components are responsible for collectively performing different functions (i.e., structural, mechanical, and electrical). The recovery model result identifies the complete restoration time of these functions. In the figure, the length of each bar signifies the total time required for each function to be restored. This time is the time when all components within a given building functions category (i.e., structural is to be restored first and architectural last) are restored.

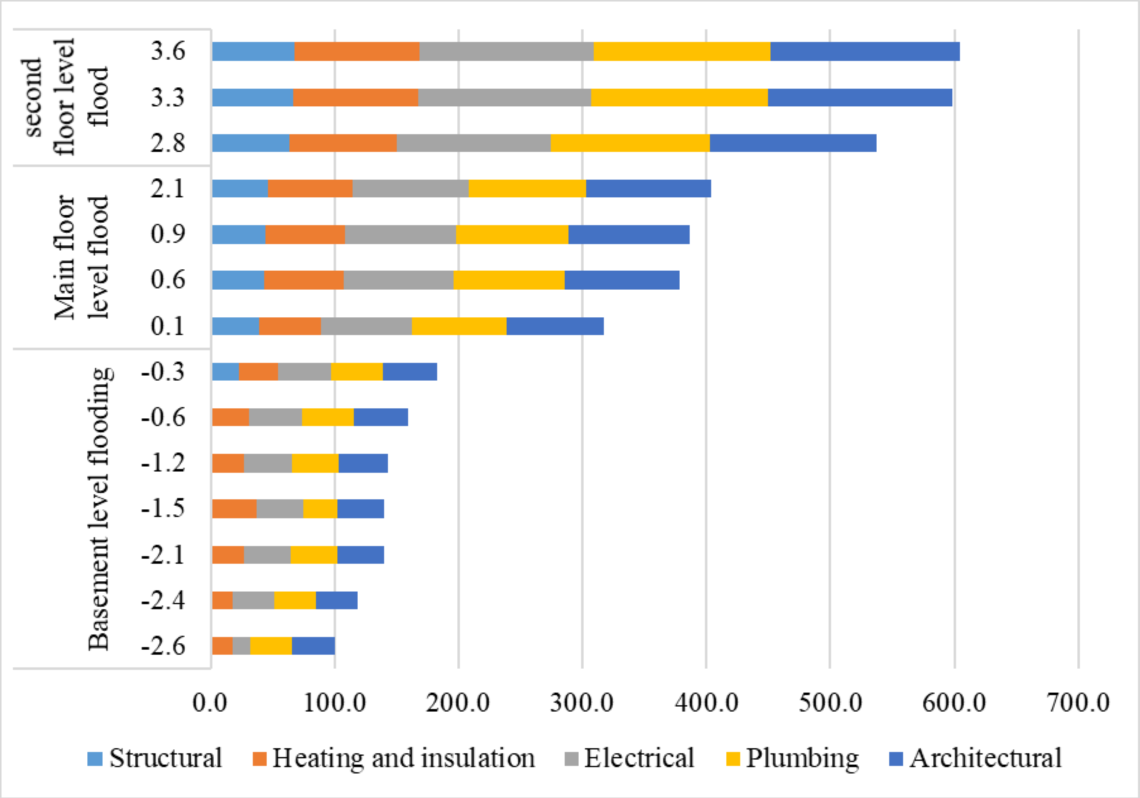


Figure 15 Recovery time of a Single detached two story with basement building for variable flood Damage States (DS-A, -2.6 m depth of water to DS-N, 3.6 m depth of water). These recovery times were determined using Sequence model (Iteration 1).

Here, it is observed that in most of the cases, the plumbing and architectural functions of a building are restored within a similar amount of time. Although electrical restoration time varies depending on the damage state it is found that it is consistent for 0.6 m to 2.1 m flooding and 2.8 to 3.6 m flooding. This is because 0.6 m signifies that all the electrical works existing in main floor needs to be restored. A similar case arises for the 2.8 m flood for the second floor. The structural restoration time is not required until -0.3 m depth of water inside the structure. The restoration time for the heating and insulation function also varies with the damage state (e.g., increasing at -1.5 m and decreasing at -1.2 m). This is a reflection of how the model prioritizes specific restoration activities. These results illustrate some of the patterns and trade-offs that restoration planning decisions have on recovery of the functions. However, these findings by themselves do not define the timeline at which the building can be determined as habitable. The following section provides further insight on this.

3.4.4 Building component recovery

One of the key findings of this research is the expected component level (e.g., flooring, drywall) restoration completion time within the overall recovery. This finding can be considered as baseline data as no similar data could be found in the literature search. The component level recovery timeline is presented in Figure 16 for the P-3 order permutation. Damage State (DS)-A= -2.6 m, DS-H= 0.1 m and DS-N= +3.6 m are selected for presentation among the fourteen DSs.

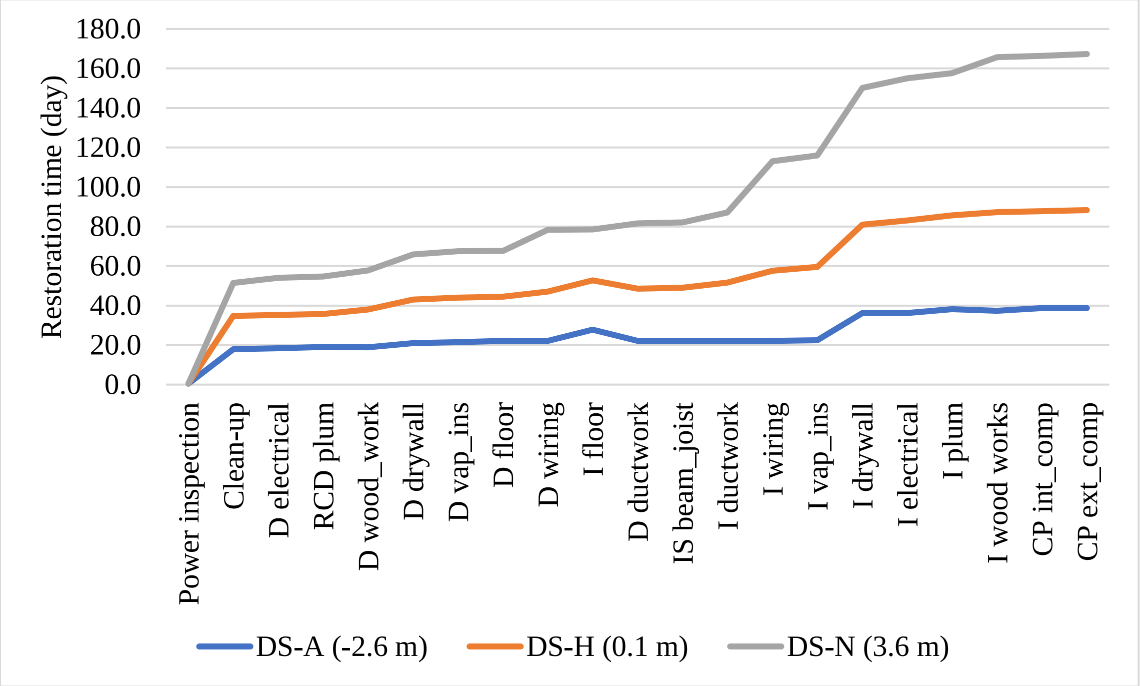


Figure 16 Building component restoration times for the Damage States A, H and N (depth of flood for these damage states, DS-A= -2.6 m, DS-H = 0.1 m and DS-N= 3.6 m). D= demolition, RCD= remove, clean and demolition, IS= Inspection and Service, I=Installation and CP= clean and paint.

Here, it is determined that the whole building clean-up phase for the main floor level flooding takes about a month to complete. This complies with Hazus-MH 2.1 assumption for clean up phase (Department of Homeland Security, 2013; table 14.12). However, Hazus doesn't provide other component level restoration time estimations.

The timeline curves (Figure 16) show sharp bends at various phases of recovery (i.e., installation of flooring and installation of drywall). These bends may depict valuable information about the recovery process. From the recovery timelines, the flooring and drywall is seen to be restored quite a time before the complete recovery of the building (for DS-H about 7 days and for DS-N around 20 days). At this phase the house may be considered habitable as a structure as most of the crucial building functions, such as: structural integrity, heating and ventilation, most of the electric works are restored. The rest of the work that needs to be completed are: kitchen and washroom cabinets, baseboard, door and window fixtures; faucets, commode, bathtub installation; electrical outlets, light fixtures and overall cleaning, painting. Although these are crucial works, they can be addressed one room at a time.

3.4.5 Possible Risk Reduction Measures

From the results, we have identified a range of possible risk reduction measures that may be considered throughout different phases of recovery. The measures reside in three categories. The first category involves recovery implementation. The second one includes recovery design related measures focusing on the coordination of the different types of specialized labour. Finally, the third category deals with community level recovery planning and suggests two probable pathways.

(1) For recovery implementation

Construction and repair works are complex in nature and involve many interlinked tasks that need to be scheduled with proper co-ordination and timing. This research deals with several recovery pathways consisting of many repairs works for each damage case (Appendix F) and suggests the best one complying with the fastest recovery possible. Appointing supervisors to regulate the co-ordination will help with accurate implementation and to save time.

(2) For recovery design

This section deals with the recovery design considerations. As we know, involvement of around eight different types of expert workforce (i.e., electrician, plumber, pipe fitter) has been identified throughout this recovery process and among them, carpenter was found to be critical to the recovery optimization for fastest possible recovery. While allocating workforces to a community level recovery, increasing the number of carpenters to the heavily damaged buildings (experiencing 0.1 m up to building height depth of water) will contribute to quicker recovery.

Again, detailed listing of workforces along with their distribution pattern related to buildings experiencing variable flood damages has been identified (Appendix E). This information can prove useful while designing a recovery plan.

(3) For planning recovery

While dealing with a stock of residential buildings, the impact of two different resource assignment extremes could be explored for prioritising building recovery. The first one aims to recovery the fraction of the stock of buildings quickly and the second focuses on recovering the community within the shortest possible time.

For achieving the first approach, it is recommended to begin the recovery process with the buildings that experienced basement level flooding (-2.7 m up to -0.3 m depth of water inside structure) only. This may help to return a portion of the evacuated population within the shortest possible time and help them to get back to their normal life.

For the second, the available workforce would be prioritised to first address the buildings that experience the most damages (i.e., those with second floor level flooding). This pathway may lead to similar waiting time for all the evacuated people and hence may be perceived as more equitable.

Substantially, flood water deals with moisture and contaminations from indistinct sources, it is recommended to complete the clean-up phase for all the buildings within a community even before prioritising repair, regardless of the extent of damages to avoid secondary damage (i.e., mold growth, buckling of wood works).

Chapter 4: Conclusion

The findings from this study suggest that systemic post-disaster recovery of a building influences the time to gain back the initial functional capacity. There is evidence that prioritizing workforce resources plays an important role in determining the timeline of restoration. The case study recovery analysis of a representative building (located in Bridgeview area, Surrey, BC) following a long term (2-3 days) riverine flooding is performed considering the complete possible damages to the building. The recovery model includes: damage inspection, flood clean-up and physical restoration works. Also, six possible restoration permutations were assessed for each of the flood heights (Damage States A to N). The results of this model can estimate the recovery timeline along with functional and component level restoration data. The order permutation approach illustrates a means to reduce the recovery process timeline compared to the scant restoration times available in the literature (such as Hazus 4.2, Federal Emergency Management Agency, (2019))

One of the key findings are pronounced increases in the recovery curve for small increase in flood depths (at 0.1 m and 2.8 m flood depth) that may have great value in a community level flood recovery design. The establishment that the ordering of the carpenter's efforts is critical in reducing overall restoration time is another important finding. However, the recovery time may relate to some uncertainty as it was derived from a single intensity of flood hazard that is the depth of water. Again, the representative building of the case study may have variation in characteristics (i.e., main floor elevation, material) compared to existing buildings in that region. These factors may lead to recovery time differences. Furthermore, uncertainty considerations associated with weather, workforce productivity, material transportation disruption, and warning time before the flood event are not considered. With the available data the impact of these uncertainty factors cannot yet be assessed, however this work suggests that addressing issues of uncertainty in future studies may be valuable in refining our understanding of flood recovery of buildings. For such efforts, location specific recovery cost estimation can be investigated through collaboration with local contractors, insurance providers, local government, home owners, and commercial and industrial experts. More detailed recording and publishing of empirical recovery times may further help in addressing issues of uncertainty and help refine understanding of flood recovery risk in the Canadian regions where flood is represented as one of the extreme challenges to property owners.

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Appendix A

Online survey findings for representative building selection for Bridgeview area, building materials and specifications

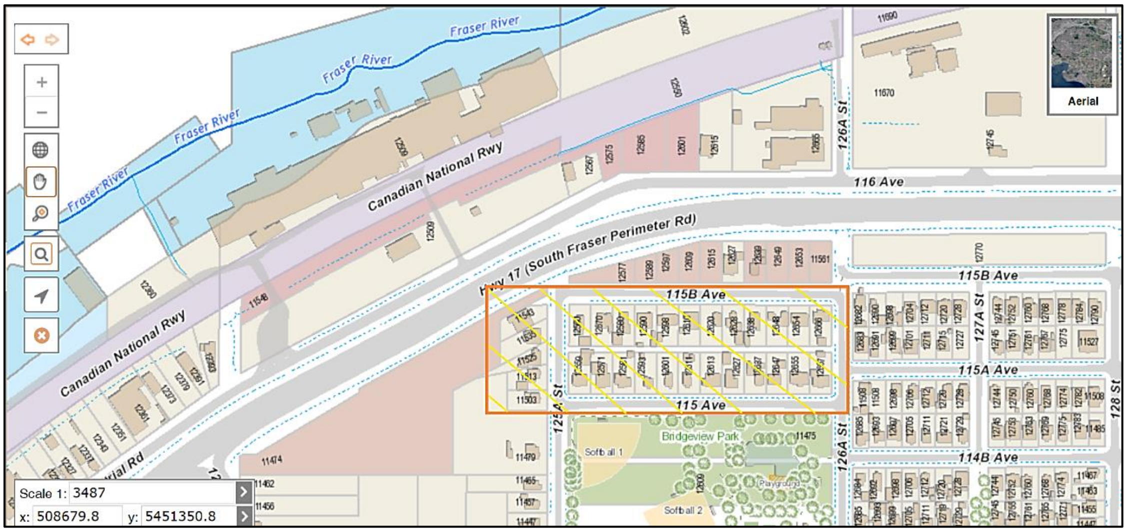

Figure A 1 RF- Single family residential zone, Bridgeview, north Vancouver (City of Surrey Mapping Online System (COSMOS), 2019). Here brown box with yellow hatched area is the surveyed area based on online data to determine representative building of that region for recovery modeling.

Table A 1 Selected building detail of RF- Single family residential zone, Bridgeview, north Vancouver (City of Surrey (2019a), BC Assessment (2019))

ID	Building No.	Avenue	Year built	Type	Total Area (Sq. ft.)	With Basement	No of storey	Total (land+ building) value ($)
1	12560	115B	1940	basic	1054	N	1	615,600
2	12570	115B	1945	basic	1370	N	2	625,500
3	12580	115B	1949	basic	2298	N	1	628,300
4	12590	115B	1958	standard	1221	N	1	639,600
5	12598	115B	1960	standard	1370	Y	1	628,000
6	12610	115B	1947	basic	1742	Y	1.5	618,600
7	12620	115B	1944	basic	772	N	1	605,800
8	12628	115B	1944	basic	1320	N	2	629,900
9	12638	115B	1945	basic	1662	N	2	625,500
10	12648	115B	1945	basic	888	N	1	609,900
11	12654	115B	1979	standard	2551	Y	2	660,500
12	12666	115B	1943	basic	1920	N	2	627,100
13	12613	113B	1953	basic	1015	N	1	588,600

14	12667	115	1959	standard	1515	Y	1	617,200
15	12655	115	1992	standard	2783	Y	2	724,000
16	12647	115	1956	standard	976	N	1	615,300
17	12637	115	1962	basic	816	N	1	615,400
18	12627	115	1945	standard	1680	Y	2	630,300
19	12613	115	1981	standard	2385	Y	2	722,000
20	12611	115	1946	basic	724	N	1	607,700
21	12601	115	1955	basic	847	N	1	607,300
22	12637	115	1962	basic	816	N	1	647,000
23	12593	115	1946	basic	782	Y	1.5	611,500
24	12581	115	1946	standard	1708	N	2	658,400
25	12571	115	1956	standard	1530	N	1.5	627,900
26	12559	115	1955	standard	2274	Y	2	639,400
27	11535	125A	1988	standard	2661	Y	2	715,800
28	11525	125A	1987	standard	1098	Y	1	671,500
29	11388	124	1941	Basic	1097	Y	2	772,800
30	11279	132	1961	standard	935	Y	1	664,400

* Basic: Modest, economical housing of its era, built with minimal design features and few, if any, decorative features.

**Standard: Very typical for its era, having met basic building code requirements of the time, and was built with average quality building materials (BC Assessment, 2019).

Table A 2 Building component specification for representative building.

Components	Quality	Page no (Gordian, 2019)
Carpeting	Average grade carpeting	(P 246)
Kitchen cabinets and counter tops	Four 24-inch Island base cabinet	(P 227)
Bathroom cabinets	One 42-inch w, 2 door, 2 drawers	(P 224)
Windows	Double hung, two light, 3 ft. by 2 ft.	(P 108)
Doors	2.5 ft. by 6ft 8 inch (solid core)	(P 195)
Stairs	Job- built	(P 47)
Electrical service panel	150 Amp.	(P 165)
Furnace	110 MBH	(P 156)
Water heater	40 Gallon	(P 149)
Plumbing fixture	Floor mounted commode and porcelain sink	(P 251, 252)
Baseboard	2.5-inch base molding	(P 201)
Flooring	Ceramic tile flooring (Average grade)	(P 243)
Wall and ceiling Drywall	5/8-inch fire rated	(P 178)
Poly vapour barrier	Vapor barrier	(P 168)
Insulation	6-inch R-19	(P 168)
Mechanical ductwork	8" insulated, considering 40 L. m.	(P 152)

Appendix B

Post-disaster phases of residential building recovery, such as: inspection, preparation and clean-up

Awakening of lives through picking up pieces and restoring houses is one of the toughest challenges people face after a widespread flood event. Following are the information related post- disaster recovery recommended by Emergency Management, BC (Emergency Management BC, 2015) and U.S. department of housing and urban development office (U.S. Department of Housing and Urban Development and Office of Lead Hazard Control, 2015).

Inspection after a flood event (interior of the building) to ensure specific objectives, these may be:

1. For safe access to the house. This means no downed power lines, road washouts or debris and volatile fumes posing a travel danger.
2. Power source of the house needs to be inspected by an electrical inspector or electrician.
3. Heating systems and large appliances by qualifies technician.
4. Building inspection for buckled walls or floor and travel hazards such as: glass and hazardous debris.

Preparation phase for restoration may include following activities, such as (This phase was considered excluded from the studies scope for associated uncertainties):

1. Ensuring that BC Hydro has disconnected the electricity prior inspection and restoration (written declaration is required before reconnection is required).
2. Listing things and keeping record of damaged items before starting clean-up and repairing damage.
3. Contacting insurance agents or authorities to verify if damage caused by flooding is covered by insurance policy or Disaster Financial Assistance (DFA).
4. Organizing and developing a recovery plan. Contacting workforces and estimating materials accordingly.
5. Getting power, water and gas systems into operation.

Clean-up phase after a flood event may consist of the following:

1. Cleaning, disinfection, rinsing and keeping dry all surfaces, wall and floor areas of the flooded house.
2. Removing, cleaning and disinfect non-permanent building contents (such as: furniture, appliance and carpeting) and debris deposition.
3. Disinfection of floor drains and sump pumps.

Appendix C

Detailed physical restoration activities of a single residential building for three significant Damage States, H and N (0.1 m and 3.6 m depth of water inside structure)

Table C 1 Restoration scheme for Damage State H (0.1 m depth of water inside structure). Depths are measured from main floor.

Activity ID	Abbreviation	Restoration activity
1	D Wood work	Demolition of Baseboard of basement
		Demolition of Bathroom cabinets of basement
		Demolition of Doors, wood casings and door jambs of basement
		Demolition of Windows of basement
		Demolition of Baseboard of main floor
		Demolition of Kitchen cabinets of main floor
		Demolition of Bathroom cabinets of main floor
		Demolition of Doors, wood casings and door jambs of main floor
		Demolition of Stairs
		Demolition of Doors and hardware of garage
2	D Furnace	Demolition of Furnace
3	RCD Plum	Remove and clean Bathroom toilet, sink and tub of basement
		Remove and clean Bathroom toilet, sink and tub of main floor
		Demolition of Hot water heater
4	IS Sump_weep	Inspection and clean Sumps and weeping tile
5	IS Beam joist	Inspection and clean Beam and floor joist
6	D Drywall	Demolition of Drywall to walls and ceilings of basement
		Demolition of Drywall to walls and ceilings of main floor
7	D Vap_ins	Demolition of Poly vapour barrier and insulation of basement
		Demolition of Poly vapour barrier and insulation of main floor
		Demolition of Poly vapour barrier and insulation of garage
8	D Electrical	Demolition of Wiring, electrical outlets, switches, light fixtures of basement back to the service panel
		Demolition of electrical service panel
9	D Ductwork	Demolition of Ductwork
10	I Ductwork	Installation of Ductwork
11	I Electrical	Installation of electrical service panel
		Installation of Wiring, electrical outlets, switches, light fixtures of basement back to the service panel
12	I Vap_ins	Installation of Poly vapour barrier and insulation of basement
		Installation of Poly vapour barrier and insulation of main floor

		Installation of Poly vapour barrier and insulation of garage
13	I Drywall	Installation of Drywall to walls and ceilings of basement
		Installation of Drywall to walls and ceilings of main floor
14	I Wood work	Installation of Baseboard of basement
		Installation of Bathroom cabinets of basement
		Installation of Doors, wood casings and door jambs of basement
		Installation of Windows of basement
		Installation of Baseboard of main floor
		Installation of Kitchen cabinets of main floor
		Installation of Bathroom cabinets of main floor
		Installation of Doors, wood casings and door jambs of main floor
		Installation of Stairs
		Installation of Doors and hardware of garage
15	I Furnace	Installation of Furnace
16	I Plum	Installation of Bathroom toilet, sink and tub of basement
		Installation of Bathroom toilet, sink and tub of main floor
		Installation of Hot water heater
17	D Floor	Demolition of Flooring of basement
		Demolition of Flooring of main floor
18	I Floor	Installation of Flooring and Carpeting of basement
		Installation of Flooring and Carpeting of main floor
19	CP Int_comp	Clean and paint Structural components of basement
		Clean and paint Structural components of main floor
		Clean and paint Structural components of garage
20	CP Ext_comp	Clean and paint Exterior building finishes

Table C 2 Restoration scheme for Damage State N (3.6 m depth of water inside structure). Depths are measured from main floor.

Activity ID	Abbreviation	Restoration activity
1	D Wood work	Demolition of Baseboard of basement
		Demolition of Bathroom cabinets of basement
		Demolition of Doors, wood casings and door jambs of basement
		Demolition of Windows of basement
		Demolition of Baseboard of main floor
		Demolition of Kitchen cabinets of main floor
		Demolition of Bathroom cabinets of main floor
		Demolition of Doors, wood casings and door jambs of main floor

		Demolition of Stairs
		Demolition of Doors and hardware of garage
		Demolition of Windows of main floor
		Demolition of Windows of garage
		Demolition of Baseboard of second floor
		Demolition of Bathroom cabinets of second floor
		Demolition of Doors, wood casings and door jambs of second floor
		Demolition of Windows of second floor
2	D Furnace	Demolition of Furnace
3	RCD Plum	Remove and clean Bathroom toilet, sink and tub of basement
		Remove and clean Bathroom toilet, sink and tub of main floor
		Remove and clean Bathroom toilet, sink and tub of second floor
		Demolition of Hot water heater
4	IS Sump_weep	Inspection and clean Sumps and weeping tile
5	IS Beam joist	Inspection and clean Beam and floor joist
6	D Drywall	Demolition of Drywall to walls and ceilings of basement
		Demolition of Drywall to walls and ceilings of main floor
		Demolition of Drywall to walls and ceilings of second floor
7	D Vap_ins	Demolition of Poly vapour barrier and insulation of basement
		Demolition of Poly vapour barrier and insulation of main floor
		Demolition of Poly vapour barrier and insulation of second floor
		Demolition of Poly vapour barrier and insulation of garage
8	D Electrical	Demolition of electrical service panel
		Demolition of Wiring, electrical outlets, switches, light fixtures of Basement
		Demolition of Wiring, electrical outlets, switches, light fixtures of Main floor
		Demolition of Wiring, electrical outlets, switches, light fixtures of Garage
		Demolition of Wiring, electrical outlets, switches, light fixtures of Second floor
9	D Ductwork	Demolition of ductwork of basement and main floor
		Demolition of ductwork of second floor
10	I Ductwork	Installation of second floor
		Installation of Ductwork
11	I Electrical	Installation of electrical service panel
		Installation of Wiring, electrical outlets, switches, light fixtures of Basement back to the service panel
		Installation of Wiring, electrical outlets, switches, light fixtures of Main floor back to the service panel

		Installation of Wiring, electrical outlets, switches, light fixtures of Garage back to the service panel
		Installation of Wiring, electrical outlets, switches, light fixtures of Second floor back to the service panel
12	I Vap_ins	Installation of Poly vapour barrier and insulation of basement
		Installation of Poly vapour barrier and insulation of main floor
		Installation of Poly vapour barrier and insulation of second floor
		Installation of Poly vapour barrier and insulation of garage
13	I Drywall	Installation of Drywall to walls and ceilings of basement
		Installation of Drywall to walls and ceilings of main floor
		Installation of Drywall to walls and ceilings of second floor
14	I Wood work	Installation of Baseboard of basement
		Installation of Bathroom cabinets of basement
		Installation of Doors, wood casings and door jambs of basement
		Installation of Windows of basement
		Installation of Baseboard of main floor
		Installation of Kitchen cabinets of main floor
		Installation of Bathroom cabinets of main floor
		Installation of Doors, wood casings and door jambs of main floor
		Installation of Stairs
		Installation of Doors and hardware of garage
		Installation of Windows of main floor
		Installation of Windows of garage
		Installation of Baseboard of second floor
		Installation of Bathroom cabinets of second floor
		Installation of Doors, wood casings and door jambs of second floor
		Installation of Windows of second floor
15	I Furnace	Installation of Furnace
16	I Plum	Installation of Bathroom toilet, sink and tub of basement
		Installation of Bathroom toilet, sink and tub of main floor
		Installation of Bathroom toilet, sink and tub of second floor
		Installation of Hot water heater
17	D Floor	Demolition of Flooring of basement
		Demolition of Flooring of main floor
		Demolition of Flooring of second floor
18	I Floor	Installation of Flooring and Carpeting of second floor
		Installation of Flooring and Carpeting of basement
		Installation of Flooring and Carpeting of main floor
19	CP Int_comp	Clean and paint Structural components of basement
		Clean and paint Structural components of main floor
		Clean and paint Structural components of garage
20	CP Ext_comp	Clean and paint Exterior building finishes

Appendix D

Restoration activity dependency maps of a single residential building for Damage States- A, C, F and N (-2.6 m, -2.1 m, -0.6 m and 3.6 m depth of water inside structure)

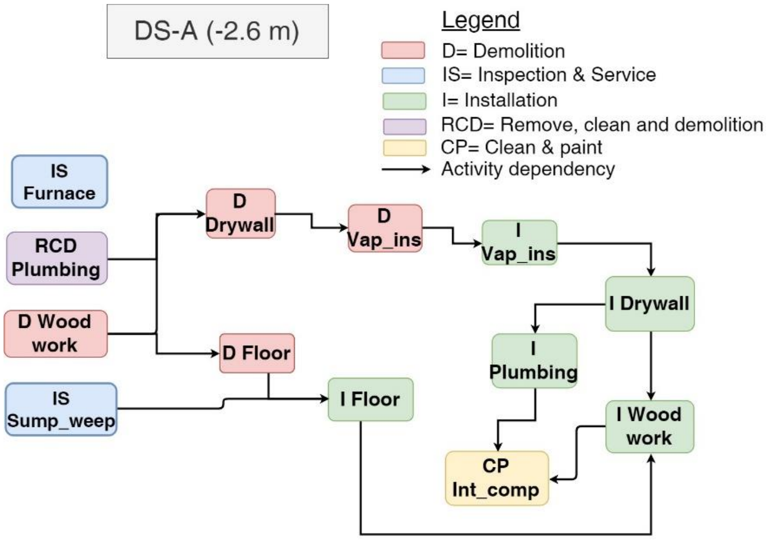

Figure D 1 Schematic diagram of dependency among the restoration activities for a single building recovery post-encountering Damage State A (-2.6 m depth of water inside structure).

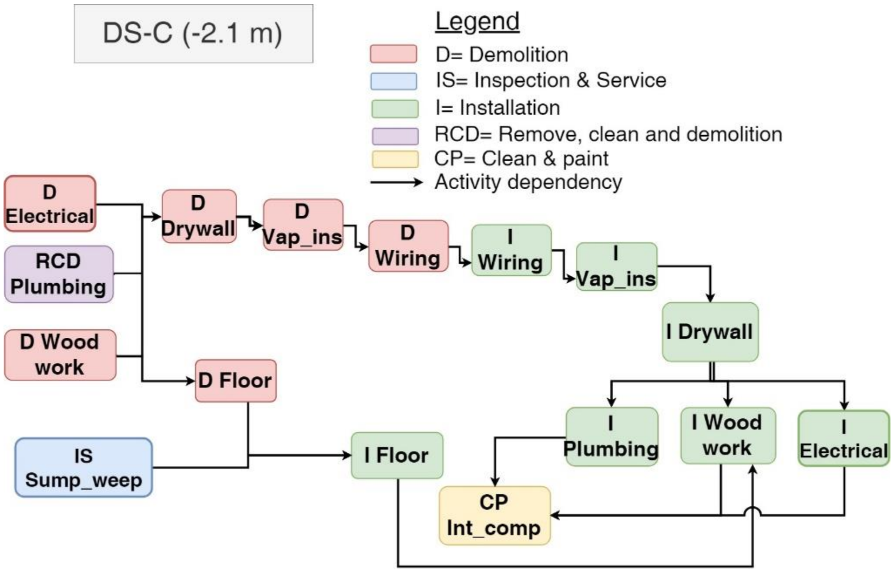

Figure D 2 Schematic diagram of dependency among the restoration activities for a single building recovery post-encountering Damage State C (-2.1 m depth of water inside structure).

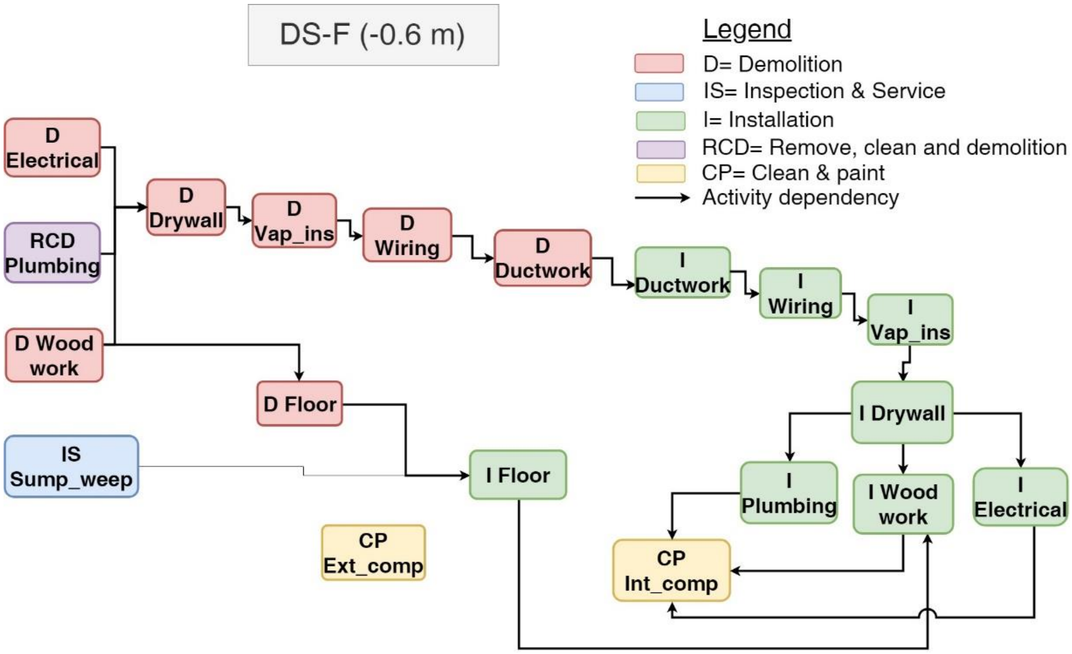

Figure D 3 **Schematic diagram of dependency among the restoration activities for a single building recovery post-encountering Damage State F (-0.6 m depth of water inside structure).**

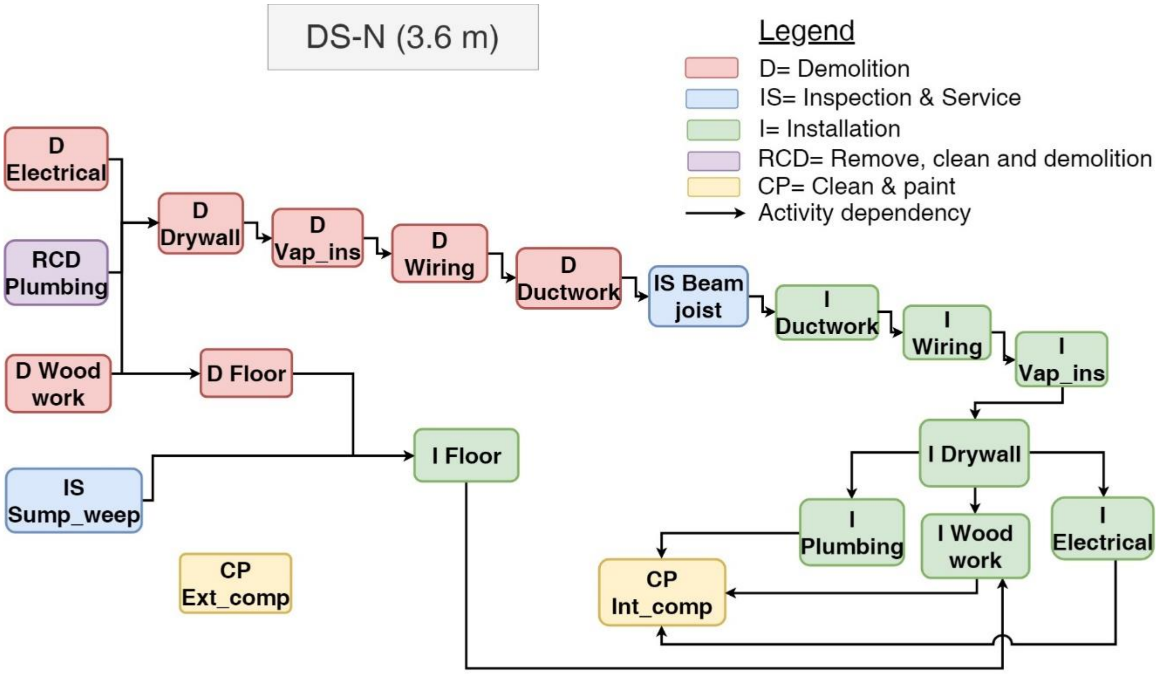

Figure D 4 Schematic diagram of dependency among the restoration activities for a single building recovery post-encountering Damage State N (3.6 m depth of water inside structure).

Appendix E

Single residential building restoration dependencies (workforce and activity) used in GMOR for the Damage States A, H and N (-2.6 m, 0.1 and +3.6 m depth of flood inside structure) using Iteration 1 in GMOR recovery model

Table E 1 GMOR input dependency among the restoration works for a single building recovery post-encountering Damage State A (-2.6 m depth of water inside structure)

Restoration Activities	Restoration resources	Restoration dependencies
Power_inspection_DS-A	{Electrician:1}	
Clean_up _DS-A	{Skilled_labour:1}	[Power_inspection_DS-A]
D_wood_work_DS-A	{Carpenter:1}	[Clean_up _DS-A]
RCD_plum_DS-A	{Plumber:1}	[Clean_up _DS-A]
IS_furnace_DS-A	{Electrician:1}	[Clean_up _DS-A]
IS Sump_weep	{Skilled_labour:1}	[Clean_up _DS-A]
D_drywall_DS-A	{Carpenter:1}	[D_wood_work_DS-A, RCD_plum_DS-A]
D_floor_DS-A	{Carpenter:1}	[D_wood_work_DS-A]
I_floor_DS-A	{Carpenter:1}	[D_floor_DS-A, IS Sump_weep_DS-A]
D_vap_ins_DS-A	{Insulation_worker:1}	[D_drywall_DS-A]
I_vap_ins_DS-A	{Insulation_worker:1}	[D_vap_ins_DS-A]
I_drywall_DS-A	{Carpenter:1}	[I_vap_ins_DS-A]
I_wood_work_DS-A	{Carpenter:1}	[I_drywall_DS-A, I_floor_DS-A]
I_plum_DS-A	{Plumber:1}	[I_drywall_DS-A]
CP_int_comp_DS-A	{Painter:1}	[IS_furnace_DS-A, I_plum_DS-A, I_wood_work_DS-A]

Table E 2 GMOR input dependency among the restoration works for a single building recovery post-encountering Damage State H (0.1 m depth of water inside structure)

Restoration activities	Restoration resources	Restoration dependencies
Power_inspection_DS-H	{Electrician:1}	
Clean_up _DS-H	{Skilled_labour:1}	[Power_inspection_DS-H]
D_wood_work_DS-H	{Carpenter:1}	[Clean_up _DS-H]
RCD_plum_DS-H	{Plumber:1}	[Clean_up _DS-H]
IS Sump_weep_DS-H	{Skilled_labour:1}	[Clean_up _DS-H]
D_electrical_DS-H	{Electrician:1}	[Clean_up _DS-H]
D_drywall_DS-H	{Carpenter:1}	[D_wood_work_DS-H, RCD_plum_DS-H, D_electrical_DS-H]
D_floor_DS-H	{Carpenter:1}	[D_wood_work_DS-H]

I_floor_DS-H	{Carpenter:1}	[D_floor_DS-H, IS Sump_weep_DS-H]
D_vap_ins_DS-H	{Insulation_worker:1}	[D_drywall_DS-H]
D_wiring_DS-H	{Electrician:1}	[D_vap_ins_DS-H]
D_ductwork_DS-H	{Pipe_fitter:1}	[D_wiring_DS-H]
IS_beam_joist_DS-H	{Wood_engineer:1}	[D_ductwork_DS-H]
I_ductwork_DS-H	{Pipe_fitter:1}	[IS_beam_joist_DS-H]
I_wiring_DS-H	{Electrician:1}	[I_ductwork_DS-H]
I_vap_ins_DS-H	{Insulation_worker:1}	[I_wiring_DS-H]
I_drywall_DS-H	{Carpenter:1}	[I_vap_ins_DS-H]
I_electrical_DS-H	{Electrician:1}	[I_drywall_DS-H]
I_wood_work_DS-H	{Carpenter:1}	[I_drywall_DS-H, I_floor_DS-H]
I_plum_DS-H	{Plumber:1}	[I_drywall_DS-H]
CP_int_comp_DS-H	{Painter:1}	[I_plum_DS-H, I_wood_work_DS-H, I_electrical_DS-H]
CP_Ext_comp_DS-H	{Painter:1}	

Table E 3 GMOR input dependency among the restoration works for a single building recovery post-encountering Damage State N (+3.6 m depth of water inside structure)

Restoration activities	Restoration resources	Restoration dependencies
Power_inspection_DS-N	{Electrician:1}	
Clean_up _DS-N	{Skilled_labour:1}	[Power_inspection_DS-N]
D_wood_work_DS-N	{Carpenter:1}	[Clean_up _DS-N]
RCD_plum_DS-N	{Plumber:1}	[Clean_up _DS-N]
IS Sump_weep_DS-N	{Skilled_labour:1}	[Clean_up _DS-N]
D_electrical_DS-N	{Electrician:1}	[Clean_up _DS-N]
D_drywall_DS-N	{Carpenter:1}	[D_wood_work_DS-N, RCD_plum_DS-N, D_electrical_DS-N]
D_floor_DS-N	{Carpenter:1}	[D_wood_work_DS-N]
I_floor_DS-N	{Carpenter:1}	[D_floor_DS-N, IS Sump_weep_DS-N]
D_vap_ins_DS-N	{Insulation_worker:1}	[D_drywall_DS-N]
D_wiring_DS-N	{Electrician:1}	[D_vap_ins_DS-N]
D_ductwork_DS-N	{Pipe_fitter:1}	[D_wiring_DS-N]
IS_beam_joist_DS-N	{Wood_engineer:1}	[D_ductwork_DS-N]
I_ductwork_DS-N	{Pipe_fitter:1}	[IS_beam_joist_DS-N]
I_wiring_DS-N	{Electrician:1}	[I_ductwork_DS-N]
I_vap_ins_DS-N	{Insulation_worker:1}	[I_wiring_DS-N]
I_drywall_DS-N	{Carpenter:1}	[I_vap_ins_DS-N]
I_electrical_DS-N	{Electrician:1}	[I_drywall_DS-N]
I_wood_work_DS-N	{Carpenter:1}	[I_drywall_DS-N, I_floor_DS-N]
I_plum_DS-N	{Plumber:1}	[I_drywall_DS-N]

CP_int_comp_DS-N	{Painter:1}	[I_plum_DS-N, I_wood_work_DS-N, I_electrical_DS-N]
CP_Ext_comp_DS-N	{Painter:1}	

Appendix F

Single residential building component restoration timeline for the Damage States A to N (-2.6 m to +3.6 m depth of flood inside structure) using Iteration 1 in GMOR recovery model

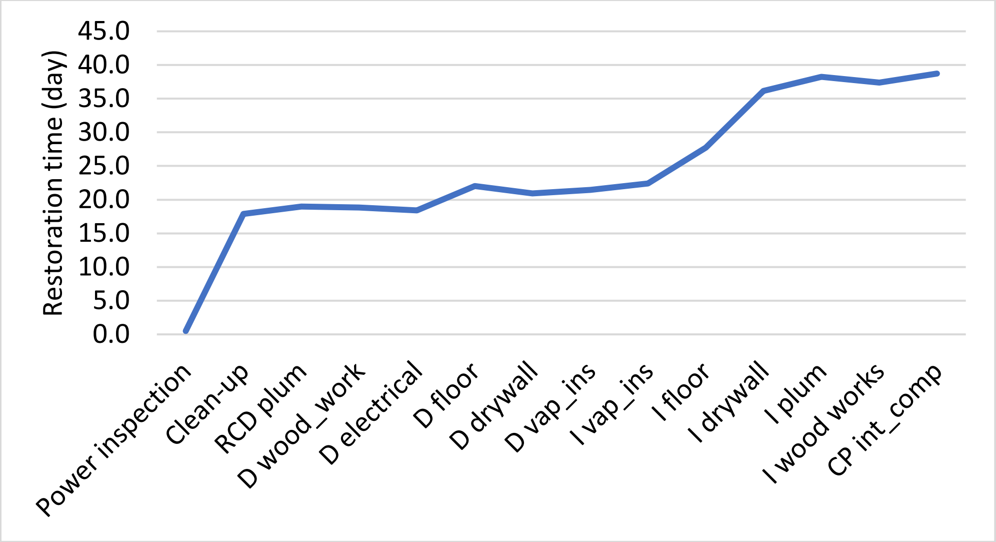

Figure E 1 Iteration 1 end times of building component restoration for the Damage States A. (depth of flood, DS-A= -2.6 m)

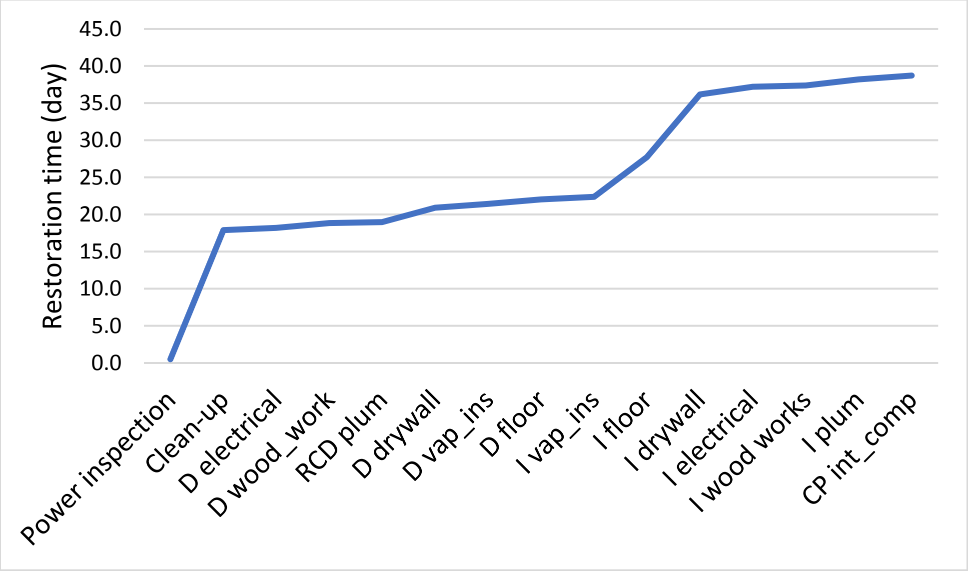

Figure E 2 Iteration 1 end times of building component restoration for the Damage States B. (depth of flood, DS-B= -2.4 m)

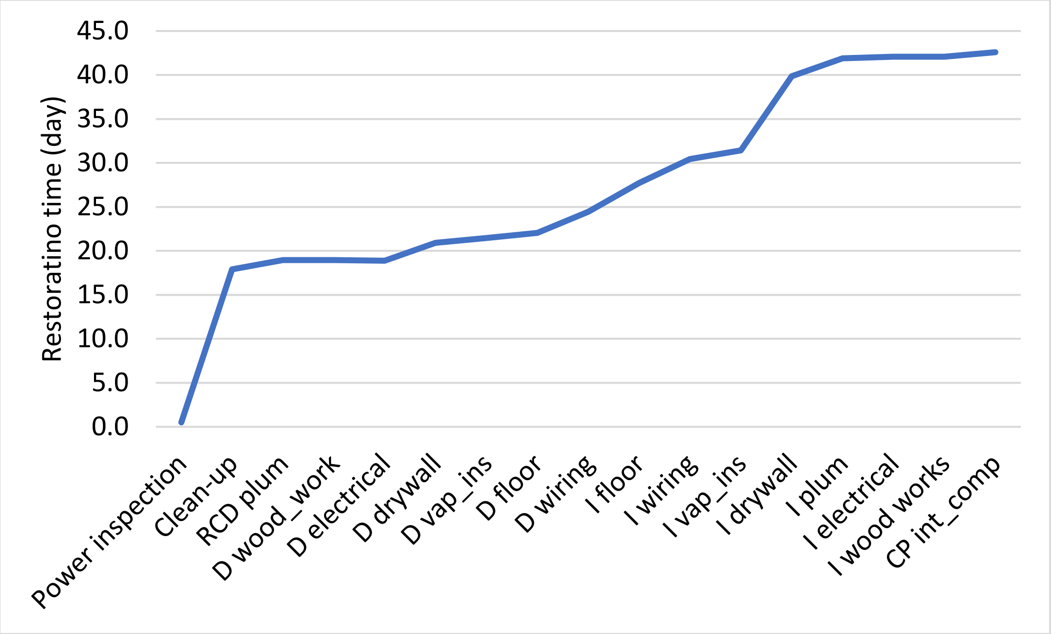

Figure E 3 Iteration 1 end times of building component restoration for the Damage States C. (depth of flood, DS-C= -2.1 m)

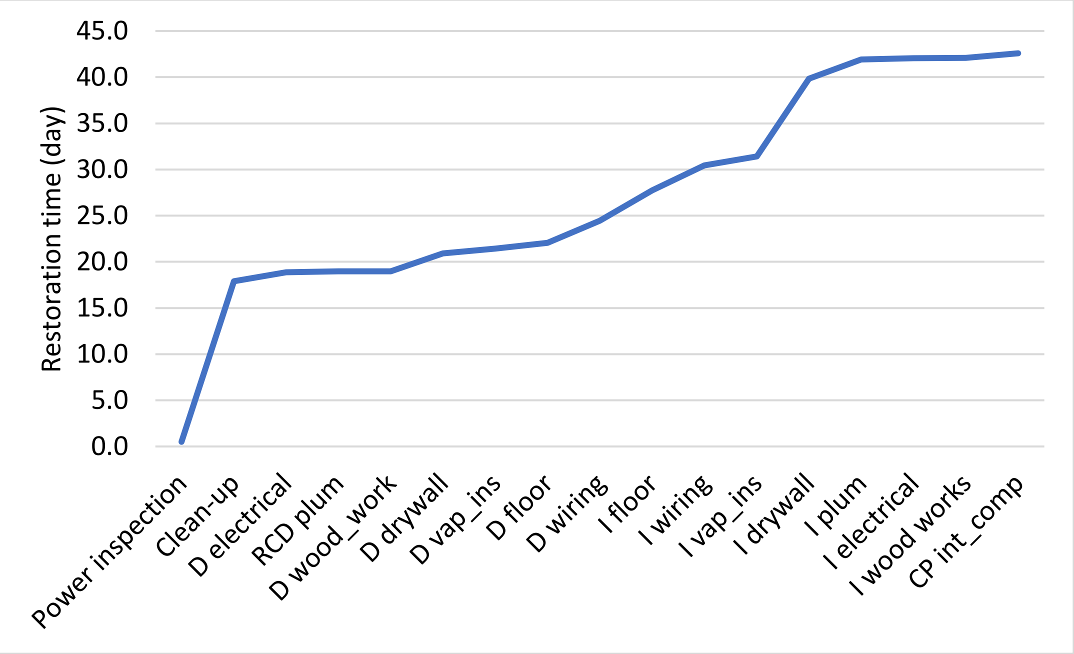

Figure E 4 Iteration 1 end times of building component restoration for the Damage States D. (depth of flood, DS-D= -1.5 m)

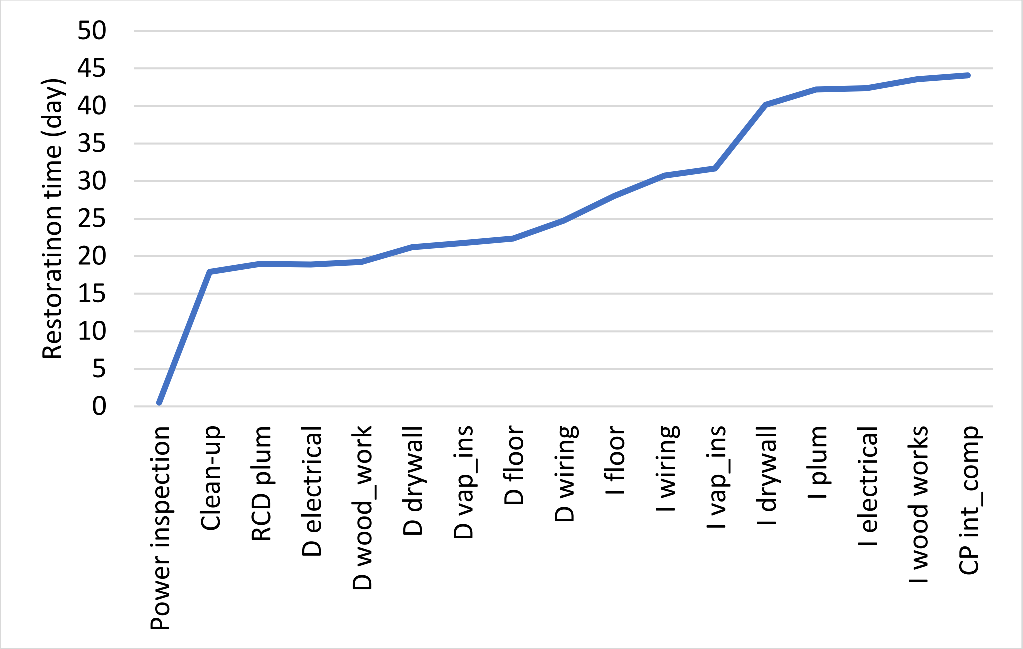

Figure E 5 Iteration 1 end times of building component restoration for the Damage States E. (depth of flood, DS-E= -1.2 m)

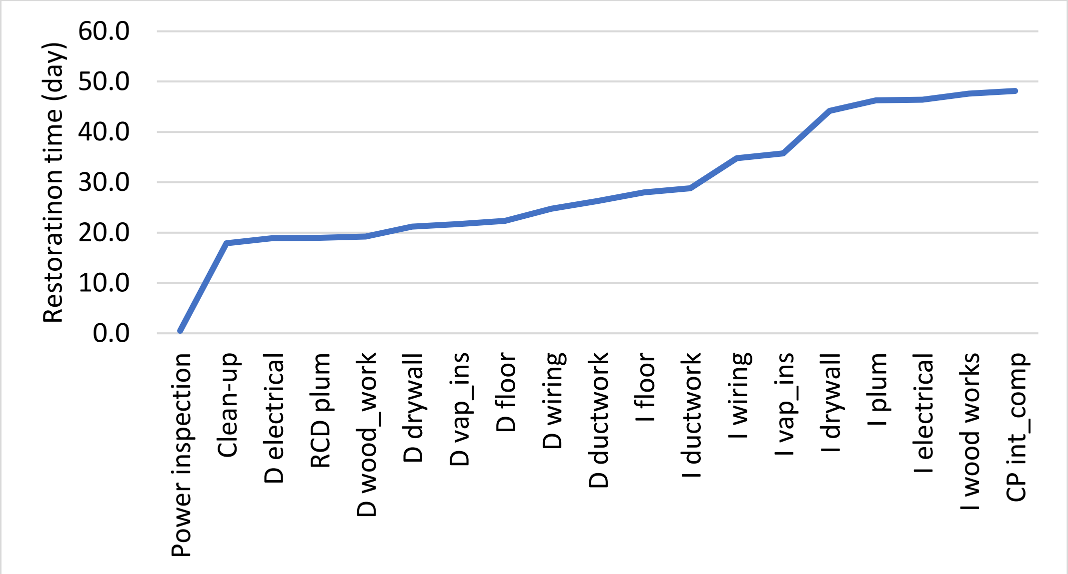

Figure E 6 Iteration 1 end times of building component restoration for the Damage States F. (depth of flood, DS-F= -0.6 m)

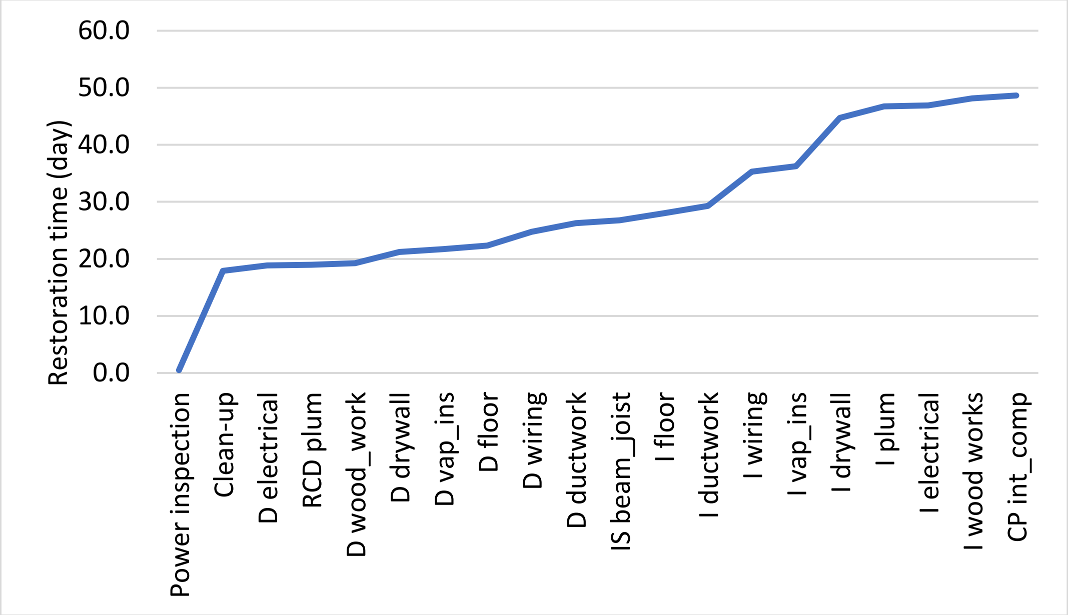

Figure E 7 Iteration 1 end times of building component restoration for the Damage States G. (depth of flood, DS-G= -0.3 m)

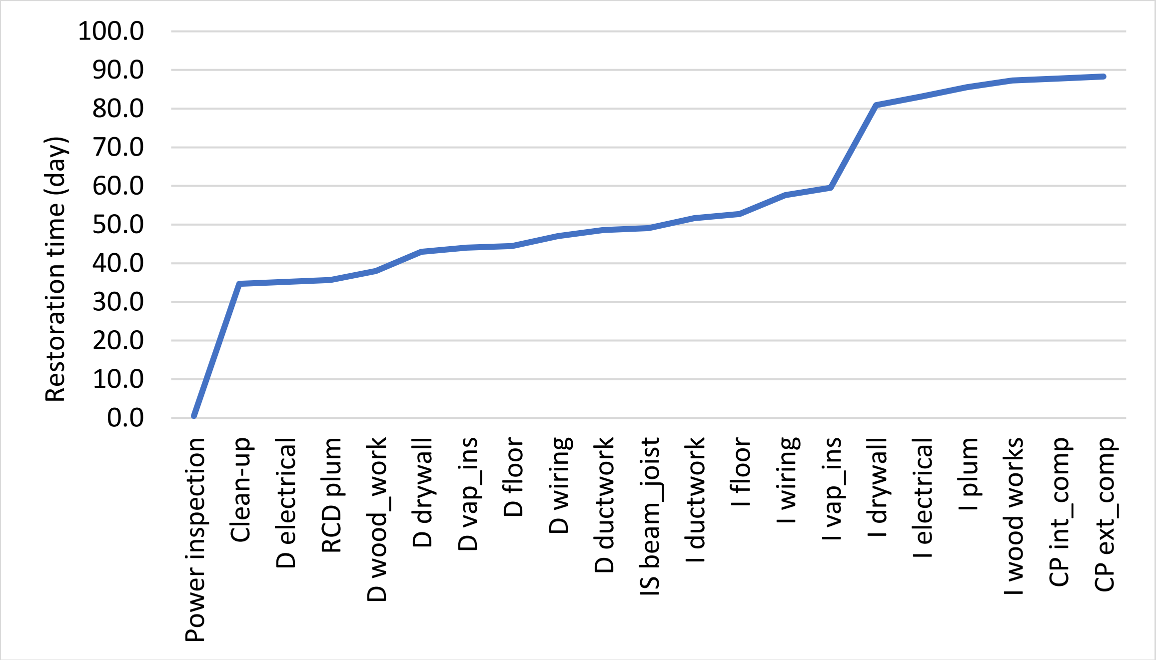

Figure E 8 Iteration 1 end times of building component restoration for the Damage States H. (depth of flood, DS-H= 0.1 m)

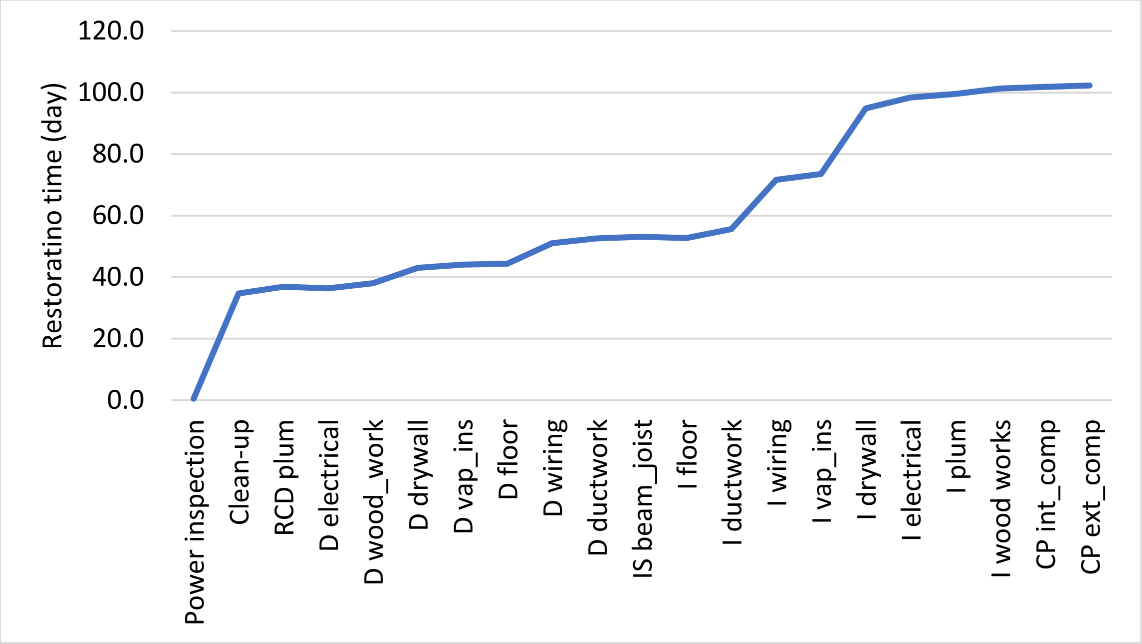

Figure E 9 Iteration 1 end times of building component restoration for the Damage States I. (depth of flood, DS-I= 0.6 m)

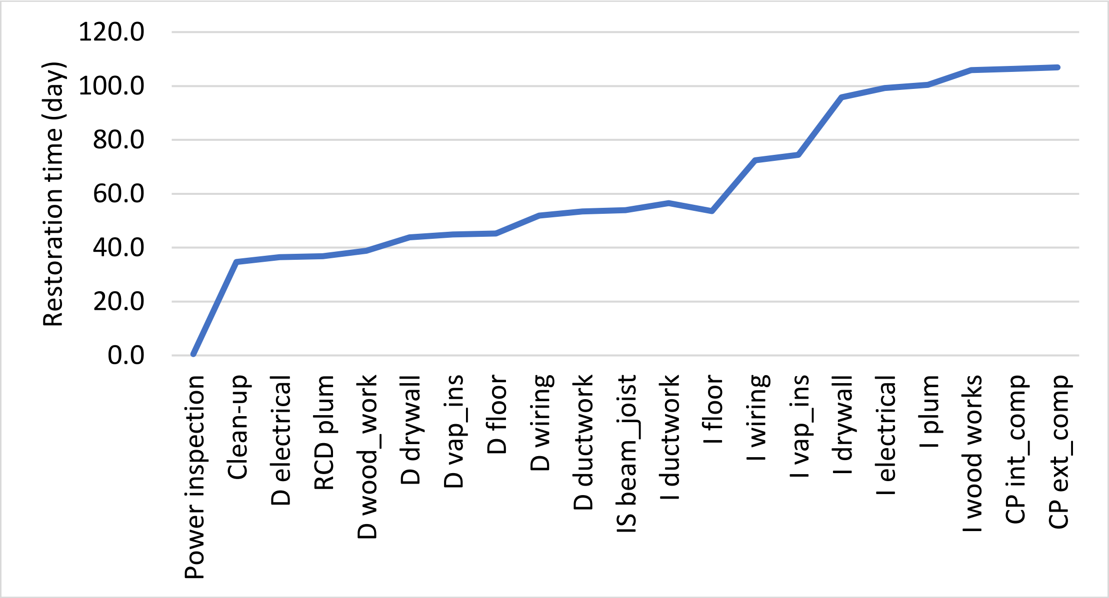

Figure E 10 Iteration 1 end times of building component restoration for the Damage States J. (depth of flood, DS-J= 0.9 m)

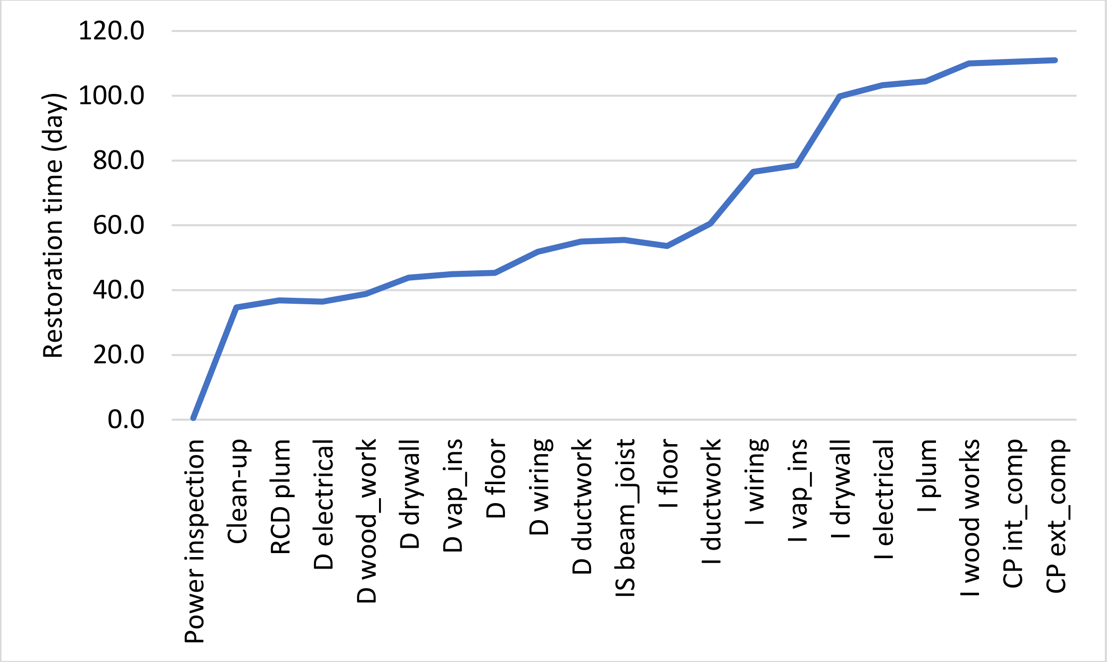

Figure E 11 Iteration 1 end times of building component restoration for the Damage States K. (depth of flood, DS-K= 2.1 m)

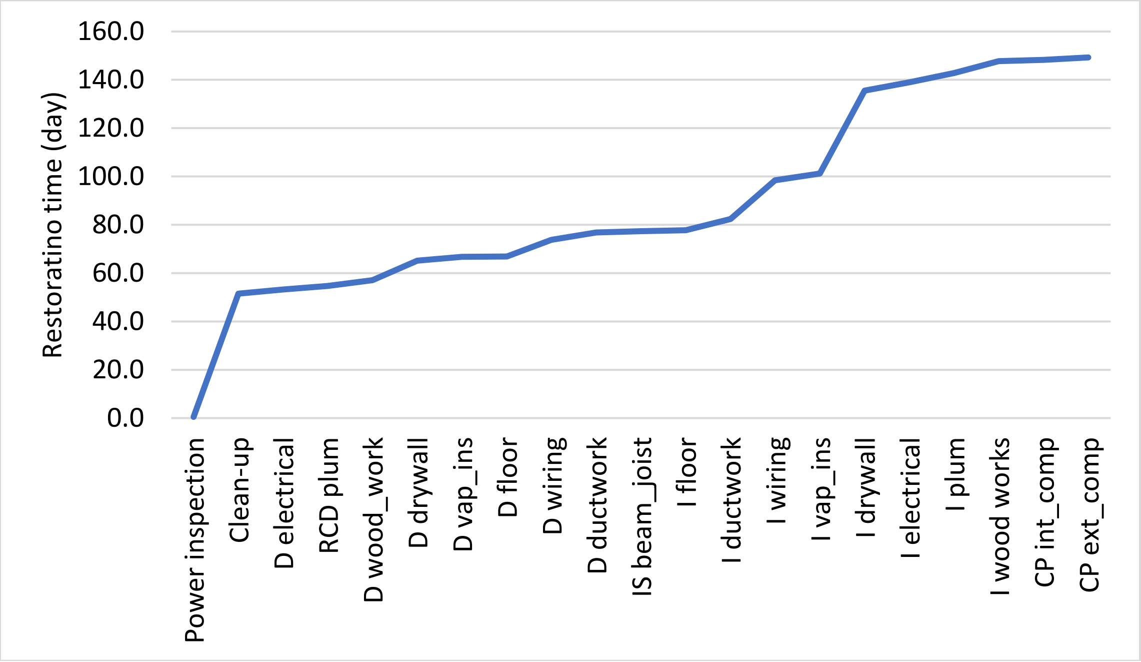

Figure E 12 Iteration 1 end times of building component restoration for the Damage States L. (depth of flood, DS-L= 2.8 m)

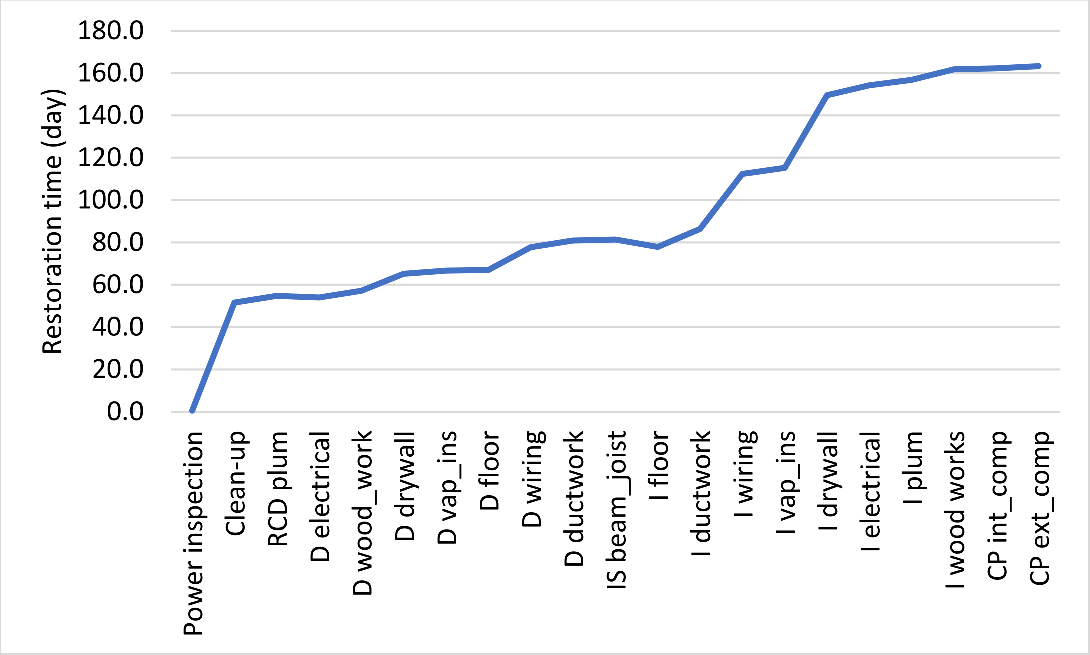

Figure E 13 Iteration 1 end times of building component restoration for the Damage States M. (depth of flood, DS-M= 3.3 m)

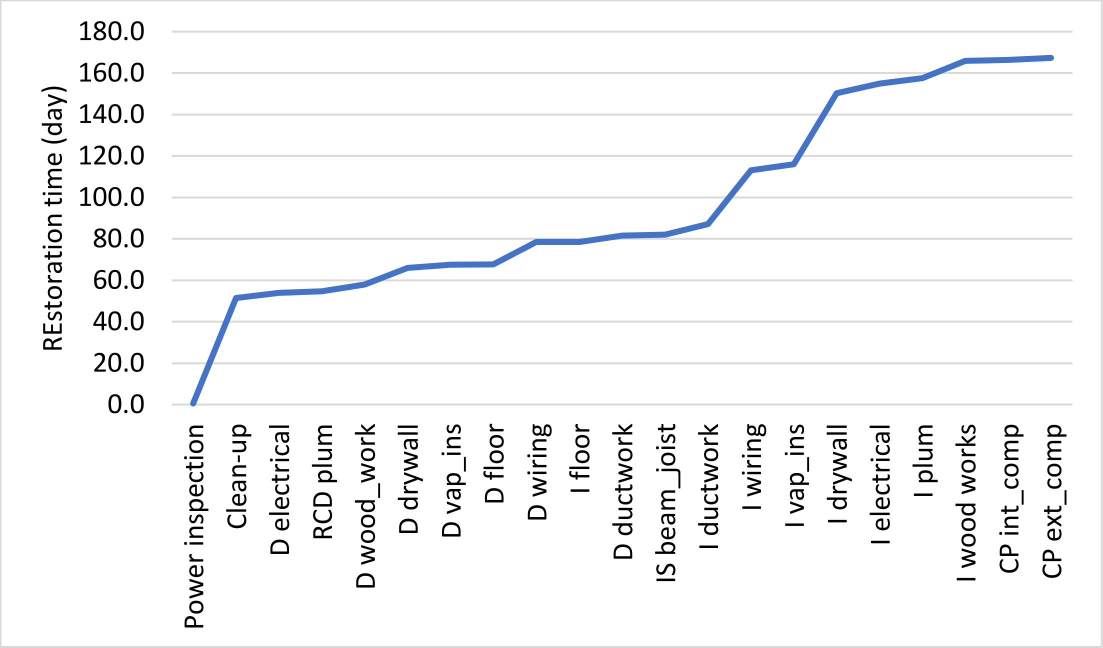

Figure E 14 Iteration 1 end times of building component restoration for the Damage States N. (depth of flood, DS-N= 3.6 m)