Balancing Forecast-based Action and prevention efforts for risk reduction

A case study of wind-induced building damage in the Philippines.

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DISCLAIMER

Acknowledgments

'and all this science I don't understand, it's just my job five days a week'

Though I listened to Elton John's *Rocket Man* for exactly 6207 minutes (source: Spotify) during this thesis, I never actually worried for long about if there was science I did not understand. Throughout this thesis, I have been greatly supported and assisted by professionals who truly lifted the work on my thesis. Firstly, I am extremely grateful to my supervisors, Prof Dr. Maarten van Aalst, Dr. Dinand Alkema, Drs. Nanette Kingma and Dr. Marc van den Homberg for their continuous support, critical questions, and opportunities to further my research. I would also like to thank Aklilu Tesladik for his technical, and extremely patient, support; Damien Riquet for his everlasting willingness to think along in connecting me to the right people; Kostas Bischiniotis for the in-depth discussions, and infectious excitement; Dr. Pacheco and Dr. Hernandez and their colleagues at UPD-ICE for their valuable insights; and the various people at Buildchange and the Shelter Cluster for their useful feedback to sharpen my thinking. When I started my thesis, I could not have imagined I would end up being supported by so many people who inspire me beyond this thesis. In such a way, nothing will ever feel like 'just my job five days a week'.

Still, this was a very intense and unconventional academic year. With not many places to go, most days were spent behind the screen, on the couch in positions not too comfortable, with one hand petting Mycah (the dog), and the other trying to get work done. There were times that I did feel Elton John quite accurately described thesis life during covid-times with this one sentence. Whenever I was stuck on a single aspect for yet again a full week, my sister would play it loudly and we'd sing along emphasizing this sentence more than anything. I am extremely grateful for having all these happy distractions surrounding me. My friends, in Enschede, Langeraar, and remotely. My family. Bas and Mycah.

With working from home having been the standard. It has made me realize more than ever how blessed I am with the place(s) I can call home, providing a supportive environment on so many levels. Even excusing me for doing the dishes when I just really wanted to finish writing that one paragraph or getting provided the snacks I wanted when I needed them most has truly made the difference.

A note to all owners of tropical cyclone-struck, lightweight wooden houses

Tatiana Howard used to say that windsurfing is all about working with nature rather than fighting against it. As you have experienced the destructive forces of extreme winds on your homes, you may think that me being a windsurfer sets us apart.

I do not think it does. At least. Not in my experience.

Whenever my dad took me out to competitions, I would find most of the kids brought several sails '*in case they'd break one*'. In that respect, I was a bit of an odd one out. I felt a certain fondness caring for this one sail I had. Before every competition, I would check it for any imperfections, spots that may potentially rip, and strengthen those temporarily with duct tape. The harder the forecasted winds, the more I would cover my sail.

'*with all the money you are spending on your duct tape, you might as well have bought a new sail*' a guy said on a particularly windy day when I covered about a third of my sail in duct tape. I did not argue, simply did not consider it an option. After about 10 minutes on the water, a gust took me off my board and catapulted me right through my sail. When a boat came to pick me up and bring me back on land, I thought about what this guy had said. Not only had I bought about 15 rolls of duct tape, now I also had to invest in a new sail. Repairing it would also have been an option, but maybe an entirely new one could provide more security.

I genuinely had no clue what the best option was in the long run. Was a one-time investment going to be more cost-effective? Or would incidental repairs with temporary strengthening be better? I would have liked to know that answer. Or at least, would have liked to know approximately, so that I could have made up my mind.

At that point, I understood even if I knew – the problem would not be solved immediately. If a new sail was the best option - who was going to fund it? Also, would there be additional benefits to factor in? Would owning an entirely new one, without imperfections, bumps, and scratches, make me faster? Would a repaired one give me an even greater sense of fondness? And if yes to both, what should I prioritize. How do these aspects outweigh monetary aspects?

I am saying this because I want you to know that I (somewhat) understand what it's like to fight winds; to own something vulnerable to extreme winds; that costs are not the only aspect we should care for; and that – even when you have made up your mind on what's more desirable – it is not guaranteed that we can make it happen. However, knowing something about cost-effectiveness may further spark discussion and help us to look beyond what we have considered as our options in the first place.

This study merely aims to find out what is needed to answer a question that you may be having. A question like the one I used to have, but more relevant because your livelihoods depend on it. This study is a first step in exploring what is more cost-effective; temporarily strengthening your homes when we forecast a certain windspeed, or permanently upgrading your home to prevent damage in the first place.

Abstract

With about 10 Tropical Cyclones making landfall annually, Tropical Cyclones are the natural hazard with the highest human and economic impact in the Philippines. With the heaviest predicted to become even more intense in the future because of climate change, effective spending of scarce budgets to anticipate, prepare for, and recover from these impacts is more important than ever. Risks can be managed at different phases of the Disaster Risk Management Cycle. Traditionally, humanitarian aid organizations focused on response and recovery programs, but since increasingly better forecast information became available, anticipating the impacts through Forecast-based Action (FbA) has gained a more prominent role. The more general question is how these Forecast-based Actions relate to more permanent measures that are part of long-term risk reduction and now adaptation to climate change.

This study explores if a recently developed framework by Bischiniotis et al (2020) can be applied to compare the cost-effectiveness of forecast-based distribution of Shelter Strengthening Kits to a permanent upgrade: both being risk-reduction measures for wind-induced building damage. The use of this framework allows for exploring what the most cost-effective choice had been for this house had an actual choice been made in 2006. This study applied a couple of decision scenarios to a single house in the municipality of Santa Rita, the Philippines. Using historical observations and their forecasts between 2006 and 2020, and damage curves describing the original state of the house as well as the change in vulnerability under the interventions, this study explored the cost-effectiveness of the different interventions had an actual choice been made in 2006.

This study aimed to deepen the existing framework by exploring how case-study-specific findings can be extrapolated to get an idea of after how many years the balance between Forecast-based Action, and prevention is found, and how certain variables affect this balance. In our baseline scenario, it was found that after 18.7 years the permanent upgrade scenario starts outweighing Forecast-based Action. A sensitivity analysis indicates that this balance is highly affected by the assumed costs, damage curves, and event samples.

This study also notes that the choice would also be informed by additional benefits, including avoided indirect economic losses as well as non-monetary benefits, which were not incorporated in our analysis. This may include avoided productivity losses as well as intangible benefits such as the enhanced feeling of safety. This study proposes several directions for further deepening of this framework to address its weaknesses, as well as applications of the framework to utilize its strengths All in all, this study aims to help bridge the gap between planning for long-term climate adaptation and short-term preparedness action.

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List of Abbreviations

A-A	Anticipatory Action
AWS	Automated Weather Station
DN	Doing nothing
DRM	Disaster Risk Management
DRMC	Disaster Risk Management Cycle
DRRM	Disaster Risk Reduction and Management
DRRMO	Disaster Risk Reduction and Management Office
EAP	Early Action Protocol
EaR	Elements-at-Risk
ECMWF-(EPS)	European Centre for Medium-Range Weather Forecasts - (Ensemble Prediction System)
FbA	Forecast-based Action
FbF	Forecast-based financing
GMMA-RAP	Greater Metro Manilla Area – Risk Analysis Project
HT3	House-type 3 (typical lightweight wooden house targeted by FbA)
IFRC	International Federation of the Red Cross Red Cresent National Societies
JTWC	Joint Typhoon Warning Center
N/P DRRMC	National/Provincial Disaster Risk Reduction and Management Council
MAL	Mean Annual Losses
NOAA	National Oceanic and Atmospheric Administration
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
PAR	Philippine Area of Responsibility
PRC	Philippine Red Cross
PU	Permanent upgrade
SSK	Shelter Strengthening Kit
TC	Tropical Cyclone
UPD-ICE	University of the Philippines- Institute of Civil Engineering
WMO	World Meteorological Organisation

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1 Introduction

1.1 Background

Today, every 1 to 2 days, a weather- or climate-related disaster occurs. Disasters often disproportionally affecting the most vulnerable populations in resource-poor countries (Asia Regional Resilience to a Changing Climate [ARRCC] et al., 2020; Kennedy, Vitale, Price, Lux, & Friedrich, n.d.) The impacts of natural hazards are far-ranging, from loss of lives to wider health impacts including psychological stress; and from direct damage of infrastructure and other assets to indirect economic losses in productivity (Cinco et al., 2016; de Ruiter et al., 2020). Worrying trends concerning the frequency and intensity of natural hazards make efficient Disaster Risk Management especially urgent (Phillips et al., 2020). This implies effective spending of scarce budgets for suitable measures in all the four phases of the disaster risk management cycle (DRMC); prevention, preparedness, response, and recovery (Rüth, Bachofen, Coughlan, & van Aalst, 2020; Shreve & Kelman, 2014).

Intuitively, most people would agree that acting ahead of a disaster to prevent some or all of the impacts is preferable to responding with humanitarian aid after the damage and human suffering have already happened. Acting ahead of the hazard can save lives, livelihoods, and properties and reduce human suffering (ARRCC et al., 2020). As a result, when increasingly better and reliable forecast information became available over the years, humanitarian aid organizations worldwide were keen to complement their post-disaster response aid to an increasing component of Anticipatory Action (A-A), before the disaster, but after a forecast (or other credible information) about an upcoming hazard arrives.

A-A enhances disaster preparedness by enabling, as effectively as possible, specific pre-determined actions (World Food Programme, 2019). Although A-A fits in the DRM cycle as a 'preparedness action' it can be clearly distinguished from other preparedness practices: A-A is only activated when a forecast exceeds a pre-defined threshold, rather than activated as part of an average state of preparedness (Weingärtner, Pforr, & Wilkinson, 2020). Practitioners of A-A have different methods and approaches to the timing of actions and financing instruments and classify their initiatives differently. Common terms used to refer to A-A include *early action, Early Warning Early Action,* or *Forecast-based Action* (Weingärtner et al., 2020). This study will make use of the definition of Forecast-based Action (FbA), which is the term used by the International Federation of Red Cross Red Cresent Societies (IFRC) for approved early actions as part of an Early Action Protocol (EAP) developed by National Societies and typically also eligible for pre-agreed financing from the Disaster-Response Emergency Fund (DREF).

Over the years, the reduction of impacts through FbA has gained increasing traction (including among humanitarian agencies and donors, but also in the context of the Risk-Informed Early Action partnership launched at the 2019 UN Climate Summit). However, to build a case for further investment in these mechanisms, scientific evidence concerning the effectiveness of FbA as compared to response needed to grow. Therefore, many of the early studies tended to focus on comparing FbA to normal humanitarian response in terms of cost-effectiveness (Weingärtner et al., 2020). Now that this evidence base has grown, similar questions are triggered for comparing FbA to prevention efforts. **How does FbA relate to long-term climate adaptation and regular government actions towards disaster prevention? In other words: how can we balance long-term prevention efforts and short-term preparedness in risk reduction?** This thesis provides a case study that improves our understanding of these trade-offs between forecast-based action and prevention measures.

1.2 Research problem definition

A generally applicable framework that can be used to compare the cost-effectiveness of long-term prevention measures to short-term, Forecast-based Actions is not yet available. Recently, a paper by Bischiniotis et al. (2020) was published that stated that investigated cost-effectiveness of prevention and preparedness flood risk reduction measures. Bischiniotis et al. (2020) explored how decision-makers can select between preventive and preparedness flood risk reduction measures. The study used a fictitious case study with the starting point 1997: outlining that a decision had to be made on how to manage flood risk in an area over the coming decades. With the knowledge of the forecasts and (pseudo-)observations of the period between 1997 and 2018, Bischiniotis et al. (2020) could retroactively describe which choice, dikes or muscle wall, would have led to lower total financial losses in the given case study, and analysis of these findings helped to generate understanding as to why this would have been the case. Required for the use of this framework are the following elements (Figure 1); forecasts and observations for events in a specific time-frame (hazard metrics); information on physical vulnerability that allows for linking hazard intensity to sustained impact (physical vulnerability), including estimations of the monetary losses incurred under the different scenarios encompassing the costs made for implementation of those measures (event-based losses); and a trigger model outlining the preconditions for triggering FbA (trigger model). These together allow for calculations of total monetary losses incurred during the timeframe of events studied under different scenarios.

However, Bischiniotis et al. (2020) acknowledge that the study was based on a fictitious case for flood risk reduction measures. Therefore, the thesis is to deepen Bischiniotis' methodology in a real-world case study and to assess to what degree this methodology holds up under real-world constraints and limitations. The case study that will be explored is that of how a permanent upgrade of a house compares to a Shelter Strengthening Kit in reducing the risk of wind-induced building damage. Figure 2 outlines the research problem and case study through the Disaster Risk Management Cycle.

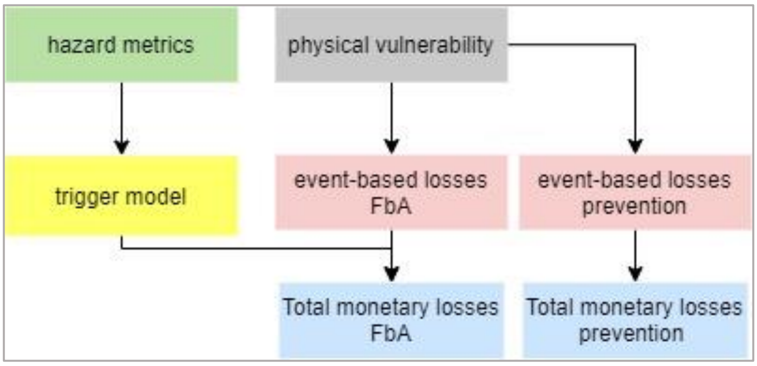

Figure 1: The building blocks of the framework by Bischiniotis et al. (2020)

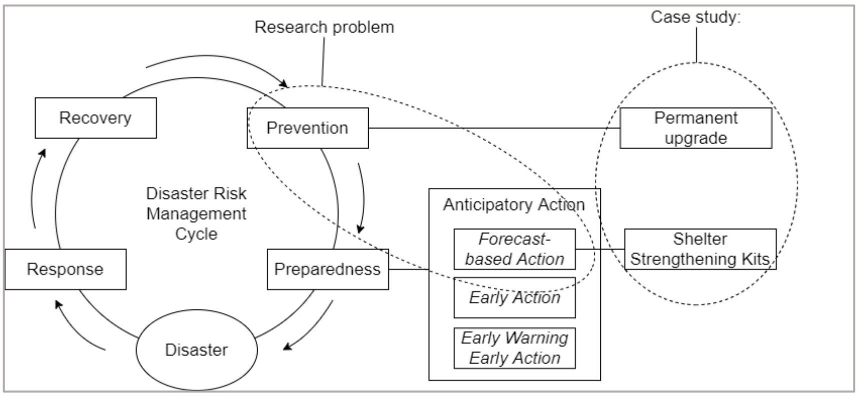

Figure 2 Outlining the research problem and case study through the Disaster Risk Management Cycle.

1.3 Case study

A case study that can improve our understanding of the trade-offs between Forecast-based Action and prevention measures can be found in the Philippines, where an EAP for tropical cyclones has been approved in 2019.

Consisting of over 7000 islands and islets, covering about 300,000 km^2, the Philippines is an archipelago state in the Western Pacific Ocean. The country consists of three groups of large islands. Luzon in the north, the Visayas in the center, and Mindanao in the South. The Philippines has 4 levels of administrative divisions. The 17 autonomous regions together make up 81 provinces, 1489 municipalities, and 42,044 barangays as of 2018 (Asian Disaster Preparedness Center [ADPC] & The United Nations Office for Disaster Risk Reduction [UNDRR], 2019).

The Philippines is highly susceptible to multiple hazards such as Tropical Cyclones (TC's), storm surges, floods, droughts, volcanism, and earthquakes. Figure 3 outlines the immense impacts that natural disasters had on the Philippines between 1901 and 2015 (Guha-Sapir, Hoyois, Wallemacq, & Below, 2016). These numbers make the country ranked third on the list of countries with the highest risk of natural disasters worldwide (World Economic Forum, 2018).

By far the greatest impact can be seen from the extreme winds (storms) that come along with TC's. These make up for 82% of the total number of economic losses, and 70% of the total number of deaths (Guha-Sapir et al., 2016; Jha, Martinez, Quising, Ardaniel, & Wang, 2018). Moreover, TC's often take along heavy rains which may result in destructive storm surges, landslides, and floods (Cinco et al., 2016).

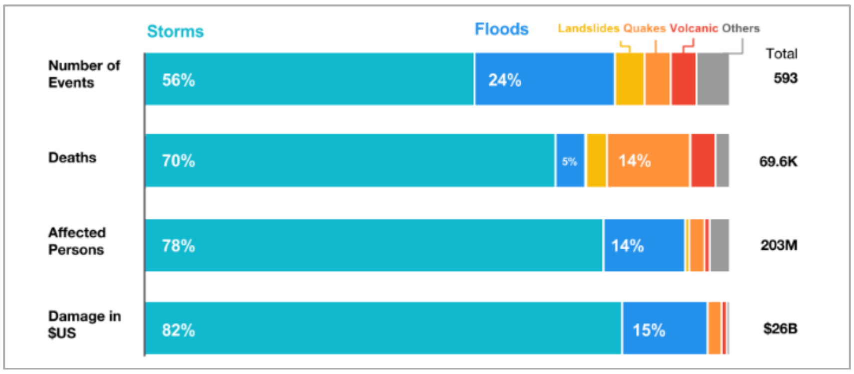

Figure 3: Natural hazards in the Philippines between 1901-2015 in numbers (source: Guha-Sapir et al., 2016)

Currently, all TC-related disaster management makes up for approximately 4% of the GDP, which severely hinders the countries overall sustainable long-term economic growth (ADPC & UNDRR, 2019).

One of the greatest impacts of Tropical Cyclones is people's homes. A couple of examples illustrating the scale of devastation include super typhoon Haiyan which destroyed over 1.1 million homes in 2006 (ADPC & UNDRR, 2019); Typhoon Frank that made about 92,000 houses inhabitable in 2008; and a series of successive typhoons that destroyed nearly 360,000 houses in 10 weeks in 2006 (Philippine Red Cross [PRC], 2019). Figure 4 shows the devastating impact of extreme winds on houses (Infante, 2013).

Figure 4: Only a few walls still stand among the damage caused by Haiyan in 2013 (source: Infante, 2013)

Not only does the damage to houses result in people being homeless, but it may also cause injury and death. In the long run, loss of property may also disturb economic activity and mental well-being (Espada, 2018). As a result, risk reduction of house damage was a prioritized Forecast-based Action in the EAP that The Philippine Red Cross (PRC) created in collaboration with the Finnish Red Cross and the German Red Cross. In 2019, this EAP was approved – outlining in detail how the distribution of Shelter Strengthening Kits (SSKs) to homeowners of the most vulnerable houses (lightweight wooden houses) could help to reduce impact. Section 2.2.1 describes the distribution of SSKs as Forecast-based Action in more detail.

This research explores how an SSK compares to a permanent upgrading of a lightweight wooden house as a prevention measure. It does so by focusing on a case study of Santa Rita, one of the 26 municipalities of West Samar, also targeted by the EAP. The geographic location of Santa Rita is shown in Figure 5. More details on the choice for this municipality specifically can be found in Annex 1.

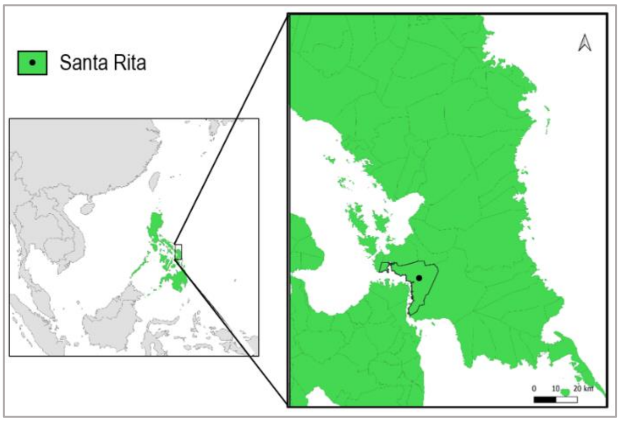

Figure 5: Geographical location of the case study area.

1.4 Wicked-problem framework

The case of SSK distribution as Forecast-based Action in Santa Rita is a particularly interesting case to compare to a prevention counterpart in terms of cost-effectiveness when viewed through the scope of the wicked problem framework (Georgiadou & Reckien, 2018).

The wicked problem framework states that wicked problems are met in cases where uncertain knowledge meets descensus among stakeholders (Table 1, D). Such wicked problems can only be solved when reduced to moderately structured problems. This can be done in two ways. The first option is that scientific research generates certain knowledge, in which case discussion between stakeholders can proceed on means (Table 1, C). The second option is that stakeholders find consensus on their goals, in which case certain knowledge needs to be generated to find out how this goal can best be achieved (Table 1, B). As a result of this, stakeholders may arrive at a structured problem, in which the debate is on technicalities (Table 1, A).

Table 1: The Wicked Problem Framework (adapted from Georgiadou & Reckien, 2018)

	Goals and values of stakeholders	
	Consensus among stakeholders	**Dissensus among stakeholders**
Certain knowledge	A. Structured problem Debate on technicalities *'we do see the additional benefit of spending our budgets toward collectively trying to bridge the gap between Forecast-based action and regular government actions towards disaster prevention, and we know how our shared goal can best be achieved'*	B. Moderately structured problem Debate on goals and values *'we do not yet see the additional benefit of spending our budgets toward collectively trying to bridge the gap between Forecast-based action and regular government actions towards disaster prevention, even though the evidence-base shows that balancing those could yield greater results'*
Uncertain knowledge	C. Moderately structured problem Debate on means *'we do see the additional benefit of spending our budgets toward collectively trying to bridge the gap between Forecast-based action and regular government actions towards disaster prevention, but we don't know anything about the means that we could employ to reach our shared goal'*	D. Wicked problems Endless debate *'we do not see the additional benefit of spending our budgets toward collectively trying to bridge the gap between Forecast-based action and regular government actions towards disaster prevention. Besides, there is no evidence showing that we should have these discussions.'*

Generally, the discussion on how to balance FbA and prevention efforts could be considered a typical wicked problem. With multiple actors involved in different aspects of the TC risk reduction system, each likely have their evaluation protocols for justifying expenditures. Strategies for long-term climate adaptation may more often require proof of economic valuation, while strategies that are part of FbA are more likely to be evaluated in terms of human suffering reduced. As a result of these different perspectives and responsibilities, and the uncertain knowledge on how different strategies compare, discussions may end up in endless debates. To move away from this wickedness, stakeholders involved in different phases of the DRMC will either have to find consensus on a shared vision on how to justify DRM expenditures, or scientific research needs to be done that facilitates discussions on finding this consensus.

In the Philippines, stakeholders involved in different phases of the DRMC are willing to establish effective coordination mechanisms between them, bridging the gap between short-term (preparedness) and long-term (prevention) disaster risk reduction (Green Climate Fund, 2019). The Provincial Disaster Risk Reduction Management Office (PDRRMO) of West Samar, has even shown willingness to invest part of their budget to the FbA of distributing Shelter Strengthening Kits to lightweight wooden houses in anticipation of tropical cyclones (D. Riquet, personal communication, February 9, 2021). At the same time, it is within the options of these PDRRMOs to invest in long-term disaster risk prevention measures, such as the permanent upgrade of housing.

The willingness of the West Samar PDRRMO to invest in FbA can be considered a sign of consensus on a common vision. The question of how the FbA of SSK distribution compares to a permanent upgrade seems to be reduced to a moderately structured problem in this case. Hence, the application of the framework of Bischiniotis et al. (2020), may help to generate insights into the aspects that require further exploration to eventually seek an optimal approach.

1.5 Research objectives

1.5.1 Main objective

To apply and adapt the methodology of Bischiniotis et al. (2020) on a real-world case study to assess its usefulness in comparing the cost-effectiveness of Forecast-based Action to permanent preventive actions to reduce the risk of natural hazards. Thereby assessing how Shelter Strengthening Kit distribution as a Forecast-based Action compares to permanent housing upgrade in reducing the risk of wind-induced building damage to lightweight wooden houses in Santa Rita.

Figure 6 shows how the sub-objectives are linked.

1.5.2 Sub-objectives and research questions

RO1. To generate **wind-hazard metrics** for the case study area

- RQ1a. What are the maximum windspeeds that occurred during tropical cyclone events in Santa Rita and what wind speeds were forecasted for these events?

RO2. To define the **physical vulnerability** of a lightweight wooden house and how this changes under the different measures.

- RQ2a. What is the ability of a lightweight wooden house to withstand high wind speeds and avoid getting damaged?
- RQ2b. How does the physical vulnerability change if a lightweight wooden house is provided an SSK?
- RQ2c. How does the physical vulnerability change if a lightweight wooden house is permanently upgraded?

RO3. To quantify **event-based-losses**

RQ3a. What are the monetary losses that can be accounted for in calculating event-based losses?

RO4. To assess the **trigger model** for Forecast-based Action scenario

RO4a. What would be the ideal trigger threshold for the Forecast-based Action scenario in the given case study?

RO5. To quantify **the total monetary losses** related to wind-induced house damage under the different scenarios, deepening the method of Bischiniotis et al. (2020).

RQ5a. How can total monetary losses be quantified for the time series under the scenario of doing nothing?
RQ5b. How can total monetary losses be quantified for the time series using the Forecast-based Action scenario?
RQ5c. How can total monetary losses be quantified for time series using the scenario of permanently upgrading the lightweight wooden house?

RO6. To perform a **sensitivity analysis** to evaluate the impact of chosen parameter values on the results under the different scenarios

RQ6a. How do the total monetary losses for this time series, under the different scenarios, change if total monetary losses were calculated using different discount rates?
RQ6b. How do different wind-hazard metrics affect the balance between FbA and permanent upgrading?
RQ6c. How does over-or underestimation of physical vulnerability affect the balance between FbA and permanent upgrading?
RQ6d. How does over- or underestimation of monetary losses affect the balance between FbA and permanent upgrading?
RQ6e. How does the use of a different trigger model affect the balance between FbA and permanent upgrading?

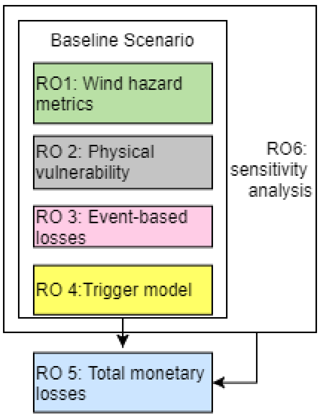

Figure 6: Relation between sub-objectives

1.6 Thesis outline

The next chapters are organized in the following order. Chapter 2 addresses relevant information in the context of the case study. Chapter 3 presents a literature review on the building blocks of Bischiniotis et al. (2020), tailored to the case study. Chapter 4 outlines the methodology followed to answer the research questions. In chapter 5, results are presented and analyzed. Chapter 6 presents the conclusions and recommendations for future research. Annexes provide more detailed elaborations on relevant concepts as well as relevant research outputs

2 Case study context

This chapter starts by providing more insights into Disaster Risk Management in the Philippines (section 2.1). Section 2.2 elaborates on the concepts of Early Action Protocols (EAP) and Forecast-based Action (FbA). Including an explanation of the FbA of distributing Shelter Strengthening Kits (SSKs) to eligible lightweight wooden houses (HT3). Lastly, section 2.3 outlines relevant contextual information about Santa Rita.

2.1 Disaster Risk Management in the Philippines

Disaster risk reduction has been embraced as a fundamental factor at all levels of governance. Since 1970, the legal foundations of disaster risk reduction and management have been upgraded and emphasized response-centric interventions alongside planning for prevention and preparedness. In 2003, local risk governance legislating enabled the use of local calamity funds for preparedness measures. However, those funds were considered insufficient to promote and support change at the local level. Therefore, the Philippine Disaster Risk Reduction and Management Act of 2020 was enacted (better known as The Republic Act 10121). The main aim of the Republic Act 10121 was to drive DRRM momentum across different governance levels (ADPC & UNDRR, 2019).

Currently, The National Disaster Risk Reduction and Management Council (NDRRMC) is the highest central body for coordinating disaster management in the Philippines, including all phases of the disaster management cycle. Under the NDRRMC, The Department of Social Welfare and Development leads the disaster response pillar, implying that they plan for, coordinate, and lead all immediate disaster relief efforts. The Office of Civil Defense is the executing body of the NDRRMC, responsible for disaster risk reduction and management programs. Part of their responsibility is to ensure that risk-informed spatial planning occurs per the Comprehensive Development Plan and the Comprehensive Land Use Plan (ADPC & UNDRR, 2019; Center for Excellence in Disaster Management and Humanitarian Assistance [CFE-DM], 2018).

the NDRRMC has a multi-tiered organization. Every province, city, and municipality has a Disaster Risk Reduction and Management Office (DRRMO). On a smaller administrative scale, there are the Barangay Disaster Risk Reduction and Management Committee (BDRRMC) and Local Disaster Risk Reduction and Management Offices (LDRRMO's) to strengthen the local level risk governance (CFE-DM, 2018).

The Republic Act 10121 stipulates that DRRM Offices have 70% of the funds as set aside for prevention, mitigation, and preparedness, while 30% is dedicated to response (ADPC & UNDRR 2019). Frequently reoccurring themes for long-term prevention and mitigation plans are that of comprehensive embedding of DRRM into the educational system as well as governance reforms to create proactive rather than reactive communication.

The NDRRMC has a great number of partners involved in various levels of their organization. One of the key Disaster Management Partners in the Philippines is the Philippine Red Cross (PRC). Aided by the International Federation of Red Cross and Red Cresent Societies (IFRC) they support humanitarian coordination at the different levels of the NDRRMC (PRC, 2019). To ensure small-scale execution of their services, most of the provinces in the Philippines have their own PRC chapters. Though one of their recognized functions is the organization of emergency relief operations to alleviate human suffering (CFE-DM, 2018), they have been part of the global paradigm shift from response to preparedness.

2.2 Forecast-based Action

Forecast-based Action (FbA), is the term used by the International Federation of Red Cross Red Cresent Societies (IFRC) for approved early actions as part of an Early Action Protocol (EAP) developed by National Societies.

An EAP includes a risk analysis on potential hazard impacts and describes the early actions that should be taken once a pre-defined forecast threshold is reached. To apply for funding of the EAP, a National Society must develop the EAP in adherence to an extensive list of guidelines. Once an EAP is revised and approved by the IFRC Programme and Operations Division, the EAP will become operational. When the pre-defined trigger threshold is reached, action will be triggered and funding will be automatically released through the Forecast-based Financing (FbF) mechanism (IFRC, 2020).

The EAP for Tropical Cyclones by the PRC was approved in 2019 and currently targets the regions of East Samar, North Samar, and West Samar. These regions are chosen for their exposure to TCs, high vulnerabilities, and the experience of the PRC chapters in these regions (PRC, 2019)

2.2.1 Shelter Strengthening Kits

The Early Action Protocol for Tropical Cyclones by the PRC has outlined the destruction of lightweight wooden houses as a prioritized impact in the province of West Samar. The FbA targeting this impact is the distribution of Shelter Strengthening Kits (SSKs). The main goal of SSKs is to reinforce houses, reducing the funds required for repair works, and making them accessible to the households immediately after impact, thus minimizing the time spent in evacuation centers and temporary shelters (PRC, 2019). Box 1 outlines the usual sheltering process in the months after an event.

Considering that the kit needs to be installed in just a few hours by both technical as well as non-technical people, and that information sharing needs to take place effectively, the SSKs are relatively simple solutions for reducing the impact of wind loads on housing. The SSKs are designed by BuildChange. Figure is a simple representation of an SSK (in blue) attached to a house. Materials used for SSKs are rope, wood, and reinforced steel bars. Figure 8 shows the installation of an SSK by PRC volunteers.

The targeted houses are referred to as HT3 houses. These HT3 houses are lightweight wooden homes with walls and roofs made of local materials such as nipa, bamboo, or wooden planks (Figure 9). Additionally, to qualify as an HT3 house, it should also meet certain criteria related to the size of walls, number of floors, type of columns, and foundation.

Houses that would be classified HT3 houses are usually owned by families with relatively low incomes. According to the Shelter Cluster, they are especially vulnerable to extreme winds as owners generally improve their shelter little by little when money is available. In making these improvements, they often start on strengthening the walls, using natural materials from the local context. Doing so, the main structural components like framing and foundations are often not prioritized (Victorio, M.M, personal communication, March 4, 2021).

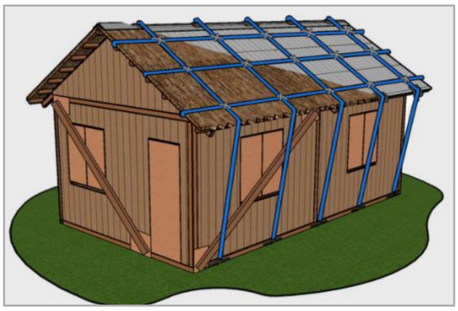

Figure 7: A graphical representation of a Shelter Strenghtening Kit (in blue) installed on a house (PRC, 2019).

Figure 8: Philippine Red Cross volunteers Install a Shelter Strengthening Kit on a HT3 house (PRC, 2019)

Figure 9: A typical lightweight wooden house. If the type of columns and foundation are also assessed to meet eligibility criteria, this house would be considered a HT3 (PRC & ICRC, 2015).

2.2.2 Triggering for Shelter Strengthening Kits

The trigger model for SSK distribution is developed by 510 Global and composes of two main parts. When a typhoon is approaching the Philippines Area of Responsibility (PAR), or when cyclogenesis happens within the PAR, the first part of the model takes a forecasted track and translates this to a wind footprint using the parametric model by Willoughby et al. (2006). The second part, known as the 510 Model, utilizes a machine-learning algorithm to translate the wind footprint to a spatially variable impact map.

Next, an automatic alert containing this impact map and a combined vulnerability index for all municipalities at risk is sent to the FbF technical advisor and the Disaster Management Services.
Following this is a human-in-the-loop process: the technical advisor uses this information to assess whether the predicted impact exceeds the trigger level, and which municipalities will be chosen to receive aid. This choice considers the accessibility of roads and the latest weather conditions, for example. At present, the trigger level is set at when more than 10% of houses in at least 3 municipalities are forecasted to be completely destructed. (PRC, 2019).

Every 6 hours, this message to the technical advisor is repeated with updated information until the tropical cyclone makes landfall or exits the PAR. During this alert stage, funding and materials are mobilized in preparation for a potential trigger. When at 72 hours before landfall the threat remains imminent (meaning the pre-defined threshold impact is expected to be exceeded), SSK distribution is triggered. Materials are initially moved to concerned chapters, after which allocation to barangays can be done. In the target municipalities, the most at-risk barangays are identified. In these barangays, fieldwork is performed using the Shelter Strengthening Kits Assessment form. This is done to identify HT3 houses which are eligible for receiving an SSK.

SSKs are distributed to warehouses, and the process of construction is started. A team of 5 workers (2 skilled, 3 unskilled) can install 8 SSKs in a day. It should be noted that once triggered, a change of track or decrease of magnitude of the TC, will not lead to cancellation of activities.

Box 1. Sheltering process in case of house damage

When house damage occurs after the passage of a tropical cyclone, families of affected houses are temporarily sheltered elsewhere, until their homes are repaired or an alternative is found. Hirano (2012) studied how sheltering was organized in the response to the effects of typhoon Washi, which made landfall in the Philippines in 2011. This study provides insights into the settlement options during post-disaster response and recovery (Hirano, 2012). Figure 10 visually outlines this sheltering process. During the first month post-disaster, families often make use of emergency settlement options. These include staying with host families, renting another house, planned tent cities, spontaneous camps, and converted public buildings such as schools or churches. After about a month, households who have their homes repaired can return. In case repairs take longer, households transition to transitional settlements that provide sufficient living standards (Hirano, 2012). After typhoon Haiyan (2013), for example, when over 1.1 million homes were completely destructed, the rebuilding of new homes took months, and families were provided temporary shelter in bunkhouses such as the one in Figure 11 (ADPC & UNDRR, 2019); Department of Public Works and Highways [DPWH], n.d.)

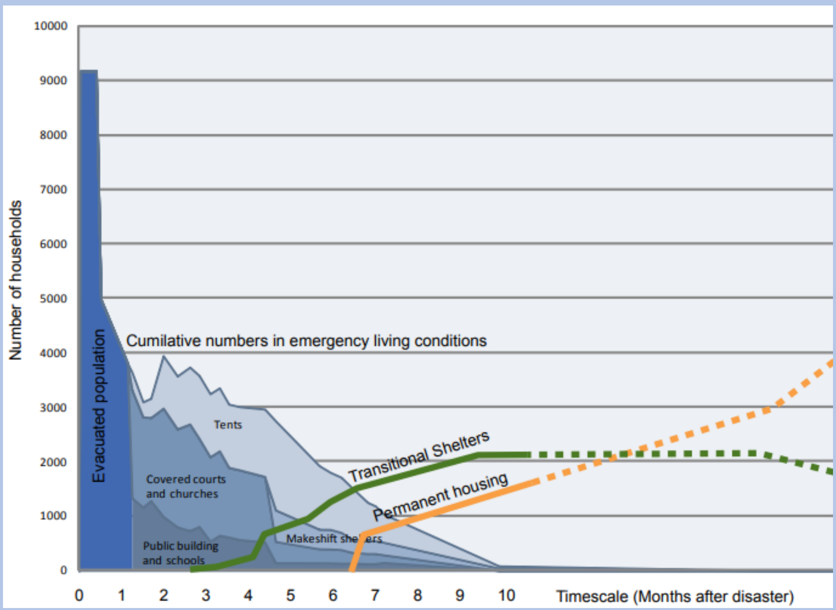

Figure 10: Household numbers according to settlement options after TC Washi (Hirano, 2012)

Figure 11: Bunkhouses constructed as temporary Shelter provided after Haiyan (DPWH, n.d.).

2.3 Santa Rita

Santa Rita (Figure 5) is a municipality of the province of West-Samar, one of the poorest provinces in the Philippines (PRC & International Committee of the Red Cross [ICRC], 2015). Santa Rita is host to 38 barangays. The municipalities' population growth has followed the national pattern; while only 18,808 people resided in Santa Rita in 1960, this number rapidly grew to 25,202 in 1990, 30,118 in 2000, and 41,591 in 2015 (Philippine Statistics Authority [PSA], 2016). The population density is 139 people per km^2.

2.3.1 Hazard

There is considerable spatial variability in TC frequency, with the majority of events affecting the northeast regions (ADPC & UNDRR, 2019; Cinco et al., 2016; PRC, 2019). This puts Santa Rita among the most highly exposed municipalities. The Philippines Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), which is the National Meteorological Agency of the Philippines, also noted more intense windspeeds at similar return periods for these regions. The maps in Figure 12 show the expected wind speeds at different return periods for the East Visayas region, which hosts Santa Rita (PAGASA, n.d.). When considering TC hazard over time, Cinco et al. (2016) did not note a significant increase in tropical cyclone intensity and frequency between 1951 and 2013 for the East Visayas, though their research highlights to note that the huge uncertainty in historical data (Cinco et al., 2016).

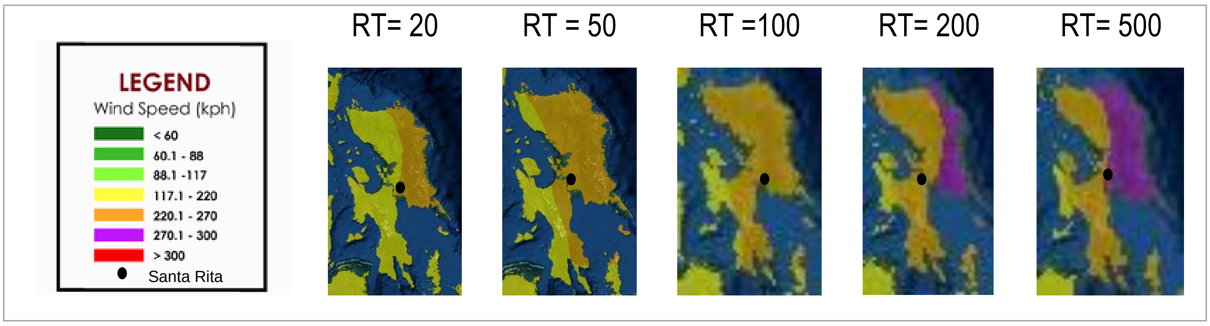

Figure 12: A close-up of the Regional Severe Wind Maps by PAGASA, showing the expected wind speeds at different return periods for the East Visayas, hosting Santa Rita (PAGASA, n.d.).

2.3.2 Elements-at-Risk

Though TC hazard has not significantly increased over time, economic losses due to TC events have (Cinco et al., 2016). This can be explained by population increase, which, consecutively, has led to a greater number of Elements-at-Risk (EaR) (ADPC & UNDRR, 2019). The EaR that this study considers specifically is an HT3, a lightweight wooden house that meets additional requirements related to columns and foundation (section 2.2.1).

As outlined in section 2.2.2, the usual procedure for identifying which houses qualify as HT3, and are eligible for receiving an SSK, is through the SSK assessment form. Though this has not previously been done for Santa Rita, an estimation can be made as to how many would qualify as an HT3. Per the 2015 Census, there were 8803 houses in Santa Rita. 40% of these homes were estimated to be constructed by using lightweight material only (eg. wood, bamboo, nipa)(PSA, 2015). As a result, these houses would be included based on the inclusion criteria of construction material. BuildChange estimates that about 50% of these houses would still be excluded given that they do not meet additional requirements such as the type of columns and foundation (Ombao, R., Personal Communication, December 18, 2020). This would imply that there are approximately 1715 HT3 houses in Santa Rita. However, the spatial distribution of those is not known.

2.3.3 Vulnerability

´Vulnerability´ is a widely used term in Disaster Risk Management. In its broadest sense, vulnerability refers to the fragility and susceptibility elements at risk, and their capacity to cope with hazardous conditions (Birkmann et al., 2013). EaR could be any object, living being, activity, or process adversely

affected directly, or indirectly, by a hazardous phenomenon. The vulnerability of a physical object, such as a building, is referred to as physical vulnerability (Westen, Kingma, & Montoya, 2009). Social vulnerability is the susceptibility of social groups to sustain adverse effects (Birkmann et al., 2013). Section 4.3 will provide extensive scoping on the physical vulnerability of the HT3 houses. This section aims to describe the social vulnerability of Santa Rita in a more general sense. This is done to get a better understanding of how the population may be affected when their homes are struck by extreme winds.

In 2012, 48% of Santa Rita's population was estimated to live below the poverty line, implying limited resources to cope with the impacts of potential damage to their homes. 55% of the households were estimated to occupy their lot rent-free. Rent-free occupation can be considered a proxy of informal settlements which implies a high number of vulnerable houses (510 Global, n.d.; PSA, 2020). Santa Rita does not have any evacuation centers per 10,000 people, and the travel time to the nearest city is 174 minutes (510 Global, n.d.). This lack of nearby facilities poses a great risk to people's continuation of life-as-usual if disasters strike.

3 Literature review

This chapter reflects on the available literature and methods on the building blocks needed for using the framework by Bischiniotis et al. (2020) (Figure 1). First, section 3.1 discusses the methods available for deriving wind-hazard metrics. Section 3.2 explores the different ways in which the physical vulnerability of houses can be defined. Section 3.3 discusses the costs that can be considered as part of looking at event-based losses. Section 3.4 outlines how trigger models can be evaluated to identify ideal trigger thresholds. Finally, section 3.5 explores ways to deepen the methodology of Bischiniotis et al. (2020) in calculating total monetary losses. In each of these sections, the link to the framework of Bischiniotis et al. (2020) is explained.

3.1 Wind-hazard metrics

The methodology of Bischiniotis et al. (2020) requires the use of hazard metrics, meaning that for a specified period in history, one has information on both the observations and forecasts for all the events in that timeframe. Given that the focus in this study is on wind-induced building damage, this study requires data on both observed wind speeds during tropical cyclone (TC) events in Santa Rita. Forecasts of these observed events are required too.

3.1.1 Observed windspeeds

There are multiple ways in which observations can be retrieved with the most suitable method depending on the application. Weather stations, for example, measure the observed wind speed at a point-location, and may therefore provide the most accurate result for this location specifically. However, in case no weather station is present for the location that one is interested in, or if one is interested in the sustained windspeeds throughout a larger geographical area, wind footprint modeling can be done to estimate these sustained wind speeds.

To understand the different ways wind footprint modeling can be done, it is essential to understand the basic physics of a TC. A TC is an organized, rotating system of clouds and thunderstorms that often originate over (sub-)tropical waters (National Oceanic and Atmospheric Administration [NOAA], 2015). TC's bring along heavy winds which spiral around a low-pressure center. In its simplest form, a typical wind footprint around the eye of a tropical cyclone looks like depicted in Figure 3 (Thompson Higher Education, 2007). At the center of the eye, the winds are calm. Moving away from the center, wind speed increases dramatically with the radius, with its maximum being at the outer edge of the cloud-free eye. After this, the wind decreases again with radius, where the wind speed approaches zero at several hundred up to 1000 km away from the eye of the storm (Willoughby & Rahn, 2004). Damaging windspeeds are generally confined to a 100-kilometer radius from the cyclone center (Willoughby & Rahn, 2004).

However, in reality, local topographic effects are the reason that wind fields do not follow such a smooth transition as shown in Figure 13 . Topographic effects may cause wind speed variations on smaller scales (Tan & Fang, 2018). Modeling approaches that take into consideration these topographic effects were only recently developed, and very few studies so far have made use of these approaches (Done et al., 2019; Tan & Fang, 2018). Models taking into consideration terrain effects combine parametric wind field models with boundary layer models (Done et al. 2019). Parametric wind field models require TC parameters which are usually available from TC datasets (Tan & Fang, 2018). These parameters include latitude, longitude, maximum wind speed, the radius of maximum wind, and maximum environmental pressure (Done et al., 2019; Willoughby, Darling, & Rahn, 2006). The boundary layer models require spatial information such as landcover, terrain height, and surface roughness (Done et al., 2019). Parametric wind field models can also be used without boundary layer models, in which case topographic effects are not accounted for, but the process is computationally more efficient. As a result, these parametric wind field models are more widely used for the analysis of the hazard component of catastrophe models (Done et al., 2019; Vickery, Lin, Skerlj, Peter, Twisdale Jr, & Huang, 2004).

Nevertheless, if one were to compare TC best track data of different meteorological agencies, one would find slight deviations. This is because meteorological agencies all use different techniques to estimate the position and intensity of a TC (Xiaotu et al., 2017). For this reason, observations are often referred to as best-track data. For the West Northern Pacific Region, four agencies provide TC best track analysis. These are the 1) Shanghai Typhoon Institute of China Meteorological Administration (CMA), 2) the Japan Meteorological Agency (JMA), the Joint Typhoon Warning Centre (JTWC), and 4) the Hong Kong Observatory (HKO) (Xiaotu et al., 2017). Best track data is reported at 6-hourly intervals (Neumann, n.d.)

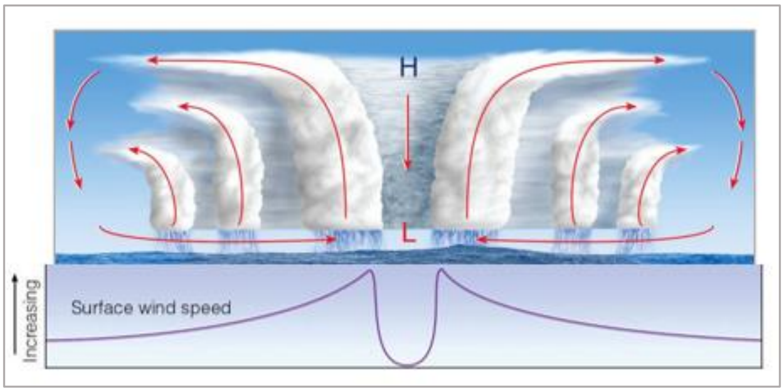

Figure 13: A simplified visual representation of the wind footprint around a tropical cyclone (Thompson Higher Education, 2007).

3.1.2 Forecasted windspeeds

The World Metrological Organisation (WMO) has divided up the world into seven TC basins as part of their Tropical Cyclone Programme (TCP). Each basin has unique features relating to TC motion, internal structure, energy, frequency, intensity, and forecast difficulty (Neumann, n.d.). For this reason, certain methods and configurations of forecasting systems may better work better for specific basins than others (Heming et al., 2019). Heming et al. (2019) reviewed TC forecasting worldwide and outlined the presence of 8 global models, 5 regional models, 6 ensemble prediction models, and 8 Operational Forecasting Centres.

The most common methods in TC forecasting are deterministic and ensemble-based probabilistic models. Deterministic models provide a single forecast from a single method and make use of a single set of initial conditions. Deterministic runs have the advantage that they have a superior resolution (Blake, Brennan, Knabb, & Schauer, 2016). Ensemble-based probabilistic forecasts, on the other hand, do not just create a single forecast from best guess initial conditions but are a collection of several ‘member’ forecasts that were created through different forecasting methods, and different but equally viable initial conditions. Ensemble members together represent nearly all forecast possibilities, and in this way, address uncertainty in the ensemble-based probabilistic track (European Centre for Medium-Range Weather Forecasts [ECMWF], 2012). Ensemble-based probabilistic models are originally used for medium to long-range forecasting (Blake et al., 2016).

As a result of the different configurations and methods used, there are considerable differences in the forecast data provided by different meteorological agencies. While some agencies have a forecasting interval of 12 hours, others report for every 6 hours. Moreover, there may be large variations in TC intensity and position estimates if two agencies forecast the same event. TC position error is defined as the great-circle difference between a TC forecast center position and the best track position at the verification time. Forecast intensity errors are defined as the difference between the forecast as best track intensity at the forecast verifying time (Xiaotu et al., 2017). Forecast accuracy generally is better at shorter lead times.

Over the last years, however, TC forecasting by all agencies has seen significant improvements. Position errors at a 24-hour lead time are now generally below 80 km for most models. Interestingly, Xiaotu et al. (2017) also looked at the mean combined direction and magnitude errors around the actual storm location for different agencies and found that they all have their own unique bias towards specific directions.

3.2 Physical Vulnerability

Application of the framework by Bischiniotis et al. (2020) requires knowing about the physical vulnerability of the system under the existing scenario as well as how these change under the Forecast-based Action and the prevention scenario. In their study, they describe physical vulnerability by linking damage to hazard probability. However, there are other ways to express physical vulnerability. This chapter aims to explore the different ways in which the concept of physical vulnerability can be used for this case study.

As already mentioned in section 2.3.3, Physical vulnerability is the fragility and susceptibility of a physical object to cope with hazardous conditions (Birkmann et al., 2013; Westen et al., 2009). Concretely, considering the HT3s to be the elements-at-risk that this research is interested in, this research defines physical vulnerability as the degree of damage sustained by HT3 houses when a TC with a particular windspeed strike.

The physical vulnerability of a structure can be described as both damage curves and fragility curves. Whereas fragility curves depict the probability that a building with specific characteristics exceeds a certain damage state, damage curves relate the intensity with the corresponding degree of loss. For example, a damage ratio of 50% means that the cost of repairing the building is equal to 50% of its construction cost (Papathoma-Köhle, 2016; Suiza, 2017).

There are advantages and disadvantages for both fragility curves and damage curves. The advantage of damage curves over fragility curves is that they are more commonly found in literature, thereby covering a broader range of building types. A downside of damage curves is that damage states are often not defined, leaving the actual impact intangible. For example, a damage ratio of 70% may imply that 30% of the structures' total value is undamaged, however, if the structural components are part of the damaged portion, one needs to rebuild the entire house regardless. A way to overcome this limitation is to relate certain damage ratios to specific damage descriptions, like with fragility curves. Damages states are classified by their specific structural damages and consequences (Ciurean, Schröter, & Glade, 2016). Such a classification not only helps to create a clearer cost estimation but also allows for understanding in-direct consequences, such as the need for evacuation of a temporary shelter (Glade, 2003). The third difference between damage and fragility curves is their use for a larger number of elements at risk. When using fragility curves, one can use the different probabilities of exceedance to assign each building in the case study area certain damage. (eg. 10% sustains no damage, 20% has minor damage, etc.). Because damage curves relate the intensity with the corresponding degree of loss, no estimation on the variability of damage suffered can be made. This can be problematic when a windspeed occurs at a threshold of two damage states which may yield very different losses (eg. either all buildings will be classified to suffer extensive damage or all of them will be completely destructed.) In this respect, the use of fragility curves for calculations on a larger set of similar houses may be less sensitive to such deviations

In constructing damage and fragility curves, studies usually distinguish between different building types – given that houses with specific characteristics may be more prone to suffer damage than others. These classifications often cluster certain construction materials (eg. different types of wood), structural elements (frames and beams) and classify ranges for the number of stories (eg. 1-2 stories, 3-6 stories). Though many studies use a similar classification (eg. W1 for lightweight wooden houses of a single story), architectural singularities at different scales highly influence the structural behavior of a house. (Maqsood et al., 2014; UNISDR, CIMNE, & INGENIAR, 2015; United Nations International Strategy for Disaster Reduction, Centre Internacional De Metodes Numerics A L'enginyeria, & INGENIAR, 2015) For example, a W1 house per Caribbean architecture may respond very differently to a certain windspeed than a similar, typical Philippine house would (Pacheco, Hernandez Jr., Tingatinga, et al., 2014; The World Bank, 2016).

Moreover, the results of a large-scale study may be less useful to smaller-scale studies. Pacheco, Hernandez Jr., Tingatinga, et al., 2014, for example, focused on the Philippine building stock alone in constructing their curves for different building types, while Geoscience Australia looked at similar building types for the entire South-East Asia and Pacific region (Maqsood et al., 2014). In the case of the latter, the uncertainty is in not knowing how well the ´average lightweight wooden house in the Asia-Pacific region represents a typical lightweight wooden house in the Philippines.

Additionally, when interpreting the damage and fragility curves it is important to understand the averaging period used. Most studies focusing on the physical vulnerability of buildings to high wind speeds focus on the 3-second gust winds as these are found to have the best statistical relationship with TC damage (Harper, Kepert, & Ginger, 2010; Tan & Fang, 2018; Wehner, Ginger, Holmes, Sandland, & Edwards, 2010; World Meteorological Organization [WMO], 2006). The WMO standard for estimating the mean wind, however, is a 10-minute average. WMO considers this a sufficiently long period to incorporate turbulence (short period fluctuations), while at the time representing a period of near-constant background mean wind (Harper et al., 2010). For this reason, it may be needed to convert between averaging periods (Harper et al., 2010).

3.3 Event-based losses

In Bischiniotis et al. (2020), the monetary losses during a flood event are found through using the GLOFRIS model, which provides damage estimates by combining inundation maps with a map of asset values and a depth-damage function to represent vulnerability. In the case of the present study, where the Element-at-Risk is a single HT3 house it is possible to go beyond losses incurred due to house damage.

The most obvious and direct monetary losses that can be taken into consideration are costs related to repair (including rebuilding)(Glade, 2003; Vickery et al., 2006). Other studies, even go into further detail by estimating damage to a house's inventory (Pant & Cha, 2019; Westen et al., 2009). However, indirect economic losses can also greatly add up but are much more difficult to quantify (Sieg et al., 2019). Nevertheless, as outlined in section 3.2, when damage state classification is done, this may at least allow for consideration of economic impacts beyond the direct impact on housing. Knowing whether there is a need for evacuation, can help make estimates about the consecutive sheltering costs. Nevertheless, such displacement of people losing their homes, may also (temporarily) place them further from their jobs, resulting in discontinuation of their careers, which disrupts the economy in ways that are hard to quantify (Salgado-Gálvez, 2018).

3.4 Trigger model

Bischiniotis et al. (2020) explored the impact of using several trigger thresholds for triggering FbA. More specifically, their study considered the impact of triggering only when a specific percentage of ensemble member forecasts exceed the flood threshold. The evaluation of these trigger models was done through a contingency table, which categorizes hazard intensity based on the type of (in-)action. A forecast is considered correct if both forecast and observation are in the same category. If not, action is taken in vain, or an event is missed.

From this, it follows that a first step in evaluating an ideal trigger threshold requires a definition of what should be considered 'correct action'. The issue with translating this approach to one that fits the present case study is that the aim of SSKs is not to fully prevent any damage from happening. Though of course desired, action can also be correctly taken if impacts are reduced. Therefore, the definition of 'taking action correctly' needs to be found.

Several options are possible in defining 'taking action correctly'. Firstly, In the EAP, the threshold is set at when 10% of all houses in at least 3 municipalities are expected to be fully destroyed. This includes all houses, and not just a specific house type (estimated equivalent is wind gusts of 140km/h) (PRC, 2019). As a result, it could be expected that if indeed the observed wind speed had surpassed this threshold, action would have been considered to have been correctly taken. However, since this study performs calculations on a single house, it could also be argued that if the event-based losses under FbA are lower than when no action is taken, that this implies correct action. Yet another option, is to view correct action from the perspective of homeowners, in which case any damage prevented could also be considered action to be correctly taken, regardless of whether event-based losses of FbA are higher (which could happen if trigger costs exceeded repair costs).

3.5 Total monetary losses

Bischiniotis et al. (2020) calculated the total monetary losses that occurred over the timespan that their study considered and used this to compare the cost-effectiveness of the different measures. Moreover, they looked at the relative change required for each parameter to alter the most cost-effective strategy. To adapt and deepen the methodology, this study considered ways in which these case-study-specific results could be generalized to advise future decision-making. However, because it is highly unlikely that the same intensity events happen in the same period in the future, case study results do not easily translate to advising decision-makers in different contexts.

The most important aspect in generalizing findings is knowing about the return period of the events in the sample. This gives an idea of how well the events considered in this study represented events occurring at larger timescales. Besides, it allows for the creation of risk curves, from which annual risk and its associated losses can be calculated (Westen, 2009). For this, the return period of the events needs to be acquired. Since tropical cyclone frequency and intensity are not homogeneously distributed over the Philippines, this study could not make use of existing literature, which mostly reports on nationally aggregated return periods of tropical cyclones in the Philippines (Espada, 2018). The only study identified that created regional wind hazard maps, reporting on the expected 20, 50, 100, 200 and 500 year windspeeds was by PAGASA (Figure 12).

4 Methodology & Data

This chapter outlines the data and methods used to successfully answer the research questions. First, section 4.1 explains the methodological flowchart. After that, this chapter starts following the research objectives of this study. Section 4.2 describes the methodology used for deriving the wind-hazard metrics for the case. Section 4.3 outlines the approach taken to identify the physical vulnerability of houses eligible for receiving Shelter Strengthening Kits (SSKs) and how this changes using the different measures. Section 4.4 describes how event-based losses for each event are quantified. Then, section 4.5 explains the method used to identify the ideal trigger threshold. The outputs of these steps serve as input for calculating total monetary losses under the baseline scenario, which is described in section 4.6. This section also explains how the deepening of Bischiniotis et al. (2020) is done. Lastly, section 4.7 describes the approach taken to the sensitivity analysis.

4.1 Methodological flowchart

Figure 14 is an expanded version of Figure 1 and Figure 6. Figure 1 showed how the building blocks of Bischiniotis et al. (2020) feed into each other. Figure 6 showed how research objectives are linked. Figure 14 is tailored to the case study at hand and shows how answering the different research questions is linked. Observed windspeeds are held against the damage curves of the three different measures; doing nothing (DN), implementing an SSK (HT3+SSK), or having the house permanently upgraded (PU). For each, the reached damage state is noted. Different damage states imply different monetary losses (event-based losses). In the case of the permanent upgrade scenario, total monetary losses are represented by the sum of event-based losses under the permanent upgrade scenario. Similarly, for the DN scenario, the total monetary losses are the sum of event-based losses under the doing nothing scenario. For the FbA scenario, however, the forecasted wind speed of the event at hand needs to be held against the trigger threshold. Depending on whether SSK distribution would have been triggered, event-based losses of having FbA as a measure, or having DN as a measure are added up to arrive at total monetary losses. Next, follows the extrapolation of these total monetary losses to find out after how many years a balance would be found between different measures.

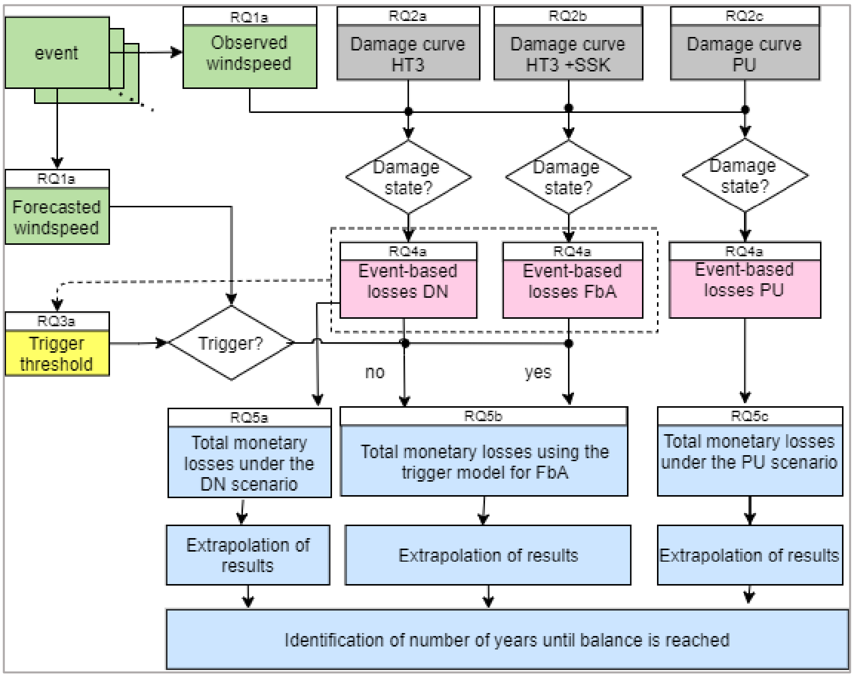

Figure 14: Methodological flowchart

4.2 Wind-hazard metrics

Historical observations as well as how these events were forecasted for Santa Rita needed to be derived. To adhere to the lead-time required under the official trigger model, forecasts at a 72-hour lead-time are derived. Annex 2 shows how the data used as part of these steps was retrieved and managed.

4.2.1 Observed windspeeds

Since there are no weather stations present in the case study area, wind footprint modelling needed to be done. State-of-the-art methods that take into consideration (such as Done et al. (2019)) could not be used given the lack of data on topographical features in the case study area. To somehow account for this uncertainty, the topography of municipalities was considered part of the inclusion criteria for choosing a case-study area, with relatively flat municipalities being included (Annex 1) Moreover, since there is no information on the spatial distribution of HT3s, it is unknown for which location exactly wind speeds need to be derived. For this reason, Santa Rita's centroid position was taken, implying the assumption is made that calculations are done for a single HT3, located at Santa Rita's centroid (Figure 5).

As a result, this study made use of the parametric model by Willoughby et al. (2006). The first step in applying Willoughby et al. (2006) was to obtain historical tracks of interest. For this, the IBTrACS database was consulted, which contains global tropical cyclone best-track data, collected from agencies in every ocean basin. JTWC is the reporting agency for the basin of interest. Initially, this study considered all events starting from 1980 when geostationary satellite coverage improved, and observations became more reliable. A .csv file with all global typhoon events from 1980 onwards was downloaded from the IBTrACS database. Since a data gap was identified between 1981-1985, it was decided to extract events in the period 1986-2020.

While damaging hurricane winds are generally confined to a 100 km radius from the cyclone center (Willoughby & Rahn, 2004), all events within a 1000 km radius from Santa Rita were included given that they may not have impacted Santa Rita, but they may have, at some point, been forecasted to affect Santa Rita, in which case they should be included in the study. Moreover, unnamed events were excluded, given that it would not have been possible to identify the forecast for these events.

413 events were left after these inclusion criteria were applied. For those events, the wind footprint was modeled and the observed wind speed at Santa Rita's centroid was extracted (see example in Figure). Given that JTWC makes use of a 1-minute averaging period, these windspeeds needed to be converted to a 3-second gust, which is found to have the best statistical relationship with wind-induced building damage. The in-land conversion factor for a reference period of 60 seconds to a 3-second gust duration is 1.49 (Harper et al., 2010).

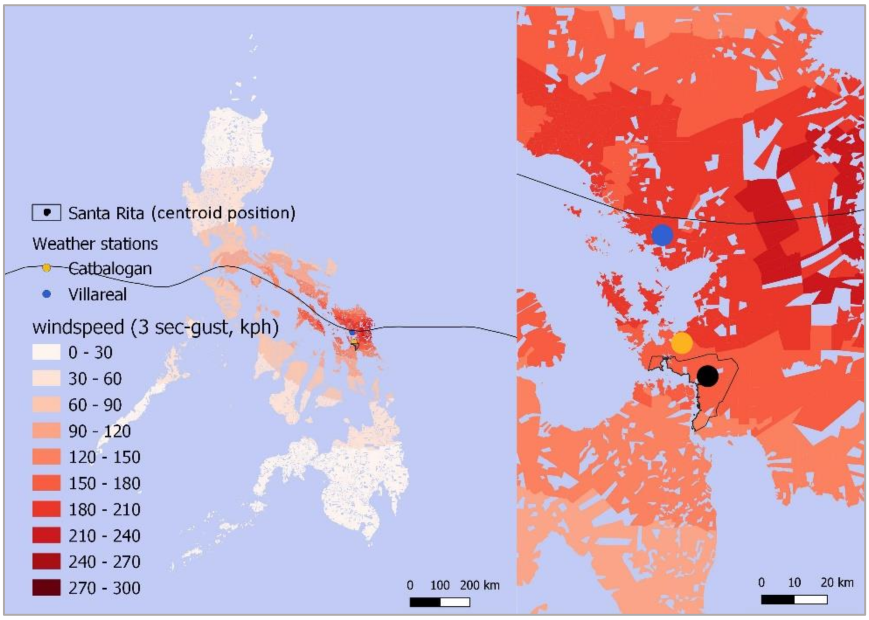

Figure 15: Example of windspeed modelling for Hagupit 2014

4.2.2 Forecasted windspeeds

In finding the historical forecasts for the 413 events that observations were modeled for, this study wanted to use the historical forecasts of JTWC to facilitate consistency between forecasts and observations. However, because this required manually retrieving these forecasts for all 413 events from the Forecast Track Archive (Regional and Mesoscale Meteorology Branch & National Oceanic and Atmospheric Administration, 2021), it was decided to use readily available data from the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF-EPS). It may be that because of conversion factors, or modelling approaches, ECMWF forecasts may either better, or worse approximate the JTWC observations. To explore to what extent this happened, literature on forecast accuracy was also consulted. This is reflected upon in the results (section 5.1).

The ECMWF-EPS forecasts were freely available from mid-2006 onwards. All data up to May 2020 was downloaded. The dataset included all events that occurred within the Philippine Area of Responsibility. ECMWF-EPS issues 50 ensemble forecasts as well as the ensemble-based probabilistic forecast for each forecasting timestamp at a 12-hour interval (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce; Japan Meteorological Agency/Japan; Met Office/Ministry of Defence/United Kingdom; China Meteorological Administration/ Meteorological Service of China, 2008).

The first step was to exclude all events that did not fall within the geographical and temporal overlap with the observations: all events pre-2006 were excluded from the observations; events that forecasts were available for, but no observed windspeeds were modeled for were excluded and vice versa. Figure 16 shows the spatial overlap between the observation and forecast dataset. In total, there were 155 events that both observation and forecasts were available.

The next step was to do wind footprint modeling for the ensemble-based deterministic forecast at each forecasting timestamp, for each of the 155 events, using the same method as described in section 4.2.1. Given that ECMWF uses a 10-minute averaging period, a conversion factor of 1.66 needed to be applied to get to the 3-second gust (Harper et al., 2010). For each event, this resulted in knowing at what timestamp a certain windspeed was forecasted for Santa Rita's centroid coordinates. However, since this study aims to mimic the actual EAP that the FbA is part of as much as possible, it was needed to identify the forecasted wind speed at trigger lead-time (72 hours). For this reason, it was needed to identify the track representing the 72-hour forecast for each event. Since no data is stored on the predicted time until landfall, an alternative approach needed to be formulated. The best option was found to be manually checking landfall time for each event, and then subtracting 72 hours to find the timestamp at which the 72-hour forecast would likely have been issued. The issue with this approach is that no 72-hour timestamp can be identified for non-landfalling TC's. To avoid these complications as much as possible, the following approach was taken.

For each of the 155 events, the maximum forecasted wind speed was identified. This forecast and the corresponding observation were held against the following criteria: if neither the maximum forecast nor the observation exceeded 80km/h, the events were excluded from the analysis. This threshold was taken because no damage would have been expected if windspeeds under 80km/h were to be sustained (section 5.2). Hence, forecasts under 80km/h would also not ever have led to a trigger of the FbA.

The remaining 13 events were then checked on their landfall time using visual inspection of NOAA's Historical Hurricane Track dashboard (NOAA, 2020). It was found that all 13 events had made landfall. Knowing the approximate landfall time allowed for plotting the derived forecasts over time and identifying the 72-hour forecast. Because ECMWF only forecasts every 12 hours, some cases required the closest approximation for a 72-hour timestamp.

A flowchart outlining this process of going from ECMWF forecasts to estimations of wind speeds at different lead times is presented in Annex C. Annex D has plots of how forecasted wind speeds for Santa Rita developed over time for each of the 13 events.

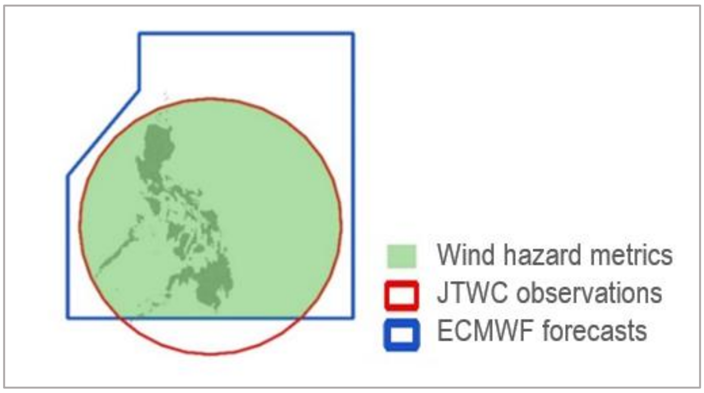

Figure 16: Spatial overlap of JTWC best track data and ECMWF forecasts

4.2.3 Verification of wind field modeling for point-locations

To explore to what degree the use of the methodology by Willoughby et al. (2006) for retrieving the wind speed at a point location was erroneous, verification was attempted. This was done by modeling observed wind speeds at the coordinates of two Automatic Weather Stations (AWS) near Santa Rita: Villareal and Catbalogan (Figure 15). Similar to Fang, Ye, & Yu. (2020), events were identified within the period that the AWS was operational. Eight events between 2016-2020 were identified and visual inspection of

NOAA's Historical Hurricane Tracker dashboard was done to identify the time frame within which the weather station must have experienced the greatest windspeeds (NOAA, 2020). After that, the AWS station data was consulted to identify the highest recorded peak within that timeframe (Department of Science and Technology, 2020). All 8 events were recorded by the Catbalogan AWS, and 4 events were recorded by the Villareal AWS. Since the averaging period for the AWS is not known, and consultation through various channels was unsuccessful, all possible conversion factors were applied on both the modeled observations and AWS data to identify the most likely averaging period of the AWS. Next, recorded and modeled wind speeds were converted to the 3-second gust. These modeled wind speeds were compared to the recorded wind speeds.

4.3 Physical vulnerability

As part of the second research objective, the vulnerability of a typical HT3 house is explored., as well as how this vulnerability changes under the two interventions studied: the installation of SSKs or the implementation of a permanent upgrade. First, the methodology for deriving the physical vulnerability of an HT3 is explained. Next, the same is done for the vulnerability for an HT3+SSK. Lastly, it is explained what this study considers a permanent upgrade, and how the physical vulnerability was defined for this.

4.3.1 Vulnerability of HT3 houses

To date, no research is done into the physical vulnerability of HT3s specifically. Hence, literature was consulted to identify curves that could represent the HT3s. It was deemed important to verify findings from existing literature with BuildChange, given they performed house-classification for the EAP, and designed the SSKs. Unfortunately, this consultation was unsuccessful. Hence, literature research into the best HT3-representative curve was done. The initial search included both fragility and damage curves and focused on three main criteria:

1. The degree to which the building type description matched that of an HT3
2. The degree to which the geographical scope of the study represented the Philippines.
3. The availability of damage curves for other building types (possible permanent upgrades)

The first two criteria are directly related to a damage curve being representable for an HT3 house in the Philippines, the third criterium was put in place because this study aimed at using curves from the same source for calculations to facilitate consistency during calculations for the 'permanent upgrade' that was yet to be defined.

Based on these criteria four plausible curves were identified (Table 2). Three of those came from the hands of researchers at the Institute of Civil Engineering at the University of the Philippines (UPD-ICE). Hence, UPD-ICE was consulted to advise on which one to use as a representative of an HT3 house. They were provided with several documents on the structural characteristics of the HT3 houses. Based on this, they advised using the W1 curve that they created as part of the Greater Metro Manilla Area – Risk Analysis Project (GMMA-RAP), though a clear warning was issued to mind the huge uncertainty. Without actual structural research, their advice should also be considered an educated guess (UPD-ICE, personal communication, February 9, 2021).

Table 2: Studies considered as HT3 representative curves

Study	Type of curve	House type representative of HT3	Geographical scope	Curves constructed for other building types?	Source
UPD-ICE (GMMA-RAP)	Damage curve	W1	Philippines	Multiple	(Pacheco, Hernandez Jr., Castro, et al., 2014)
UPD-ICE (lecture slides)	Damage curve	W1	Philippines	Multiple	(Pacheco, Hernandez Jr., Tingatinga, et al., 2014)
Geoscience Australia	Damage curve	W1	South-East Asia and Pacific	Many	(Maqsood et al., 2014)
UPD-ICE (Suiza, 2017)	Fragility Curve	W1	Philippines	None	(Suiza, 2017)

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4.3.2 Physical vulnerability under the Forecast-based Action scenario

Since no research is done into the physical vulnerability of HT3 houses that are strengthened with an SSK, educated assumption-making needed to be done to draft a damage curve describing an HT3 strengthened with an SSK. UPD-ICE was willing to think along in making this educated guess, however, they needed more information on the design intent of the SSK, which could not be obtained in the time available for conducting this research. For this reason, assumptions needed to be made concerning how an HT3 strengthened with an SSK would respond to increasing wind speeds. *What types of damage do SSKs prevent from happening? And what happens if windspeeds get so intense that an SSK fails?* Since damage ratios themselves do not help to answer those questions, it was found that damage state classification would be required to at least specify the type of damage incurred at different damage ratios, so that assumption making could be done accordingly. The eventual assumptions made and the resulting curve are presented in section 5.2.

Literature was consulted to explore how damage state classification could be done. It was found that UPD-ICE made use of the HAZUS damage state classification in their study that the damage curve for HT3 was retrieved from. The HAZUS classification is used in many studies on wind-induced building damage worldwide (Maqsood et al., 2014; Suiza, 2017; Vickery et al., 2004). For their GMMA-RAP study, UPD-ICE linked the following damage ratios to the damage states as per table Table 3.

Table 3: Damage state classification, linked to damage ratios

HAZUS classification (Vickery et al. (2006))		GMMA-RAP damage ratio (0-100) to damage state (Maqsood et al., 2014)
Damage state	Description	
No damage	Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	0% - 1%
Minor damage	Maximum of one broken window, door, or garage door. Moderate roof cover loss that can be covered to prevent additional water from entering the building. Marks or dents on walls requiring painting or patching for repair.	1%-11%
Moderate damage	Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to the interior of building from water.	11% - 19%
Severe damage	Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to the interior from water	19%-40%
Complete destruction	Complete roof failure and/or failure of the wall frame. Loss of more than 50% of roof sheathing	40% - 100 %

4.3.3 Physical vulnerability under the permanent upgrade scenario

To answer how physical vulnerability changes when an HT3 house gets permanently upgraded through building an entirely new home, it was necessary to first define what the permanent upgrade would look like. As mentioned in section 4.3.1, this study intended to be consistent with the use of damage curves, meaning that both the damage curve representing an HT3 and the damage curve describing the permanent upgrade, came from the same source. However, looking at the other building types studied as part of the UPD-ICE research, it was found that neither of these could be used. The first reason was that there was no information provided on the typical costs of the house types presented. Even though a literature search into typical construction costs of certain house types did provide some handles for further assumptions making, there was another reason that eventually made this study decide on a different approach. This reason was that the houses that damage curves were constructed for, such as the one in Figure 17 does not fit the local and cultural context (CM Builders, 2016; FEMA, n.d.; Pacheco, Hernandez Jr., Tingatinga, et al., 2014, UPD-ICE, personal communication, March 3, 2021).

Hence, this study proceeded by taking inspiration from post-disaster recovery programs. These houses were carefully designed to meet local and cultural standards and were also designed to sustain higher wind speeds. Besides, supporting reports clearly outline costs related to these houses. As part of the Haiyan recovery program, for example, the Philippine Red Cross had designed a half-concrete half-wooden house for relocating households whose houses got fully destructed. Careful consideration of construction costs allowed them to construct a single house at an average cost of €2579,-. No damage curves were constructed for these houses, but they are estimated to be able to withstand winds within a range of 200-250 km/h. In further discussion, the Shelter Cluster outlined that it would be better to consider these homes a semi-permanent upgrade (Victorio, M.M, personal communication, March 4, 2021).

As a result, the assumption was made that investing an additional 25% of it its current costs in structural elements, could achieve structural integrity at the higher end of this range of wind speeds. This is without specifying the type of structural elements. Hence, one would arrive at a similar-looking house as Figure

18, which could be built at the cost of €3188,- and withstand wind speeds up to 250 km/h (point of complete destruction).

However, knowing the point at which complete destruction is expected to occur does not suffice for drafting a damage curve. Initially, UPD was consulted to advise on this. However, answering this question would require detailed information on the design intent. Given the timeframe of this study, this could not be obtained. Hence, a second-best approach was needed to be formulated, which implied assumption making in respect to the shape of the damage curve. The assumptions made and the eventual curve used for the baseline scenario are shown in section 5.2

Figure 17: A typical concrete moment frame, low-rise house in Manilla (Pacheco, Hernandez Jr., Tingatinga, et al., 2014.)

Figure 18: The Philippine Red Cross half-wood/half-concrete house as part of the Haiyan Recovery Programme (Victorio, M.M., personal communication, March 4, 2021).

4.4 Event-based losses

Answering the question of the degree of monetary losses that can occur because of wind-induced building damage during a TC event (event-based losses) is needed for finding the ideal trigger threshold that will eventually be used for the calculations of total monetary losses. As outlined in the literature review (section 3.3) there is a broad range of direct and indirect monetary losses that can be taken into consideration.

The event-based losses that this study includes are limited to repairs and sheltering. The latter is an important consequence for this study specifically, given that one of the goals of SSK distribution is to reduce the time that households need to spend in evacuation centers and transitional shelters. Trigger costs are also considered, but these are only relevant for the scenario of FbA.

This study looked at the event-based losses incurred for a single house under three different measures: doing nothing (DN), taking Forecast-based Action (FbA), and having the permanent upgrade (PU) implemented. This means, that for each event in the time series, the losses under all three measures are calculated. Table 6 gives an overview of which costs are considered for the different scenarios under the different damage states. Event-based losses are always considered based on the damage state reached, for which the damage curve of the respective measure is used (Figure 14).

All costs are brought back to euros, currency conversion rates of November 5th, 2020 apply (XE, 2020).

4.4.1 Trigger costs

The costs considered part of triggering are costs related to purchasing of materials, transport, training, and organization of volunteers, and construction. The material and construction costs for a single SSK are known from the EAP. The costs for construction material are €112 and a team of workers is paid €2,- per SSK (PRC, 2019).

Estimating the other costs is more uncertain since the EAP was only created in 2018, and no reports have been made on triggers yet. To estimate these costs, the EAP activation report for early action to Cyclone Amphan in Bangladesh was consulted. Though these forecast-based Actions did not concern SSK distribution, some assumptions could be made concerning costs for training volunteers, logistics, and personnel. From the evaluation report, it was known how many people were reached and what the total money spent on personnel, workshops, and logistics entailed. This was brought back to costs for a single household (assuming a household size of 5 people) (PRC & ICRC, 2015). It was assumed these costs would reflect the costs for personnel, workshops, and logistics for a single house under SSK distribution. However, knowing that this was the first EAP Activation in Bangladesh, it was assumed that 50% less will be spent during future activations as refresher courses cost less than initial money spend on training. As a result, 50% was taken off the costs that were found to be spent on a single household, which then came down to €4,-. In total, this added up to €117,- per household during a trigger.

4.4.2 Repair costs

Assumptions based on typical repair costs of HT3 houses under different damage states are based on literature research. Shelter Cluster Philippines outlines some typical costs related to repairing typical lightweight wooden houses. They state that minor repairs typically cost around €340,-, while major repairs may require up to €680,- (Shelter Cluster Philippines, 2006). Though it is not known if their definition of minor and major repairs aligns with the damage descriptions that this study adheres to, it was assumed it did. The in-between value of € 510,- was chosen for moderate damage repairs. The costs related to complete destruction were set at €1700,-, which the Shelter Cluster estimates to be the total costs for rebuilding an HT3 (Victorio, M.M, personal communication, February 1, 2021).

Estimations related to the repair costs for a permanently upgraded house were based on the value for building an entirely new house, which also are the costs related to complete destruction. The costs of a new house are set at €3188,- (4.2.3). Since there was no way of knowing the typical repair costs under different damage states, the repair costs of an HT3 house were taken as a reference. Similar percentages of repair costs under different damage states as compared to costs for a new house were used.

To get an idea on how well the estimated damage per the damage curves reflects actual observations during the events, empirical damage data was consulted. Post-disaster reports are generally compiled by NDRRMC to report on the effects of a tropical cyclone (NDRRMC, n.d.). These reports outline numbers related to casualties, evacuation, and more. In terms of housing damage, they provide a breakdown on the regional level on the number of houses damaged and completely destructed. In this, a house is considered partially damaged when essential structural elements are still in place. These reports, however, merely state the total count and do not distinguish between the type of house that got damaged (Department of Social Welfare and Development, 2019). Had data on this been available, one could have estimated whether the observations matched the modelled damage.

4.4.3 Shelter costs

As described in Box 1, families of damaged houses might need temporary sheltering in evacuation centers and transitioning sheltering. The degree of damage sustained heavily influences the time spent in shelters. Consecutively, the time spent in shelters and may also dictate the type of shelters offered. Given the many options, costs related to sheltering are difficult to estimate. As a simplification, this study only considers construction costs (materials and manpower) for the different types of shelter, thereby neglecting any costs related to organization, logistics etc.

It is assumed that when minor damage occurs, there is no need for evacuation. For deriving costs related to sheltering under the other damage states, Figure 10 is used as a reference. From this figure, it can be seen that about 70% of the total number of people initially evacuated to evacuation centers, is no longer in need of sheltering after a month. This study assumes that moderate damage can be repaired within a month. The assumed costs related to sheltering in evacuation centers is zero, given that only construction costs are considered.

From the same figure, it seems that of those who require further sheltering, 50% move to tents initially, while the other half moves to transitional housing straight away. Eventually, all of them live in transitional housing. The assumption is made that the sheltering process described above is that of those households that sustained severe damage. Since this study only calculates the losses for a single house, we factor in the idea that half the people move to tents initially by taking 50% of the costs for single-family sheltering in tents. It is assumed that emergency tents cost about €766,- and can house two families (Hirano, 2012). Hirano (2012) mentions a transitional shelter of local material and labor, but without sanitation and site preparation to cost €349,-. Adding sanitation costs would come down to €735,- for a temporary shelter for a single-family (Philippine Red Cross & International Committee of the Red Cross, 2015). In total, this would come down to an average of €1275,-.

A similar sheltering process was assumed for those families who got their houses fully destructed. The only exception is that this study assumes their transitional housing is slightly more upgraded, given that they need to spend more time in those. In case of Haiyan, which fully destroyed 1.1 million homes the government spent approximately €1220,- on temporary shelters for households who lost their homes (Department of Public Works and Highways, n.d.; Guha-Sapir et al., 2016),. Adding the costs for sheltering in tents comes down to €1374,-.

4.5 Trigger model

In section 3.4 it was explained that the ideal trigger threshold relies highly on how one defines taking action correctly. Three definitions were presented. First, correct action could be considered when both the forecasted and observed windspeed exceed a defined threshold (regardless of the impact it may bring along). The second is considering (in-)action to be correctly performed when the least monetary losses are sustained. The third was the successful reduction of impact, regardless of the monetary losses.

It was chosen to explore the ideal trigger threshold in terms of the first two definitions. This is because this study solely focuses on cost-effectiveness. First, the effect of having different trigger thresholds is evaluated through a contingency table which gives insight into the performance of the trigger model. Secondly, the event-based losses under a scenario when no action is taken (doing nothing/DN) are compared to a scenario where the action is taken (FbA) to gain a better insight into the impact of misses and false alarms. This results in knowing which events had ideally been triggered for in terms of monetary losses. Combining these findings leads to identifying the ideal trigger threshold for this case study.

4.5.1 Contingency table

Action is considered to be correctly taken when both the forecasted wind speed at 72 hours and the observed wind speed exceed the windspeed trigger threshold but are below the point at which complete destruction of HT3 houses with SSK installed occurs. For this, the observation and 72 hour forecast as presented in Table 5 are used. Table 4 shows the contingency table used. Thresholds that define category boundaries are the following: W_1 is the trigger-level for the EAP, which is the variable that is under investigation. Thresholds between 90 and 150 km/h (with a 5 km/h interval) are explored. W_2 is the point at which complete destruction occurs for an HT3 with an SSK, which is 187 km/h.

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If both the forecast and the observation are below the trigger threshold, it is correct to take no action (CN). If homes were forecasted to be fully destroyed regardless of the SSK being implemented, and these destructive wind speeds were also observed, it is also correct not to take action (CN). It could also happen that action is not triggered because the trigger is not forecasted to be exceeded, but then windspeeds turn out to exceed W_2 . In this case, action is correctly not triggered, but for the wrong reasons (CN_u: No action taken, correct, underestimated). The same could happen for events that are not triggered because they are forecasted to exceed the point of complete destruction of an HT3+SSK, but then turn out to be so weak they do not exceed the trigger threshold (CN_o: No action taken, correct, overestimated.). Action can also be triggered wrongly, if events turn out not to have exceeded the trigger level (FA_o: Action taken, false, overestimated.) or if they exceeded the point of complete destruction for an HT3+SSK (FA_u: Action taken, false, underestimated.) Similarly, action could not be taken while it should have, either because the event was underestimated (FN_u: No action taken, false, underestimated) or overestimated (FN_o: No action taken, false, underestimated). Only if the event was triggered, and it should have, action is taken correctly (CA: Action taken, correct.)

By evaluating at what trigger threshold (W_1) most events are captured correctly (CN, CA), one can evaluate at what trigger threshold the trigger model performs best per the contingency table.

Table 4 Contingency table used to evaluate the wind-hazard metrics

Contingency table.
W_1 = the trigger level (variable) windspeed. W_2 = the windspeed at which complete destruction occurs for a HT3 + SSK (187 km/h). W_o = observed windspeed. W_f = forecasted windspeed
CN: Correct, no action taken. CN_u: No action taken, correct, but forecast underestimated windspeed. CN_o: No action taken, correct, but forecast overestimated windspeed. FA_o: Action taken, false, forecast overestimated windspeed. FA_u : Action taken, false, forecast underestimated windspeed. CA: Action taken, correctly forecasted windspeed. FN_u: No action taken, false, forecast underestimated windspeed. FN_o: No action taken, false, forecast underestimated windspeed

		Forecasted windspeed		
		$W_f < W_1$	$W_1 < W_f < W_2$	$W_f > W_2$
Observed windspeed	$W_o < W_1$	CN	FA_o	CN_o
	$W_1 < W_o < W_2$	FN_u	CA	FN_o
	$W_o > W_2$	CN_u	FA_u ,	CN

4.5.2 Event-based losses

The trigger threshold at which most events are captured correctly does not necessarily imply the fewest losses occur at this threshold. Therefore, by evaluating what losses would have occurred under the scenario of doing nothing and triggering FbA, one can get a better idea of the impact of misses and false alarms that occur under different trigger thresholds. To investigate this, the event-based losses as presented in Figure 21 are reflected upon. This gives an idea of which events had ideally been triggered for considering monetary losses.

4.6 Total monetary losses

To achieve the objective of quantifying the total monetary losses related to wind-induced house damage under the different scenarios, this study needs to deviate slightly from the method used by Bischinitos et al. (2020). They use the contingency table to translate wind-hazard metrics to a numerical model for total loss estimations, using the damage curve as a reference for the degree of damage sustained. In their case study, this works well because they can consult a single damage curve regardless of whether anticipatory action was triggered or not. This is because the measure studied does not alter the damage curve, it simply protects against greater hazard intensities. In the case of the present study, the chosen measure alters the damage curve, which results in the inability to use translate the contingency table into a numerical model. Therefore, in the case of the present study, the contingency table is more of a tool to evaluate the trigger model, than to base calculations off.

The approach taken in this study is the following. The events part of the wind hazard metrics are assessed on individual bases (event-based losses) for all three scenario's; Doing nothing (DN), taking forecast based action (FbA) using a pre-defined trigger threshold, and having the permanent upgrade in place. In the case of DN, event-based losses are summed up to arrive at the total monetary losses. For the total monetary losses under the permanent upgrade scenario, the total losses are described by the sum of event-based losses under the permanent upgrade scenario added to the construction costs of these houses. In case of FbA, event-based losses can either be those under the doing nothing scenario, or those under the FbA scenario, depending on whether the action was triggered or not. This is dependent on the chosen trigger threshold.

To deepen the framework, the initial idea was to use the PAGASA return period maps (Figure 12) to plot a risk curve (PAGASA, n.d.). This curve could then be used to retrieve the return period of the 13 observed events in this case study. This attempt is shown in Figure 19. However, PAGASA used large ranges of windspeeds in their classification (eg. orange representing wind speeds between 117 km/h – 200 km/h). Besides, there were only 5 data points that could be derived using these maps (RT=20, RT=50, RT=100, RT=200 and RT = 500). Moreover, when plotting all 13 observed events, it was found that all of them were on the lower end of the plotted curve. As a result, estimation of the return periods of the events as part of the wind hazard metrics would be too uncertain to base calculations on annual risk on.

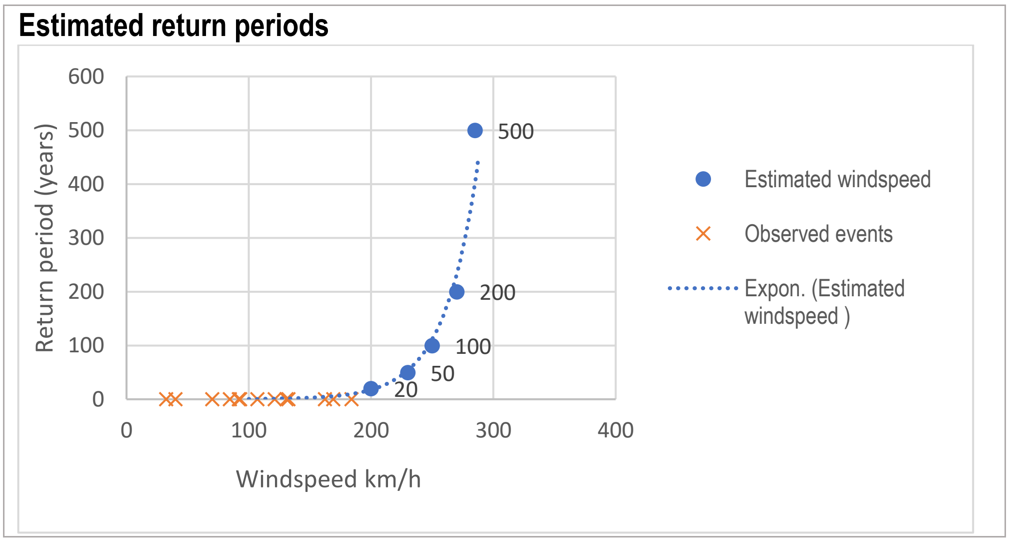


Figure 19: An attempt to identify the local return periods of the observed events for Santa Rita using estimated windspeeds from PAGASA (n.d.) windspeed severity return period maps.

Because of lacking data, the choice was made to take a different approach, for which the assumption needed to be made that the events sample of this study were representative of hazard frequency and intensity on a larger timescale. As such, it could be assumed that the monetary losses obtained in the 14 years of this case study, could be extrapolated to the future. Since linear forecasting methods are sensitive to when, within those 14 years, events occur – this could not be used. As an alternative, the Mean Annual Losses (MAL) were calculated. The MAL is described by the sum of the event-based losses (total monetary losses) under a given scenario, divided by the number of years that event data (2006-2020). This extrapolation could then be used to identify how many years it takes for the permanent upgrade scenario to outweigh the DN and PU scenario.

4.7 Sensitivity analysis

To test the sensitivity of how different variables influence the results, an extensive sensitivity analysis was done. Local sensitivity analysis was done on the use of a discount rate, different wind-hazard metrics, physical vulnerability, the assumed costs, and the trigger threshold. A global sensitivity was done to explore the impact of varying multiple parameters at once.

4.7.1 Discount rate

As described in 4.6 this study aimed to explore ways in which historical samples can be used to advise the future. For this reason, in extrapolating findings, bias as to when a certain-intensity event occurred needed to be taken away. However, when solely interested in the question of what would have been more cost-effective, had a decision been made in 2006, it is worthwhile calculating the Net Present Value of event-based losses.

Under the scenarios explored in this study, costs and benefits are generated at different points in time. With the permanent upgrade scenario, for example, the high initial costs may later provide benefits, while the doing nothing scenario has higher costs occurring during later stages of the time studied. Discounting can be done to express costs and benefits in terms of their present value. The higher the discount rate used, the lower the weight effectively given to future costs and benefits as compared to those occurring presently (Zhuang, Liang, Lin, & de Guzman, 2007).

In literature, there are significant variations in the discount rate used. The choice of the appropriate social discount rate remains a controversial issue given the choice of the discount rate used is mostly based on different views on public projects (Asian Development Bank [ADB], n.d.). In the Philippines, the discount rate used is generally higher than the global average, with rates between 12-15%, though projects with a long-term scope more frequently make use of an 8% rate (ADB, n.d.). Hence, to account for these different views, results were generated for different discount rates; 5%, 10%, 15%, and 20% . Calculations were done with a monthly timestamp, implying that events were attributed to the month that they occurred in, rather than the exact day.

4.7.2 Wind-hazard metrics

Most studies project an increase in TC peak-gust intensity of approximately 14% by 2100 per the RPC4.5 scenario (Mei, Xie, Primeau, McWilliams, & Pasquero, 2015; Shu, 2015). As part of this sensitivity analysis, it is assumed that the wind hazard metrics of this study are representative of a typical 14 years of events. As a result, adding 14% to the intensity of both observed and forecasted events of the wind-hazard metrics is meant to provide insights into how the balance between FbA and PU might shift in the future. Additionally, calculations were done for a scenario in which each of the events in the wind-hazard metrics occurred twice, to get an idea of the impact of increased frequency.

4.7.3 Physical vulnerability

Due to the great amount of assumption making involved in constructing damage curves, both the option of having underestimated, as well as overestimated all curves are being explored. Doing so, it was assumed that the shape of the curve has been estimated correctly. This assumption is well justifiable for the HT3 since this curve is taken from literature and likely describes the rate at which structural failure occurs at higher wind speeds well. Concerning the HT3+SSK curve, for which the shape was estimated by the authors of this study, this is a much rougher assumption to make. It could be that the shape of the curve was assumed wrongly, an uncertainty that is not being tested in this research. In respect to the permanent upgrade curve, this choice is well justifiable given that no structural elements that should have led to the shape of this curve have been specified. Figure 20 shows the curves that were used as part of the sensitivity analysis.

4.7.4 Event-based losses

Another factor that involved much assumption making was related to event-based losses (the costs for sheltering, repairs, and triggering (in case of FbA)). For this reason, a sensitivity analysis was done using different combinations of over and underestimating these costs. Underestimation of event-based costs implied adding 25% to the total event-based losses of the baseline scenario, while an overestimation implied a subtraction of 25%. Table 6 shows the values used for these calculations. As part of these calculations, it was also assumed that the initial construction costs of the permanent upgrade were either over-or underestimated.

4.7.5 Trigger model

In the existing EAP, the 72-hour lead-time is required because homes in target municipalities still need to be evaluated on whether they meet the requirements for receiving an SSK, after which distribution of SSKs needs to happen as well. For this part of the sensitivity analysis, we imagine a case where one can trigger 18 hours before landfall. For this, we need to imagine that Santa Rita has the human and material resources to successfully implement FbA (including having autonomy over their own trigger model). Though this may not be the case today, the idea of small-scale triggering sounds appealing for multiple reasons. First, shorter lead times can be used as time on logistics can be drastically reduced. Besides, forecasts are more accurate at shorter lead times. Additionally, shorter lead times for triggering allow for capturing events with late cyclogenesis.

To perform this sensitivity analysis the following steps are taken. First, the forecasted wind speed at the 18-hour lead-time is identified per a similar approach as done for the wind-hazard metrics, after which this windspeed is checked against the trigger threshold. Next, calculations follow the earlier described methodology.

5 Analysis and results

This chapter presents the results and an analysis of them. Section 5.1 presents the derived wind hazard metrics. Section 5.2 describes the physical vulnerability of an HT3 house as well as that of a permanent upgrade and an HT3 house strengthened with a Shelter Strengthening Kit (SSK). Section 5.3 presents the losses that would have been sustained under different interventions for the different events (event-based losses). Section 5.4 outlines the evaluation of the ideal trigger threshold. The results of these first sections serve as the inputs for the baseline scenario for calculating total monetary losses, which is presented in section 5.5. Lastly, section 5.6 outlines the results of the sensitivity analysis. For a summary of the results that serve as the baseline scenario for further calculations, Annex E can be referred to. Results of the global sensitivity analysis can be found in Annex F.

5.1 Wind-hazard metrics

As a result of the different inclusion and exclusion criteria, 13 events were identified as tropical cyclone events that wind-hazard metrics needed to be generated for. For the 13 events included in this study, landfall time was estimated, and the forecasted wind speeds for Santa Rita for each forecasting timestamp were plotted. This is visually described in Annex C. Annex D shows the plots of how modeled forecasted wind speeds for Santa Rita developed over time. Table 5 shows the estimated 72-hour forecast as well as the observations for the 13 events that were used for calculations. As can be seen, 6 events were found not to have had a 72-hour forecast as cyclogeneses had not yet occurred.

When analyzing the plots in Annex D, one would expect the forecasted wind speed at lead-time 0 to closely approximate the modeled, observed wind speed. However, there are four instances in which the JTWC observation deviates much from the EMCWF forecast at lead-time zero (Rammasun, Melor, Utor and Fengshen). There could be several reasons for this. Firstly, the fact that JTWC and EMCWF use different averaging periods, which require different conversion factors, may yield errors. A second explanation can be found in the approximation of landfall time (lead-time 0) for the forecasts. Since some events did not make landfall in the Visayas (the island group hosting Santa Rita), but went straight over it, the maximum observed wind speed in Santa Rita may not have been at the time the event made landfall.

As a check on the forecast accuracy of the modeled events, literature was consulted. According to a study by Xiaotu et al. (2017) the mean absolute maximum windspeed error for EMCWF forecasts at 72 hours is 66 km/h. At 24 hours, the mean absolute maximum windspeed error is down to 55 km/h (converted to a 3 sec-average) (Xiaotu et al., 2017). Given that forecasts have gotten better over the years, and our study includes forecasts from before 2016, it would be expected that the mean absolute windspeed error in our dataset would be bigger than the findings by Xiaotu et al. (2017). However, when comparing the modeled observations to the modeled EMCWF forecasts for Santa Rita, it is found that the mean absolute maximum windspeed error was 34 km/h at 72 hours (and 27 km/h at 18 hours).

From this analysis, it would appear that the methodology used to derive wind hazard metrics for Santa Rita had led to this study reporting results that were better than they would have been in reality for this case.

Table 5: The modelled, observed- and forecasted wind speeds for Santa.

			Baseline scenario forecasts	**Sensitivity analysis forecasts**
Event	**Date**	**Observed windspeed (3 sec. gust, km/h)**	**Forecasted wind speed at 72 hours (3 sec. gust, km/h)**	**Forecasted wind speed at 18 hours (3 sec. gust, km/h)**
Utor	December 2006	131	No 72-hour forecast	74
Fengshen	May 2006	169	No 72-hour forecast	102
Son-Tihn	October 2012	70	No 72-hour forecast	No 18-hour forecast
Bopha	December 2012	40	101	44
Haiyan	November 2013	184	156	202
Rammasun	July 2014	92	22	67
Hagupit	December 2014	162	133	138
Mekkhala	January 2015	93	No 72-hour forecast	88
Maysak	April 2015	32	25	33
Melor	December 2015	107	74	75
Phanfone	December 2019	133	No 72-hour forecast	96
Kammuri	December 2019	85	74	96
Vongfong	May 2020	121	No 72-hour forecast	78

5.1.1 Verification of wind field modeling for point-locations

To further verify the reliability of the method used to model wind speeds at point locations, verification was attempted on modeling windspeeds at locations of Automated Weather Stations (AWS). It seemed most likely that the AWS recorded a 10-minute mean, given that the use of its corresponding conversion factor resulted in the closest approximation of the modeled values. Nevertheless, big differences were found between recorded windspeeds by the AWS and modeled wind speeds. Of the 12 recorded instances, the modeled wind speeds were found to have yielded higher wind speeds than what was recorded by the AWS 9 times. 3 times, the AWS reported higher wind speeds. In the case of overestimation, this was 59 km/h on average, while underestimation was 37 km/h on average. These are huge differences, which, if also true for our case study, would be highly problematic for the reliability of the wind-hazard metrics that were derived. However, when analysing the causes underpinning these huge differences, it is found that not much certainty can be attributed to this attempted verification for several reasons. First, the AWS did not report surface conditions but recorded wind speeds at about 70m above the surface. Secondly, a wrong averaging period may have been assumed regardless of the attempt to identify the most likely conversion factor. Thirdly, the use of conversion factors are merely best estimations. As a result, not much can conclude on how well the used wind-hazard metrics in this study are representative of what truly occurred between 2006 and 2020.

5.2 Physical vulnerability

The damage curves used in the baseline scenario are shown in Figure 20. These are the W1 curve from the GMMA-RAP study by Pacheco, Hernandez Jr., Castro, et al., (2014) as representative for an HT3. And the assumption-based curves constructed by the authors of this study for an HT3+SSK, and a permanent upgrade.

The assumptions underpinning the damage curves for an HT3+SSK and a PU are the following:

- The HT3 curve is used as a reference for the curve of the HT3+SSK. It is assumed that the SSKs are strong at delaying structural failures that are part of the minor and moderate damage class. However, when damage occurs, it is expected that wind will enter the building and destroy the home altogether. Hence, an extremely steep gradient of the curve is expected from the moderate damage class onwards.
- As for the permanent upgrade, it was assumed that complete destruction would occur at 250 km/h (section 4.2.3). As a result, this was the only known point on the curve, from which further assumption making was done. It was assumed that the wind speed at which damage first starts to occur was higher than both that of the HT3 as well as the HT3 strengthened with an SSK. This resulted in having an idea of the first and last point on the curve. The shapes of damage curves for different structures were studied to make an educated guess about what the curve would look like between those points. It was found that generally, the stronger the structure, the lesser the gradient of the curve. Hence, it was assumed that the curve would have quite a low gradient as compared to the HT3 house and the HT3 house strengthened with an SSK.

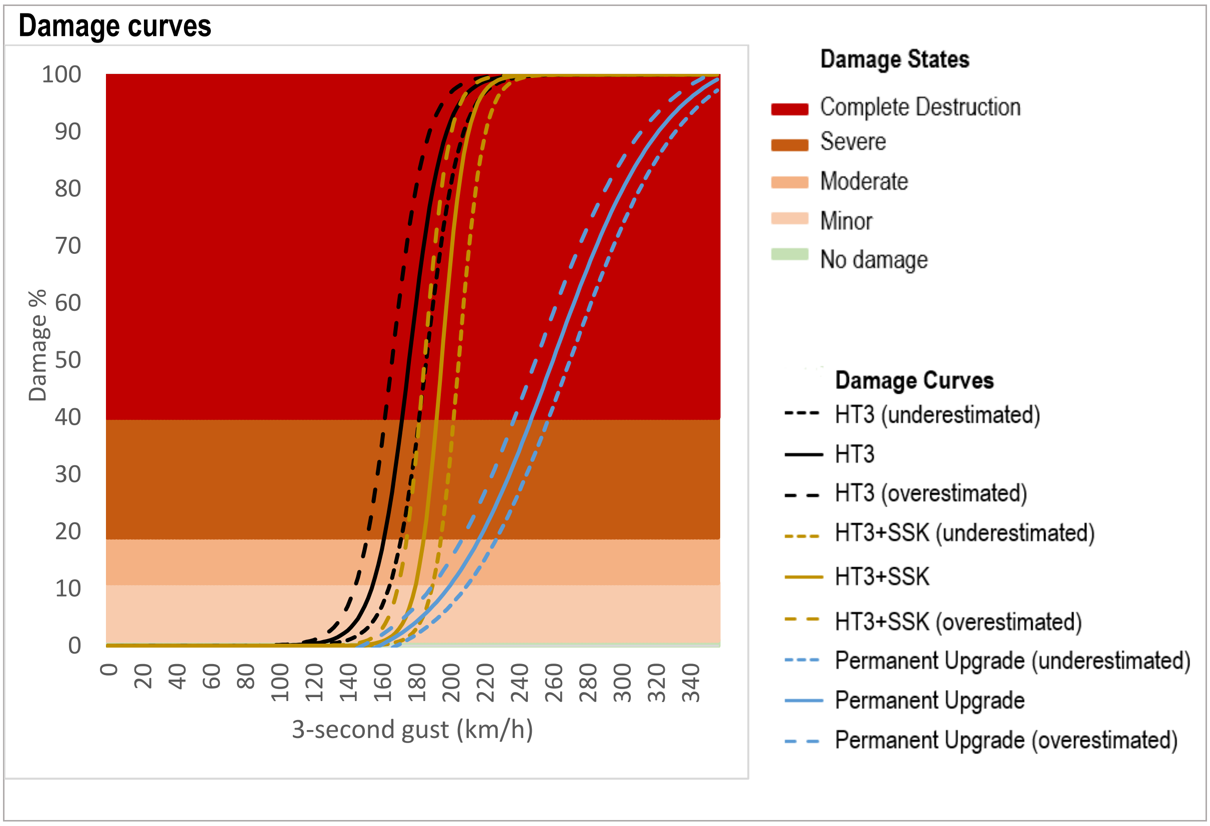


Figure 20: The damage curves used for the baseline scenario and their over-and underestimated curves used as part of the sensitivity analysis.

5.3 Event-based losses

Section 4.4 outlined that repair costs, shelter costs, and trigger costs (in the case of FbA) were considered event-based losses. Table 6 has an overview of the assumed costs involved under the different measures taken: had FbA been triggered (FbA), if nothing was one (DN), or if the house had been permanently upgraded (PU). These costs as dependent on the damage state reached due to hazard intensity. Shelter costs are dependent on the damage state reached but are the same for all three scenarios. As can be seen, trigger costs are only relevant in the Forecast-based Action scenario and are independent of the damage state reached. Repair costs are damage state-dependent and are the same for the DN and FbA scenarios. This is because no repairs are done to SSKs. For reference, section 4.4.1, 4.4.2, 4.4.3 outline the assumptions behind the chosen values for trigger costs, repair costs, and shelter costs respectively.

Table 6: A break-up of the total event-based losses as part of the baseline scenario, and the values used as part of the sensitivity analysis.

		Baseline scenario				Sensitivity Analysis	
Damage State	Measure taken	**Total event-based losses (€)**	Trigger costs (€)	Repair costs (€)	Shelter costs (€)	Total-event-based losses underestimated (€) (+ 25% baseline scenario)	Total-event-based losses overestimated (€) (-25% baseline scenario)
No damage	Doing nothing	**0**				0	0
	Forecast-based Action	**117**	117			146	88
	Permanent upgrade	**0**				0	0
Minor damage	Doing nothing	**340**		340		425	255
	Forecast-based Action	**457**	117			571	343
	Permanent upgrade	**638**		638		798	479
Moderate damage	Doing nothing	**510**		510		638	383
	Forecast-based Action	**627**	117			784	470
	Permanent upgrade	**956**		956		1195	717
Severe damage	Doing nothing	**680**		680	1212	850	510
	Forecast-based Action	**2191**	117			2739	1643
	Permanent upgrade	**2487**		1275		3109	1865
Complete destruction	Doing nothing	**1700**		1700	1375	2125	1275
	Forecast-based Action	**3192**	117			3990	2394
	Permanent upgrade	**4463**		3188		5579	3347

Using the damage curves and wind-hazard metrics, event-based losses that would have been sustained under the different measures for each event could be explored (Figure 1). In this figure, repair and rebuilding costs are distinguished. In calculations, rebuilding costs are the repair costs under the damage state of complete destruction. Analysis of Figure 1, yields the following insights.

In case of Utor and Phanfone, triggering FbA would have prevented damage. Without it, minor damage had occurred. Hagupit is similar in this sense, except the HT3 would have still sustained minor damage with an SSK. However, this still would have prevented severe damage and the need for sheltering that would have occurred if nothing was done. During all three events, fewer monetary losses would have been sustained had action been triggered. In case the permanent upgrade had been implemented, no damage would have been sustained at all during these events.

Looking at Fengshen, hazard intensity would have led to minor damage in both a permanently upgraded house, as well as for an HT3 house strengthened with an SSK. However, repairs to permanent upgrades are more expensive. Therefore, monetary losses would have been higher than for FbA. As a result of doing nothing, severe damage would have occurred, resulting in additional sheltering costs which would have added tremendously to event-based losses.

Haiyan is an interesting case as well. Results show approximately equal event-based losses would have occurred under the FbA scenario as well as with the permanent upgrade. This is because minor damage would have occurred to a permanent upgrade. Instead, moderate damage would have occurred to an HT3 house strengthened with an SSK. Moderate repairs to an HT3 house are cheaper than minor repairs to a permanently upgraded house. However, the costs for triggering FbA would have resulted in about equal event-based losses for both scenarios. Both scenarios imply fewer monetary losses than a DN scenario, in which complete destruction would have occurred, leaving the household to spend a lot of time in a transitional shelter. In the case of Son-Tihn, Bopha, Rammasun, Mekkhala, Maysak, Melor, Kammuri, and Vongfong, no damage would have occurred to either a permanently upgraded house or an HT3 house. Hence, triggering FbA would have yielded the greatest event-based losses, namely the costs for triggering.

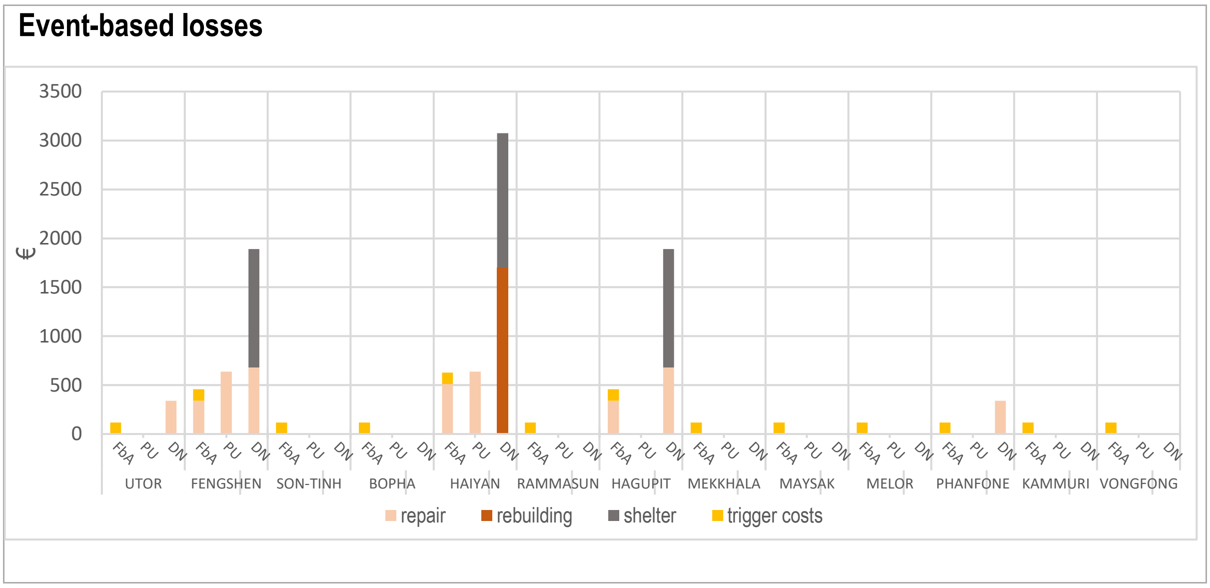


Figure 21: Event-based losses (€) that would have been sustained under the different measures that could have been taken: distribution of SSKs (FbA), permanently upgrading (PU), and doing nothing (DN).

5.4 Trigger model

As described in section 4.5, the ideal trigger threshold is explored from two definitions of taking action correctly. First, the assessment through a contingency table looks at whether events were correctly triggered based on corresponding forecasts and observations. Second, a reflection on event-based losses considers the ideal trigger threshold from a perspective of which events had ideally been triggered considering monetary losses. From the contingency table it was found that a trigger level between 120 and 130 km/h yields the best balance between an action being correctly triggered, and the fewest cases of falsely taking no action. From the evaluation of event-based losses, it was found that a trigger threshold of 130km/h would have captured events that had ideally been triggered for given monetary losses. Combining these insights, a trigger threshold of 130km/h is used as part of calculations in the baseline scenario.

5.4.1 Contingency table

Figure 22 depicts the contingency table under different trigger thresholds. As can be seen, the lower the trigger threshold, the more often no action is taken while it should have (FN). All these are cases where the forecast underestimated the storm or cases where cyclogenesis had not yet occurred and hence, no forecast information was available yet. In case of triggering between 90 and 100 km/h, there would have been an instance where the event was over-forecasted, resulting in action to be taken in vain (Bopha). With a trigger level between 90km/h and 130 km/h, action would have been triggered correctly twice (Haiyan and Hagupit). From this figure, a trigger level between 120 and 130 km/h yields the best balance between an action being correctly triggered, and the fewest cases of falsely taking no action.

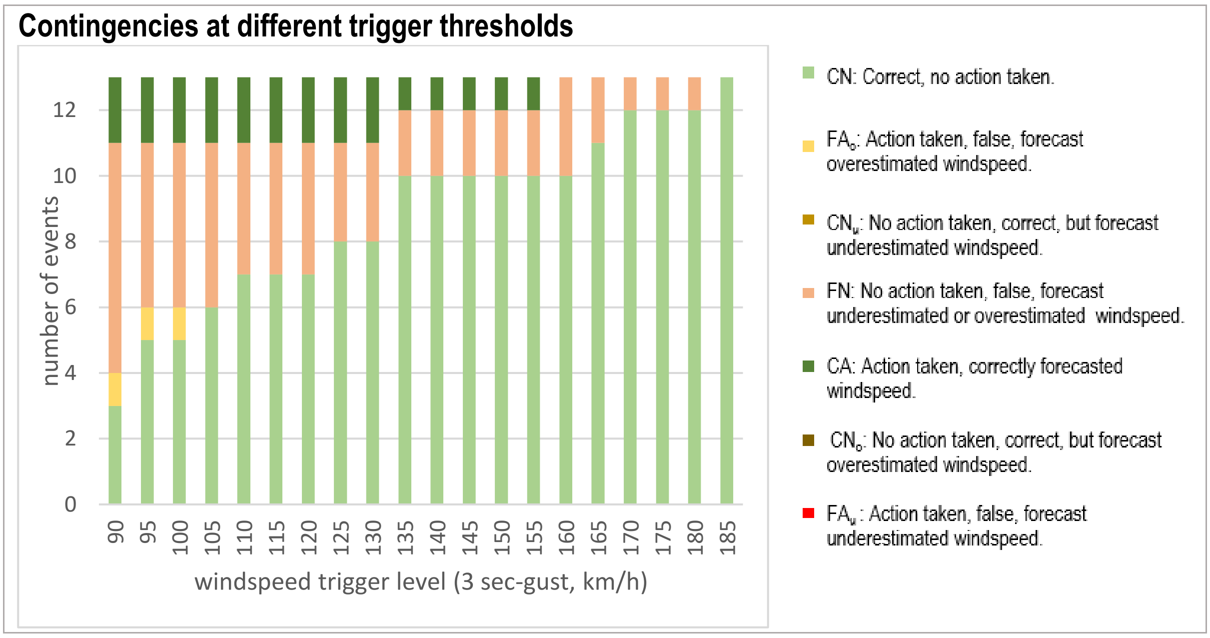


Figure 22: The contingency table at different trigger thresholds

5.4.2 Event-based losses

From the reflection in section 5.3, it can be concluded that ideally, a trigger threshold is chosen that captures Fengshen, Haiyan, Hagupit, Utor and Phanfone. However, for Fengshen, Utor and Phanfone, cyclogenesis had not yet occurred 72 hours prior to landfall. For Fengshen and Utor, forecasts were only available 30 hours prior to landfall, in case of Phanfone, this was 54 hours. As a result, regardless of the chosen trigger level, these three would be missed events (FN_u). Annex D can be used as a reference for these conclusions. A trigger threshold of 130km/h captures both Haiyan and Hagupit, and would therefore be ideal from the perspective of monetary losses.

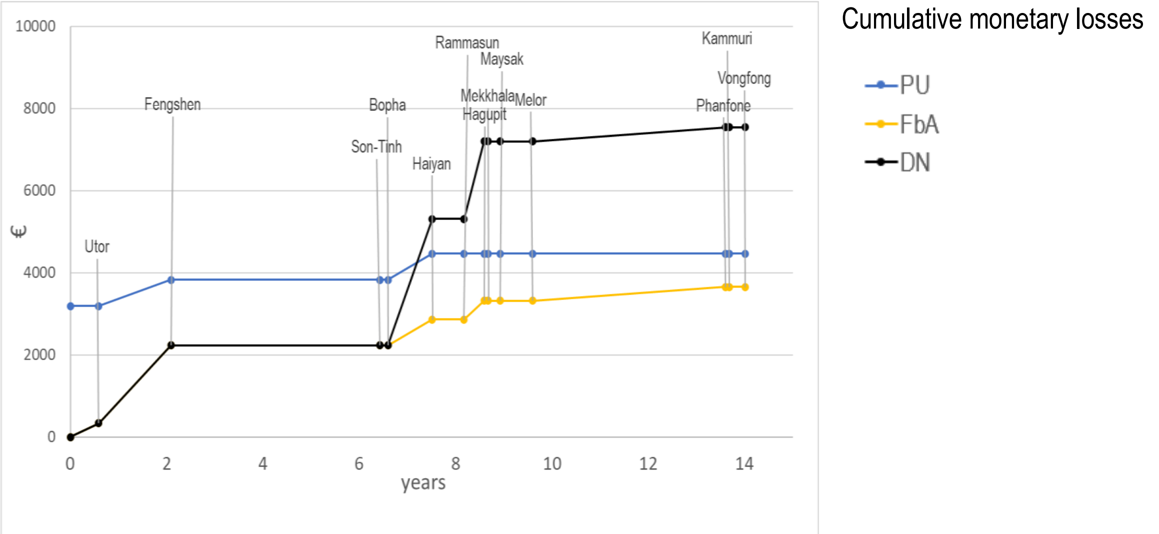
5.5 Total monetary losses

Using the assumptions of the baseline scenario (Annex E), the following results are found. Figure a shows how event-based losses add up over time under the different scenarios. As can be seen, the main portion of total monetary losses under the PU scenario is related to the initial costs. There are very few event-based losses under the permanent upgrade scenario, while event-based losses under SSK distribution are considerably higher. Nevertheless, both scenarios would have proven themselves more cost-effective than the doing nothing scenario over the time of 14 years that this study looked at. The total monetary losses amount up to € 4463 for the PU scenario, €3656 for the FbA scenario and €7538 for the DN scenario.

Figure 23b shows the extrapolation of monetary losses using the Mean Annual Losses (MAL) for each scenario. In the extrapolation, the upper limit on the number of years is set at 25 years, given that this is expected to be the approximate lifetime of a permanently upgraded house (Victorio, M.M., personal communication, March 4, 2021). For this reason, this study was most interested in finding out if, within the expected lifetime of a permanent upgrade, different scenarios would start outweighing each other. It is found that it takes 18.7 years for the PU scenario to outweigh the FbA scenario. At the same time, it only takes 7.1 years for the PU scenario to outweigh the DN scenario.

In Figure 23b, The MAL has also been plotted as part of the first 14 years. Shaded in their respective colour, cumulative monetary losses as in Figure 3a are also shown. This is done to highlight the impact of applying the MAL on actual events. From this, it can be seen that the differences between summing up event-based losses and using MAL are quite large at certain points in time. The MAL smoothens out the impact of when in time costs are made.

A. Cumulative monetary losses under the baseline scenario



B. Cumulative monetary losses of the baseline scenario extrapolation using Mean Annual Losses

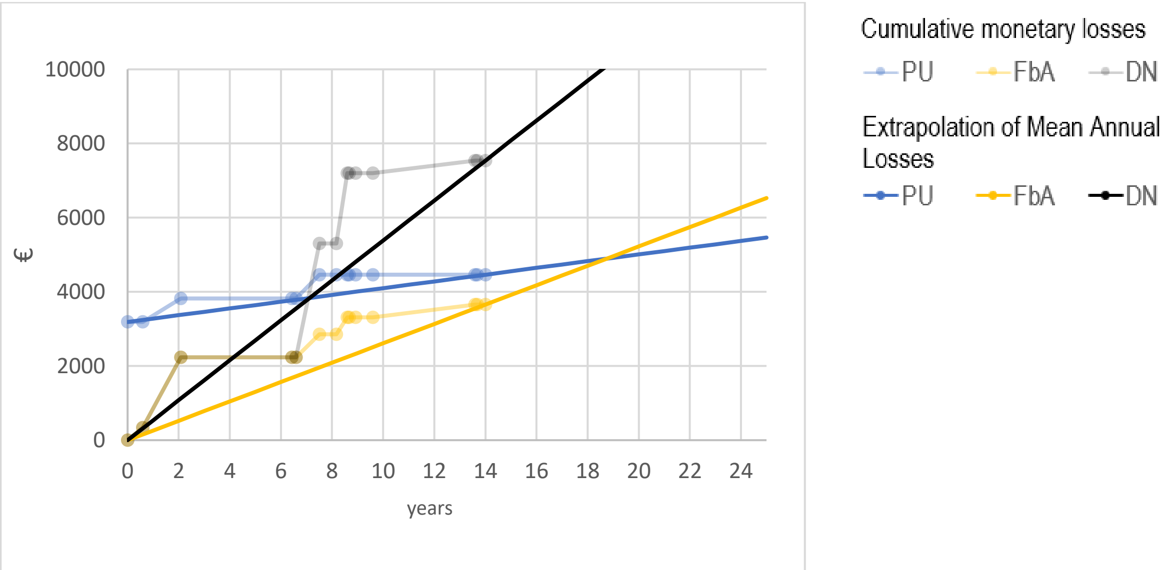


Figure 23. A. Cumulative monetary losses over time under the scenario of doing nothing (DN), permanently upgrading (PU), and FbA using a trigger threshold of 130 km/h. B. Cumulative monetary losses during the case study period extrapolated using Mean Annual Losses (MAL)

5.6 Sensitivity analysis

This section presents the results of the local sensitivity analysis. This implies that for each analysis, only a single parameter is changed from the baseline scenario. The baseline scenario can be found in Annex E. As not all combinations of sensitivities can be touched upon, Annex F provides the results of a global sensitivity analysis in which sensitivities of combinations of parameters are explored.

5.6.1 Discount rate

Figure 24 shows the results of the sensitivity analysis using different discount rates. The higher the discount rate used, the less favourable the permanent upgrade becomes. Using a discount rate of 5%, it takes 23.2 years before the permanent upgrade starts outweighing FbA. At higher discount rates, the balance point will not be reached within the PU's lifetime (29.4 at 10%, 31.9 at 15% and 36.1 at 20%). When looking at after how many years the DN scenario starts to outweigh the permanent upgrade scenario, the results are as follows: at a discount rate of 5%, it takes 9.8 years. At 10%, 13.7 years. At 15%, 17.2 years, and 21.8 years at 20%. From this, it can be concluded that results are highly sensitive to the possible inclusion of a discount rate. Though these results do give insights into what would have been most cost-effective had an actual decision been made for this case study in 2006, the findings of this sensitivity analysis cannot, in fact, be generalized given that results are biased towards when a certain intensity event occurs.

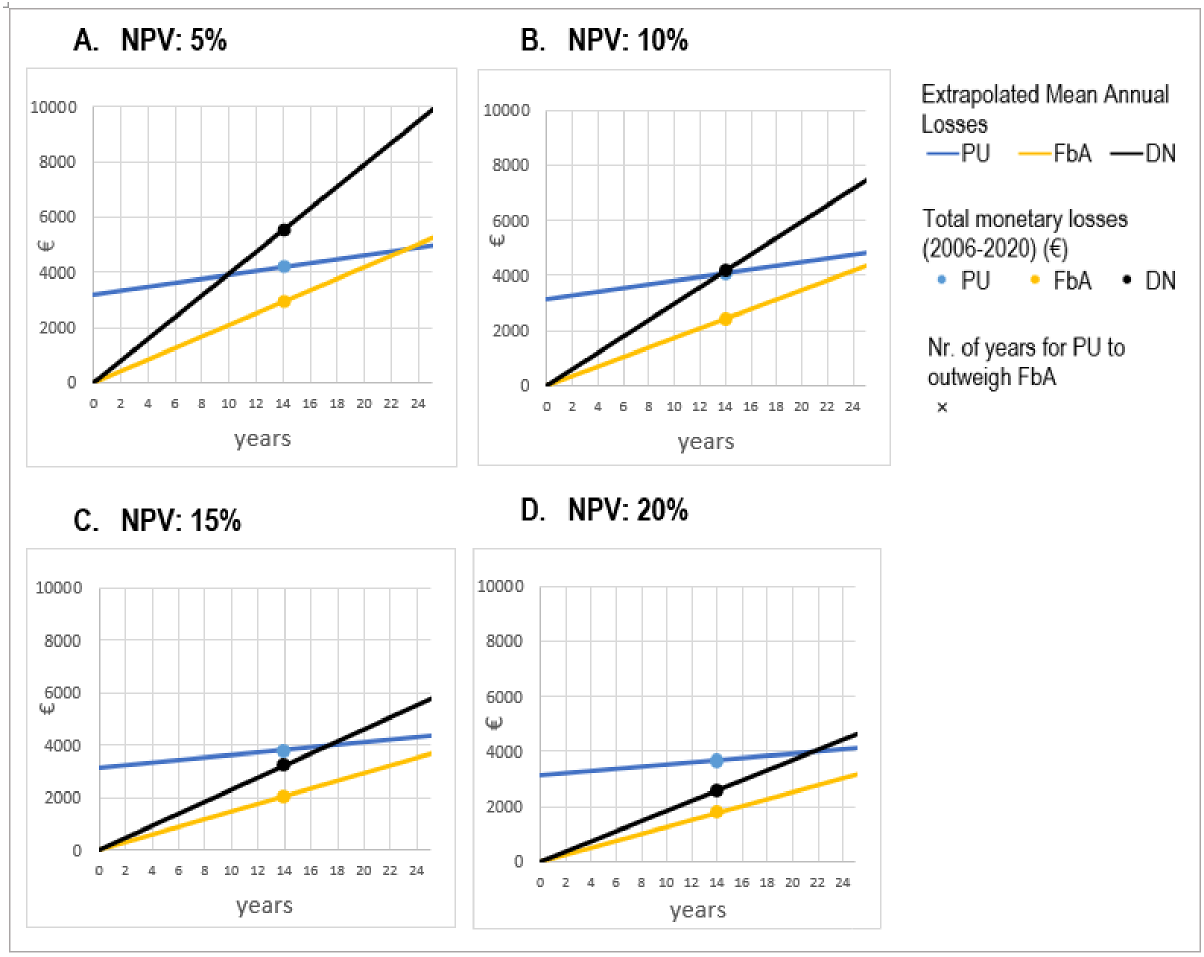


Figure 24: Sensitivity analysis results using the NPV. A. Using a discount rate of 5%. B. Using a discount rate of 10%. C. Using a discount rate of 15%. D. Using a discount rate of 20%

5.6.2 Wind-hazard metrics

Figure 25a shows how the results change had all events in this case study been 14% more intense and forecasted as such. This figure highlights that under these higher intensity windspeeds, the permanent upgrade becomes much more favourable over FbA (6.3 years) and doing nothing (5.6 years). FbA and doing nothing would yield approximately similar mean annual losses. The latter can be explained by the fact that the vulnerability curve used for HT3 + SSK has an extremely steep gradient starting at around 170 km/h wind speed. While many of the events were below this windspeed in the original wind-hazard metrics, they exceeded this windspeed when 14% was added. At higher intensities, higher damage states will more frequently be reached regardless of the SSK being implemented on an HT3 house. Figure 25b shows how the results would have been had the frequency of events been doubled (assuming the same events to have happened twice). Under these circumstances, the point at which the PU scenario outweighs the FbA scenario, as well as the DN scenario, is exactly half of what it would have been under the baseline scenario: 9.4 years and 3.6 years respectively.

A. Forecasted and observed intensity +14% **B. Event frequency doubled**

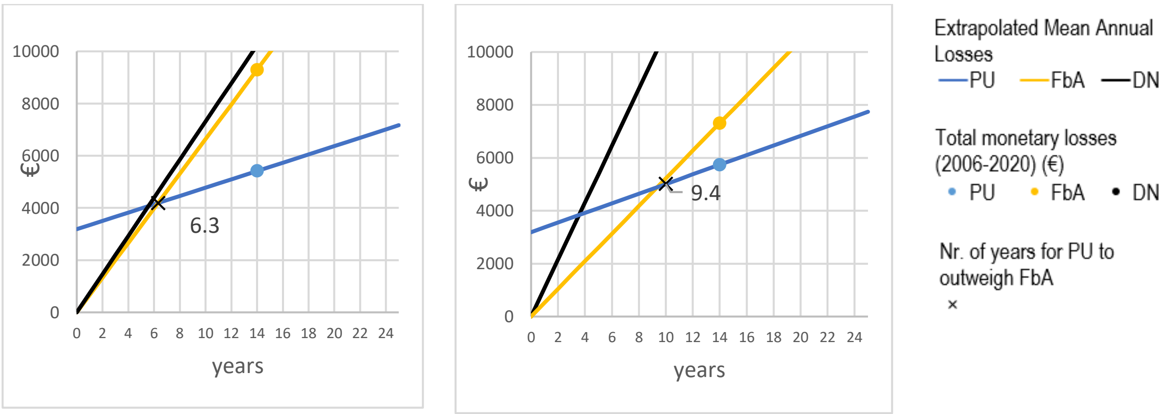


Figure 25: Sensitivity analysis results wind-hazard metrics. A. 14% added to forecasted and observed windspeeds. B: event frequency doubled.

5.6.3 Physical vulnerability

The dotted curves in Figure 20 show the curves used for the sensitivity analysis. For each of the three scenarios, there is a curve depicting a relatively weaker structural integrity (meaning that we would have overestimated the vulnerability) as well a curve describing a situation in which the structural integrity is underestimated.

Figure 26 outlines the cumulative monetary losses given the over-and underestimated physical vulnerability under the three scenarios. In each graph, the shaded line represents the monetary losses that would have been sustained during the baseline scenarios. The upper boundary outlines the cumulative MAL using the overestimated vulnerability curve, implying that more losses were sustained given that the vulnerability of the house in the main run was overestimated. The lower boundary represents the case in which the vulnerability during the main run was underestimated, in which case fewer monetary losses occur. In case of FbA, for the over and underestimated scenario, if no action is triggered, the under or overestimated curve of the HT3 alone is used.

As can be seen from these figures, the FbA scenario is most sensitive to this variation. This is because events in the sample that this study looked at occur within the range of windspeeds around the curves used for the sensitivity analysis. Looking at how these sensitivities in terms of monetary losses translate to the point at which costs are found to outweigh each other, the following is found. When the vulnerability curve of an HT3+SSK is underestimated, it will not cross within the lifetime of a PU, even if the vulnerability curve of the PU was underestimated as well. However, when having overestimated the vulnerability of the HT3+SSK, the balance will already be found after 6.3, 6.9, or 7.7 years, depending on whether the vulnerability curve of the PU is underestimated, as per the baseline scenario, or overestimated. Concerning other combinations of over- and underestimating curves for the HT3 and PU, the doing nothing scenario will always be outweighed by the permanent upgrade scenario within its lifetime, with results ranging between 4.6 and 22 years. These results highlight that damage curves are a highly influential variable.

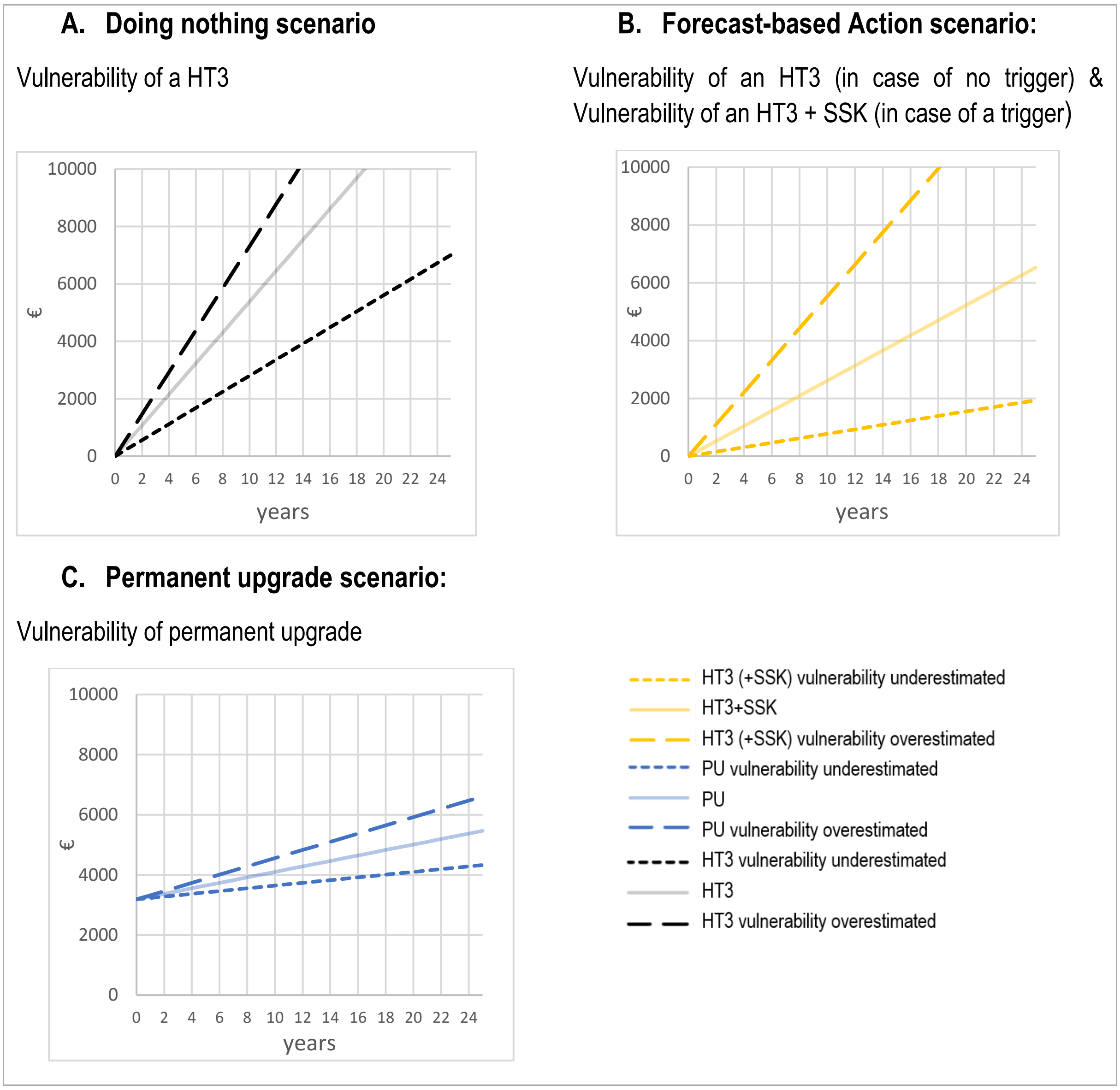


Figure 26. Sensitivity analysis results of over-and underestimating physical vulnerability. A. Cumulative monetary losses of the doing nothing scenario. B. Cumulative monetary losses of the Forecast-based Action scenario. C. Cumulative monetary losses of the permanent upgrade scenario

5.6.4 Event-based losses

Figure 27 shows how cumulative monetary losses change assuming all costs involved were either 25% underestimated, or 25% overestimated. The shaded lines represent the cumulative monetary losses under the baseline scenario.

Looking at how monetary losses translate to the number of years after which scenarios balance, yields the following results. When comparing the underestimation of the costs related to the PU scenario to the baseline scenario of FbA, it is found that the balance is found only after 27 years. For the baseline DN scenario, the balance is still found within the PU's lifetime, namely after 9.4 years. If the costs related to FbA were underestimated while the costs for a PU were as in the baseline scenario, a balance would be found after 13.5 years. In case of doing nothing, after 5.5 years. This broad range of results highlights that estimation of event-based losses should be done with care, as they have a great effect on the results.

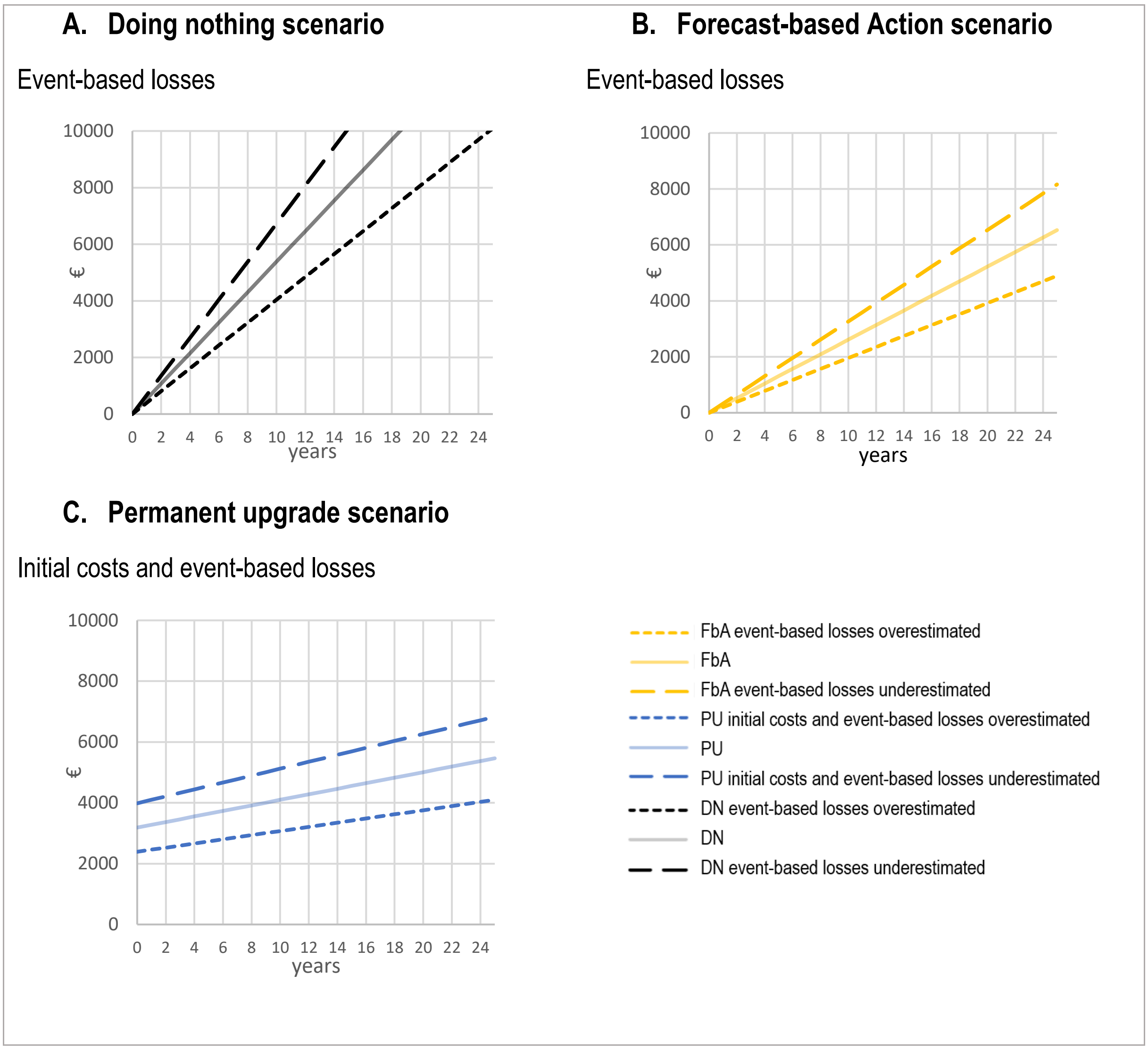


Figure 27: Sensitivity analysis results event-based losses (and initial costs). A. Cumulative monetary losses under the doing nothing scenario. B. Cumulative monetary losses under the Forecast-based Action scenario. C. Cumulative monetary losses under the permanent upgrade scenario

5.6.5 Trigger model

Figure 28 outlines the wind-hazard metrics under an 18-hour lead time. Interestingly, Haiyan was forecasted to exceed the threshold at which complete destruction is expected for a house strengthened with an SSK. However, given the observed wind, complete destruction had not occurred had an SSK been installed. Such a case raises the question of whether to trigger action even though the forecasts indicate destruction. As part of this sensitivity analysis, it was assumed that action is triggered for Haiyan as well.

From section 5.3 it was found that fewer losses would have been sustained had action been triggered for Haiyan, Hagupit, Fengshen, Utor and Phanfone. However, in the baseline scenario this was not possible for Fengshen, Utor and Phanfone given there was no 72-hour forecast available for these events. However, forecasts were available for these events under an 18-hour lead-time. Nevertheless, these events would not be triggered with the trigger threshold of the baseline scenario (130 km/h). Therefore, a lower trigger threshold would be needed. When calculating the total monetary losses under the different trigger thresholds for an 18-hour lead-time, it was found that triggering at 90km/h would yield the lowest cumulative losses.

To further explore the sensitivity of both trigger threshold and lead-time, several combinations of trigger threshold and lead-time were attempted. A trigger threshold of 90km/h and 130km/h was applied on both the 72-hour forecasts as well as the 18-hour forecasts. Figure 30 shows the plots of cumulative monetary losses under these scenarios. The PU scenario of the main run is included for reference. Similar cumulative losses are sustained under the trigger threshold of 130km/h for both 72 hours (the main run), as well as for 18 hours. Slightly higher losses are found when triggering at 90 km/h when having a 72-hour lead-time. This is due to a false trigger for Bopha, which was modeled not to have caused any damage even under the DN scenario. The results for these three scenarios are in sharp contrast with the scenario of triggering at 90km/h with an 18-hour lead-time, which yield much lower total monetary losses.

Results from this analysis indicate that the ideal trigger threshold is very much dependent on the forecasts that were available for the set of events that are part of the case study.

These results highlight that no general advice can be given on either ideal lead-time or ideal trigger threshold. The only general takeaway is that having a lower trigger threshold will result in triggering more often. As a result, one may capture possibly destructive events, though one also runs the risk of triggering unnecessarily. However, if trigger costs can be kept low, such false triggers would not be too problematic cost-wise, depending on additional event-based losses such as costs related to repair and sheltering. Nevertheless, false triggers may result in a decrease of trust, and decreased willingness to cooperate, which is undesirable.

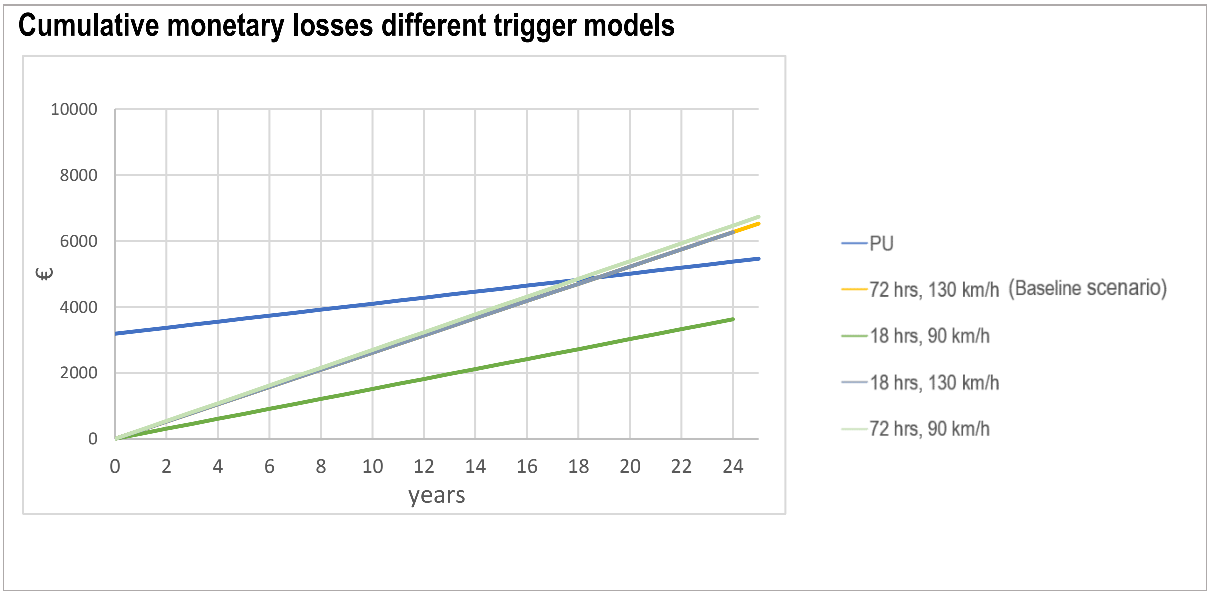


Figure 28: Sensitivity analysis results trigger threshold and lead time

6 Conclusions and discussion

The aim of this research was twofold. Firstly, this study aimed to apply and adapt the methodology of Bischiniotis et al. (2020) on a real-world case study to assess its usefulness in comparing the cost-effectiveness of Forecast-based Action to permanent preventive actions to reduce the risk of natural hazards. In doing so, it followed the building blocks of this framework for a case study. The second objective followed from this. The objective was to assess how Shelter Strengthening Kit distribution as a Forecast-based Action compares to permanent housing upgrade in reducing the risk of wind-induced building damage to lightweight wooden houses in Santa Rita.

In section 6.1, I reflect on my original research objectives and research questions. In section 6.2, I will discuss several recommended further deepenings of the methodology. Next, in section 6.3, I will outline what further research on this specific case could be done. Lastly, section 6.4 will provide concluding remarks.

6.1 Research objectives and questions

6.1.1 Wind hazard metrics

The first sub-objective considered the building block of hazard metrics. The research objective as follows: To generate **wind-hazard metrics** for Santa Rita.

> RQ 1a. What were the maximum observed windspeeds during historical tropical cyclone events in Santa Rita and what windspeeds were forecasted for these events?

For 413 events within a 1000 km radius, the maximum observed windspeed in Santa Rita was retrieved. It was found that many of these modeled events did not impact Santa Rita. Having modeled how the forecasts for these events developed over time, it was found that only 13 events were at some point during their lifetime forecasted to exceed 80 km/h, or were observed to have exceeded 80km/h in Santa Rita between 2006 and 2020. Since this study was interested in the forecast at a lead time of 72 hours, the 72-hour forecast for these 13 events was identified. Table 5 shows the maximum observed windspeeds for these events and their forecast at a 72-hour lead-time.

6.1.2 Physical vulnerability

The second objective was to define the **physical vulnerability** of a lightweight wooden house and how this changes under the different measures. Three research questions served to achieve this objective

> RQ 2a. What is the ability of a lightweight wooden house to withstand high wind speeds and avoid getting damaged?

After consultation with UPD-ICE, It was found that the damage curve of a typical W1 house in the Philippines probably best represents the physical vulnerability of a lightweight wooden house that would be targeted by the Early Action Protocol (HT3). This implies that minor damage occurs at windspeeds of about 130 km/h. At 155km/h a moderate damage state is reached. Severe damage occurs at windspeeds of 161 km/h and complete destruction occurs at 171 km/h.

> RQ 2b. How does the physical vulnerability change if a lightweight wooden house is provided an SSK?

No earlier studies were found on how an SSK changes the vulnerability of an HT3, nor could that be established within the scope of this research. Since consultation was also not successful, the following line of thinking was applied: The use of an SSK is assumed to be most effective at the lower expected damage levels. Therefore, minor damages occur at windspeeds of 163 km/h, while moderate damage will occur at windspeeds of 181 km/h. After this, windows will fail and partial damage to the roof will occur resulting rapidly in severe damage. Severe damage occurs at windspeeds of 184 km/h. At 187 km/h complete destruction occurs.

RQ 2c. How does the physical vulnerability change if a lightweight wooden house is permanently upgraded?

This question required defining what a permanent upgrade would look like. Literature on the physical vulnerability of different building types did not provide examples of housing that would fit the local context of the case study. For this reason, this study chose a house previously built as part of a recovery program. From personal conversations with the Shelter Cluster it was known that complete destruction of this house is expected to occur at windspeeds between 200 and 250 km/h. It was assumed that structural engineers would be able to further enhance its structural integrity at additional costs, to such an extent that complete destruction would occur at the higher end of the estimated range (250 km/h). A permanent upgrade drastically improves the physical vulnerability. Minor damage is assumed to occur 165 km/h, while moderate damage and severe damage are assumed to occur at wind speeds of 202 km/h and 218 km/h respectively.

6.1.3 Event-based losses

One research question was formulated for the research objective to quantify **event-based-losses**

RQ 3a. What are the monetary losses that can be accounted for in calculating event-based losses?

In the literature review (section 3.3), an extensive list of direct and indirect monetary losses was outlined. In quantifying event-based losses, this study limited itself to repair, shelter, and trigger costs. Within shelter costs, this study limited itself to just the costs related to the construction of temporary shelters. Table 6 outlines which event-based losses were linked to which damage states for three different measures under different damage states (1. doing nothing, 2. taking Forecast-based Action, 3. having the permanent upgrade in place).

6.1.4 Trigger model

The fourth research objective was to assess the **trigger model** for Forecast-based Action scenario. One research question aimed to explore this.

RQ 4a. What would be the ideal trigger threshold for the Forecast-based Action scenario in the given case study?

Identifying the ideal trigger threshold for this case study was relatively complex. This is because the definition of acting correctly may not be as clear-cut. Three definitions were given in the literature review (section 3.4), and two of those were explored as part of this study. This study eventually used a trigger threshold of 130 km/h as part of the baseline scenario as this was found to be most cost-effective given the other assumptions. However, it was also concluded that concluding the ideal trigger threshold is arbitrary when only having 13 events for analysis.

6.1.5 Total monetary losses

The fifth research objective was to quantify **the total monetary losses** related to wind-induced house damage under the different scenarios, deepening the method of Bischiniotis et al. (2020). As part of this objective, three research questions were formulated regarding total monetary losses under different scenarios. In arriving at the answers to these questions, the deepening of the framework was attempted. Doing so, this study calculated Mean Annual Losses in an attempt to genialize findings and give an indication of after how many years different scenarios are expected to outweigh each other. In the baseline scenario, it was found that it takes 18.7 years for the PU to outweigh FbA. It takes 7.1 years for the PU to outweigh DN.

> RQ 5a. How can total monetary losses be quantified for the time series under the scenario of doing nothing?

Total monetary losses can be quantified in many ways depending on the application. This is discussed in section 3.5. In this study, the event-based losses under the doing nothing scenario as per Figure 21 were summed up to arrive at total monetary losses. In the baseline scenario, this added up to €7538,-

> RQ 5b. How can total monetary losses be quantified for the time series using the Forecast-based Action scenario?

To calculate total monetary losses under the Forecast-based Action scenario, it was checked whether action would have been triggered given the forecasted windspeed of an event and the trigger threshold. Depending on this, either the event-based losses of doing nothing (DN), or the event-based losses under SSK distribution (FbA) were summed up. In the baseline scenario, this added up to €3656,-

> RQ 5c. How can total monetary losses be quantified for time series using the scenario of permanently upgrading the lightweight wooden house?

Similar to calculating total monetary losses under the FbA scenario, event-based losses can be summed up to arrive at total monetary losses under the permanent upgrade scenario. However, in this case, the initial construction costs were also added. The total monetary losses between 2006 and 2020 were €4463,-, with the main portion being the initial investment.

6.1.6 Sensitivity analysis

Research objective 7 was to perform a **sensitivity analysis** to evaluate the impact of chosen parameter values. Several research questions were formulated to assess the impact of individual parameters. Additionally, a global sensitivity analysis was performed to explore the impact of varying multiple parameters at once and to explore the range of years that it takes for the PU to outweigh FbA. The results of the sensitivity analysis are presented in Ann

> RQ 6a. How do the total monetary losses for this time series, under the different scenarios, change if total monetary losses were calculated using different discount rates?

After calculating total monetary losses, this study concluded that when solely interested in the monetary losses sustained during a fixed period (without the intention to generalize or extrapolate findings), it may be better to use the NPV. A discount rate of 5, 10, 15 and 20% were attempted. The results showed total monetary losses between €2925,- (at 5%) and €1773,- (at 20%) for the FbA scenario. Similarly, total monetary losses under the DN scenario decrease with higher discount rates €5532,- at 5% to €2574,- at

20%). The same for the PU scenario, from €4093 at 5% to €3692,- at 20%. This is a far smaller descrease than for the PU and FbA scenario, which can be explained by the fact that initial costs are included.

Using a discount rate of 5%, PU started outweighing FbA after 23.2 years, which is just within the PU's lifetime. If consideration is given to the NPV, PU becomes a less favorable solution. Nevertheless, it should be noted that using the NPV in combination with extrapolation using Mean Annual Losses is problematic. This is because the goal of using the NPV is to give consideration to when a certain-intensity event occurs, while the goal of the Mean Annual Losses is to generalize.

RQ 6b. How do different wind-hazard metrics affect the balance between FbA and permanent upgrading?

Increasing the intensity of both forecasted and observed windspeeds by 14% makes permanent upgrading a more favorable solution. In this case, it takes 6.3 years for the PU to outweigh FbA. This result highlights the need for serious consideration of prevention measures in light of climate change. Besides, it shows the sensitivity of the results concerning the event-samples used. Therefore, knowing how well representative hazard metrics are of what can generally be expected is key in contextualizing findings. As such, homogeneity of event intensity through time would be required to make results useful.

RQ 6c. How does over-or underestimation of physical vulnerability affect the balance between FbA and permanent upgrading?

The impact of over- and underestimation of the physical vulnerability of a HT3, a HT3 strengthened with an SSK, and a permanent upgrade was explored. Results showed that this highly affected the total monetary losses sustained between 2006 and 2020. This can be explained by the fact that over- or underestimation of vulnerability leads to different damage states that are reached during an event. Higher damage states imply higher monetary losses. This also affects the number of years after the balance is found. The range of years that it takes for the PU to outweigh FbA, considering all different combinations, is between 6 and 100 years. This can be explained by the steepness of the HT3 and HT3+SSK curves. Shifting those along the x-axis, may lead to a difference of multiple damage states as compared to the baseline scenario. A result of 6 years would imply the PU to be a favorable option. In case of 100 years, PU would likely never be considered when thinking about cost-effectiveness. As a result, it can be concluded that detailed information on the physical vulnerability of structures is key in performing calculations such as the ones in this study.

RQ 6d. How does over- or underestimation of monetary losses affect the balance between FbA and permanent upgrading?

Similar to the sensitivity analysis on physical vulnerability, all different combinations of over- and underestimation were tested. The range of years that it takes for the PU to outweigh FbA, considering all different combinations, is between 7 and 19 years. A result of 7 years would imply the PU to be a much more favorable option. The broad range not only highlights the need for verification of assumed costs but also stresses that more detailed mapping of both direct and indirect losses is required.

RQ 6e. How does the use of a different trigger model affect the balance between FbA and permanent upgrading?

A trigger model similar to the baseline scenario was explored, except using an 18-hour lead-time instead of a 72 hour lead time. Also, for both models, a trigger threshold of 90 km/h and 130 km/h was explored. It was found that triggering at an 18-hour lead-time with a 90km/h trigger threshold would yield the fewest monetary losses. In this case, the balance between FbA and PU would not have been reached within the lifetime of a PU and therefore, SSK distribution would be much more cost-effective. It can also be concluded that the evaluation of a trigger model is highly affected by the wind hazard metrics used. A greater number of wind-hazard metrics would be required for this.

6.2 Discussion

The framework by Bischiniots et al. (2020) provides very relevant insights into what variables affect the choice between FbA and prevention measures when considering monetary expenses. However, the actual quantitative results remain rather hypothetical. In fact, quantitative results merely outline what would have been the case today, had a decision been made an x-number of years in the past. This includes the total monetary losses that would have been sustained but also includes the findings concerning the ideal trigger threshold. Such hypothetical results can be extremely relevant as they provide insights into what should be considered for future decision-making.

The framework by Bischiniotis et al. (2020) can be developed in two different directions: One being optimizing the framework for exploring what would have been the ideal intervention had an actual choice been made in the past, which provides insights into critical aspects that need to be considered in decision making. The second is looking into how this framework can be optimized to inform decision-makers for future risks.

6.2.1 Analysis of historical cases

The framework by Bischiniotis et al. (2020) can be further optimized for the analysis of historical cases. Ideally, a study focuses on mapping as accurately as possible the total monetary losses sustained in a given time period as well as mapping all other contextual aspects that affect the choice between FbA and prevention measures. These contextual factors could be related to monetary aspects, though it would also be desired that intangible benefits and indirect monetary losses are mapped as profoundly as possible.

The present study attempted a better estimation of the actual total monetary losses through using the Net Present Value. However, consideration of the impact of consecutive disasters may be a next step. Another example includes the in-depth mapping of the indirect monetary losses because of these events.

Additionally, other contextual aspects can affect the choice between different measures, such as the exposure of the area to other hazards. The present study solely looked at cost-effectiveness considering a singular hazard. However, areas that are exposed to different hazards (such as earthquakes, storm surges and floods), require a multi-hazard approach,

Such an in-depth study allows for better grasping all factors that the choice between FbA or preventive measures. A case study for which fieldwork is possible would be most suited. Such insights also help to improve the framework for informing future decision-making.

6.2.2 Advising future decision making

The second direction of further development of the framework is to inform decision-makers on mitigating future risks. Understanding of factors that influence the choice between FbA and prevention measures may not directly lead to knowing how to most effectively manage future risks.This study attempted extrapolation using Mean Annual Losses. However, this was a second-best approach given the lack of data on hazard probability. Besides, having just 14 years of hazard data was also a limitation. To truly advise decision-makers on how future risk can be mitigated, hazard metrics of a longer period, including detailed information on hazard probability would be required. As such, the framework can be developed to give a better estimation of how results translate to future risk. Ideally, this deepening is combined with an in-depth analysis such as described in 6.2.1. This would also give decision-makers an idea of additional aspects that come into play when balancing measures.

6.3 Recommendations

As described in chapter 5 several shortcuts were taken during this study. The short-cuts made were well-justified and done deliberately with the objective in mind to apply and adapt the methodology of Bischiniotis et al. (2020). As a consequence, the findings of this case study should be used cautiously. However, generally speaking, it can be observed that both PU and FbA seem more cost-effective than to do nothing. Besides, in the many scenarios explored, a balance between FbA and PU was often found within the expected lifetime of a permanently upgraded house.

These findings do highlight the relevance for further research of this case:

A. Get more certainty on the damage curves used, including the damage state classification. The reason for this is two-fold. First, the damage curves include most of the assumptions making. Secondly, given that they are at the foundation of further cost calculations, any errors in the damage curves may affect calculations that are based on them.
B. Perform re-forecasts for the 13 events. Forecast accuracy has drastically improved over the years. Using historical forecasts to inform future decision-making is not representative of the forecast accuracy that can be achieved these days. It is likely that the use of historical forecasts more often leads to false alarms or misses.
C. Gather more secondary data on actual damage sustained in Santa Rita during these 13 events. This would have helped to verify damage curves and would also have helped to get an idea of the impact of epiphonema that is not accounted for in using this framework.
D. Consult experts to verify and adjust the assumptions made for event-based losses (sheltering, repair, triggering etc.) and include indirect monetary losses in the assessment.
E. Improve the methodology in how repair costs are dealt with. In this study, classification of damage states was done to account for the additional costs of sheltering. However, the classification of repair costs would not have had to be done. A linear function linking damage ratio to repair costs would have provided more accurate results.

However, even after these potential improvements, the outcomes will still be incomplete. Even when this methodology is further perfected, there is still the potential impact of TC-epiphenomena such as floods, storm surges, and landslides, that contribute to losses as well. This study (and methodology) solely focused on wind hazards and more specifically, on damage due to wind-loads of 3-second gusts. This study also did not include the potential impact of other wind-related risks such as air-borne missile impacts and lower wind speeds sustained at longer durations (which may cause material fatigue).

There are also several further deepening's that I would like to have tested. However, these are not suitable to explore in the current case study given the lack of required data and literature to performing these steps. The following could be explored by future research:

A. A new case study to perform the analysis on a larger building stock (eg. on municipality level). This study only performed calculations on a single house and assumed it to be located in Santa Rita's centroid position. To expand to a more realistic scenario, a new case study should meet the following requirements: 1 Have more detailed spatial data available (distribution of houses, house types + topographical features); 2. Fragility curves for different house types; 3. Detailed damage reports of historical events.

The first requirement allows for wind footprint models that take into account terrain effects (section 3.1) and help understand the heterogeneity of windspeed distribution of the buildings exposed. Secondly, fragility curves describe the probability of a certain damage state being exceeded. These are more relevant in case a larger building stock is considered (section 3.2) Thirdly, the detailed damage reports allow for evaluation of the assumed monetary losses.

B. A more realistic scenario would be a case in which the trigger model of an existing (or drafted) EAP is based on forecasted wind speed only. One example is the approved TC EAP in Mozambique, where most at-risk municipalities are targeted if the forecasted wind speed at landfall exceeds an 120km/h. The challenge with defining trigger levels for FbA is that National Societies create EAPs on a national scale. However, a trigger implies taking local action. Since many of these EAPs have not yet been triggered (or triggered just a few times) studies that lead to an understanding of how a trigger eventually leads to local impact would be valuable. The wind speed at landfall does not have to be the wind speed that hits the municipalities receiving aid. The partial use of this framework could help to generate insights into how EAP trigger levels translate to local contexts. This study modeled the windspeeds for a single municipality. If this is done for multiple municipalities, a large database of wind hazard observations on municipality level could be created, these could be compared to modeled wind speeds at landfall – which allows for a comparison of EAP trigger levels to observed wind speeds in municipalities that are triggered for. It would valuable to get a better grip on the uncertainties of the trigger design. Trigger designs should not only be based on forecasted impact if the event were to occur as forecasted. Such an analysis may also find that uncertainties need to be factored in.

C. A large set of wind hazard metrics allows for an in-depth analysis of the ideal trigger threshold, which could not be done in the present study given the limited number of events included. Such research would not just focus on the creation of contingency tables, and identification of events that had ideally been triggered like this study did. It could go into much more detail. For example, this study solely looked at triggering based on a deterministic forecast of ECMWF However, one could also consider triggering on a given percentage of ensemble forecasts exceeding a certain trigger threshold (as considered by Bischiniotis et al. (2020)). Moreover, one could compare forecasts of different meteorological organizations to find out which has the best forecast accuracy. Also, knowing whether the forecasting agency tends to over- or underestimate, can be crucial when thinking about the ideal trigger threshold.

6.4 Concluding remarks

No matter how research building on this work advances, we should not forget the reason why the paradigm shift from traditional humanitarian response to anticipatory action took place initially. This was fuelled by the insight that it would reduce human suffering. Proving that greater impact could be achieved with the available funds only came later. This study would like to highlight that the choice between FbA and prevention efforts, should also be informed by additional benefits, including avoided indirect economic losses as well as non-monetary benefits, which were not incorporated in our analysis. These include, but are not limited to indirect and intangible benefits of certain strategies. For example, a permanent upgrade may facilitate the enhanced feelings of safety. Research should always acknowledge its limitations, and choices should always be made considering the bigger picture.

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Annexes

A. Selection case study municipality

Criteria 1: Shelter Strengthening Kit (SSK)Target area of the existing Typhoon Early Action Protocol (EAP)

To make this research relevant for ongoing efforts by the Philippine Red Cross, it is essential to choose a case study location that is already targeted by an EAP.

Inclusion result: West Samar province, East Samar province, North Samar province

Criteria 2: Plans to allocate part of their DRM budget for Forecast-based Action (FbA)

If a case study area is chosen that has already expressed to mobilize additional funds from the government, this is a great chance to think about how these funds could be spend as effectively as possible.

Inclusion result: West Samar (26 municipalities)

Criteria 3: High typhoon hazard risk 6/10 or higher

In the 510 dashboard, typhoon risk is made up from the sum of both impact due to rainfall and impact due to extreme wind. These cannot be viewed separately, though this would have been relevant given the scope of this study is on wind impact only (510 Global, n.d.).

Inclusion result: Calbayog City, Jiabong, Basey, City Of Catbalogan (Capital), Villareal, Santa Margarita, Marabut, San Jose De Buan, Pinabacdao, Santa Rita, Pagsanghan, Hinabangan, Motiong, Calbiga, Paranas (Wright), Tarangnan, Gandara, Matuguinao, San Jorge.

Criteria 4: Relatively low risk to other hazards that may affect housing (total score 3/10 or lower)

510 dashboard has calculated relative risk to earthquakes, tsunami, floods and droughts. Droughts were excluded for they do not impact housing.

Inclusion result; Basey, City Of Catbalogan (Capital), Villareal, Santa Margarita, Marabut, San Jose De Buan, Santa Rita

Criteria 5: High housing vulnerability

The 510 dashboard has information on the percentage of houses that has strong roofs and strong walls. These are two separate dimensions. For this criterion, it was chosen that for both dimensions the case study area should not have more than 70%. This is because SSK houses have both light walls as well as light roofs.

Inclusion result: Santa Rita, Villareal

Criteria 6: Relatively flat area

Topographic effects may have a huge effect on the windspeed on small scales (Tan & Fang, 2018). Since forecast models do not consider differences at this resolution, it was considered best to go for a relatively flat area, because it is expected that the wind field is more homogenous there. Visual inspection of a DEM on https://en-ie.topographic-map.com/maps/lw3y/Eastern-Visayas/ Villareal was found to have elevations between 0-450 ft, spread over the entire municipality, while Santa Rita has smaller elevation differences, which are also seemingly more concentrated in a specific part of the municipality.

Inclusion result; Santa Rita

B. Data

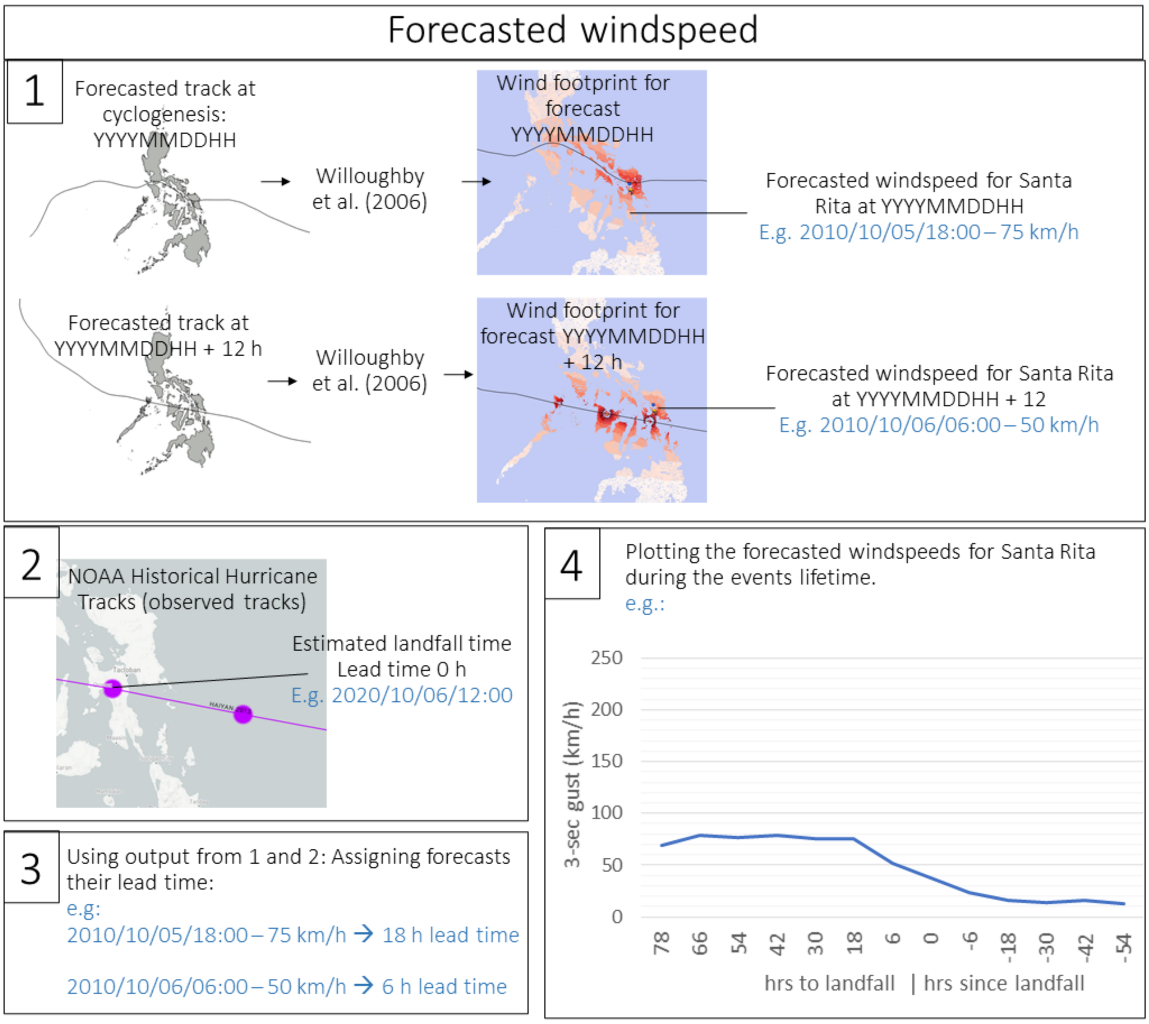
Information on data used.

	A. Observed windspeeds	B. Forecasted windspeeds
Origin of Data		
Kind of data	1980-2019 tropical cyclone best-track data; for each event maximum windspeed at different lat-long points along the track, including the radius of the track - available in CSV or Shapefile format	2006-2020 ECMWF-EPS forecast data of events that occurred within the Philippine Area of Responsibility. 50 ensemble forecasts, including a deterministic forecast issued every 12 hours.
Source of the data	International Best Track Archive for Climate Stewardship (IBTrACS)	The original source is: https://rda.ucar.edu/datasets/ds330.3/#metadata/detailed.html?_do=y . However, given the quality of the laptop of the owner, data was downloaded at 510 Global, and the file sent.
Are various data sources integrated in the datasets used?	Yes, best track data from multiple metrological institutes around the basin are compiled; Australian Bureau of Meteorology, China Meteorological Administration, Shanghai Typhoon Institute, Hong Kong Observatory, Joint Typhoon Warning Center RSMC Honolulu, HI, USA (NOAA's Central Pacific Hurricane Center), RSMC La Reunion, RSMC Miami, FL, USA (NOAA's Tropical Prediction Center) (HURDAT), RSMC Nadi, Fiji, RSMC New Delhi, India, RSMC Tokyo, Japan, TCWC Wellington, New Zealand	This dataset holds all THORPEX Interactive Grand Global Ensemble (TIGGE) tropical cyclone track model analysis and forecast data. Ensemble generated tropical cyclone track data from the European Center for Medium-Range Weather Forecasts (ecmwf), United Kingdom Met Office (egrr), National Centers for Environmental Prediction (kwbc), Japan Meteorological Agency (rjtd), China Meteorological Administration (babj), Meteorological Service of Canada (cwao), MeteoFrance (lfpw), and Korea Meteorological Administration (rksl) are included and made available for online access. New data are added to the archive from selected contributors on an ongoing basis. However, datasets can be downloaded separately. In this case study, only the ECMWF data was used.
Data owners		
Data owners	NOAA's NCDC maintains the official archive of this product in one format	The Research Data Archive is managed by the Data Engineering and Curation Section of the Computational and Information Systems Laboratory at the National Center for Atmospheric Research in Boulder, Colorado.
Data usage policty	The IBTrACS data usage policy follows that of the World Data Center for Meteorology (WDC), which employs a policy of full and open access to the data. The primary intent of IBTrACS is to support scientific research efforts	age is restricted to non-commercial, educational and research purposes only.
Data Organisation		

How was data prepared for use during the thesis?	1. the .csv file was downloaded from https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access 2. using the lat-lon coordinates of Santa Rita's centroid, and the lat-lon positions of each record in the database, all events that occurred within a 1000 km radius were identified. Events prior to 1986, and unnamed storms were deleted as these were incomplete records. All recorded points of these events were saved as 'full_tracks_1000km.csv'. This was done manually 3. the file was prepared for modelling in .R, for this data needed to be structured. data kept were: stormname, timestamp (YYYYMMDDHH), lat, lon, vmax. This file was saved as 'R_full_tracks_1000km.csv'.	1. the provided file by 510 Global was renamed to 'all_forecasted_events.csv'. 2. a VBA code was generated to organise and prepare data for modelling in .R. This VBA file was saved 'split_data'. Data kept were: storm name, timestamp (YYYMMDDHH), lat, lon, vmax. Storm name was composed of the actual name of the storm, the year it occured, the forecasting timestamp. 3. A separate .csv file was created for all events. these were saved:'[stormname]_forecast'.
Other relevant sources used to process the data that would be relevant in case this study was reproduced	.R scripts from https://github.com/rodekruis/Typhoon-Impact-based-forecasting-model were downloaded 12th of October 2020. These scripts were used for wind footprint modelling using Willoughby et al. (2020). However, they were tailored to the needs of this study. Edits made were: extraction of windspeed at Santa Rita's centroid location. Windspeed conversion factor. And several edits to enhance data processing. These edited .R scripts can be requested	.R scripts from https://github.com/rodekruis/Typhoon-Impact-based-forecasting-model were downloaded 12th of October 2020. These scripts were used for wind footprint modelling using Willoughby et al. (2020). However, they were tailored to the needs of this study. Edits made were: extraction of windspeed at Santa Rita's centroid location. Windspeed conversion factor. And several edits to enhance data processing. These edited .R scripts can be requested
What can you tell about the quality of the data?	Observations since 1980 are considered the modern era of observations since geo-observation improved since then. The integration of multiple sources in this dataset allows for a quality check.	THORPEX: A Global Atmospheric Research program was established in May 2003 by the Fourteenth World Meteorological Congress under the auspices of the WMO Commission for Atmospheric Sciences (CAS) and is a long-term research program organized under the World Meteorological Organization's World Weather Research Program.
Metadata		
What metadata comes with the data?	Metadata related to the source of information and accurate column descriptions. Technical details: https://www.ncdc.noaa.gov/ibtracs/pdf/IBTrACS_version4_Technical_Details.pdf metadata: https://www.ncdc.noaa.gov/ibtracs/pdf/IBTrACS_v04_column_documentation.pdf .	https://rda.ucar.edu/datasets/ds330.3/#metadata/detailed.html?_do=y

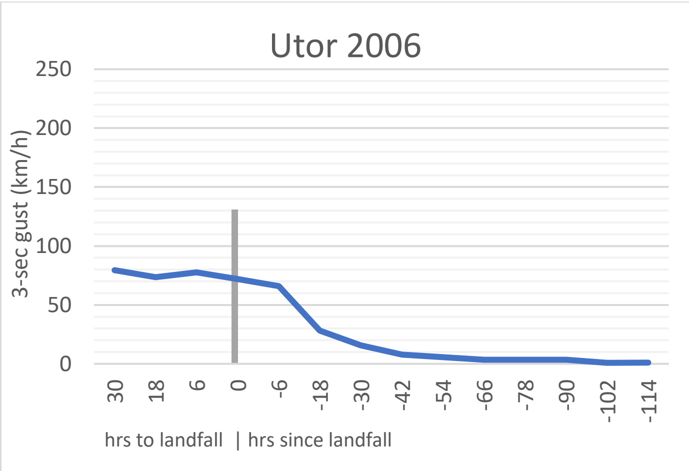
C. Visual flowchart of methodology to derive forecasted wind speeds

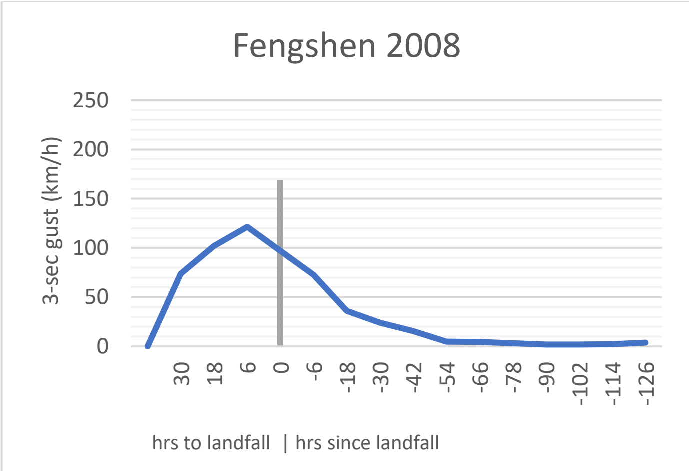
A visual representation of the methodology to translate forecasts into forecasted wind speeds for Santa Rita at different lead times (section 4.2.2).

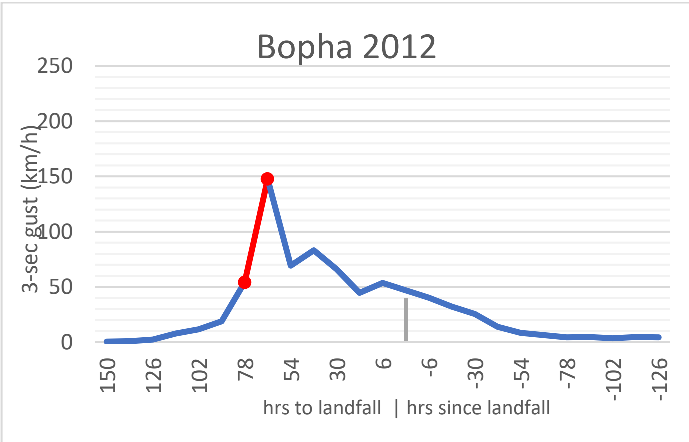


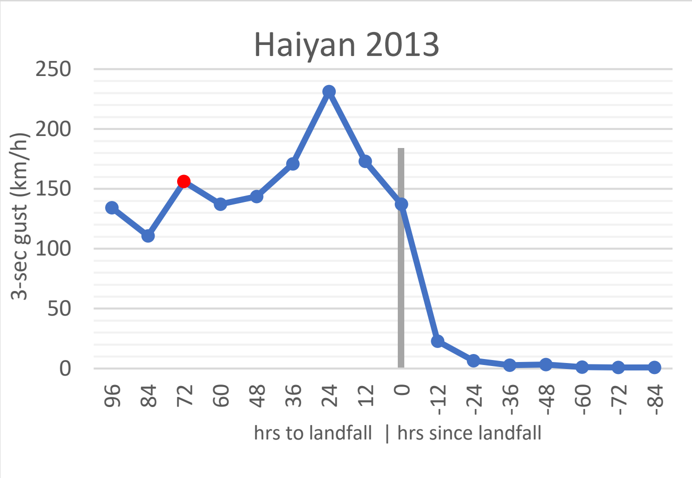
D. Forecasted windspeeds for Santa Rita during events' lifetime

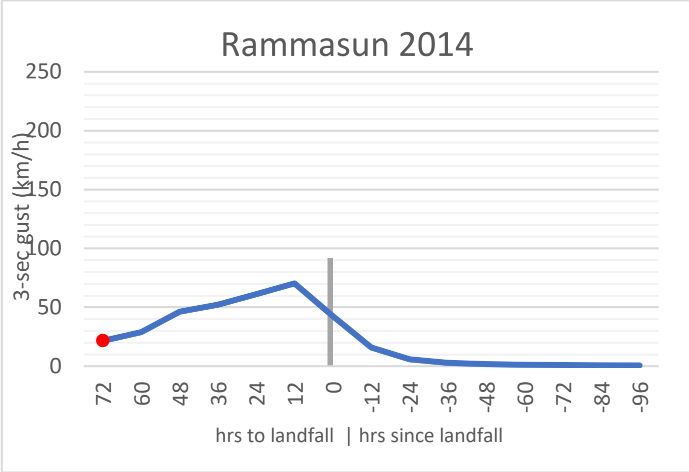
The output from the method used to derive forecasted windspeeds for Santa Rita using ECMWF-EPS deterministic forecasts. ECMWF issues a forecast every 12 hours. The Willoughby et al. (2006) method was applied to each of these forecasts to model the expected wind speed at Santa Rita's centroid location. Using NOAA's historical hurricane track database, these forecasts were assigned lead-times (example in Annex C). In the charts below the blue line is a trendline through modeled forecasts for Santa Rita. The red dot represents the forecasted windspeed for Santa Rita at a 72-hour lead-time. In case of a red line, the forecast representing the 72-hour forecast was difficult to define. Therefore, these are cases in which the average of the identified 78 hour and 66-hour forecast was used to derive the 72 hour forecast. The grey bar at lead-time 0 represents the observed windspeed modelled using JTWC data. Reflection on why modelled observed windspeed and forecasted windspeed at landfall do not align is provided in section 5.1.

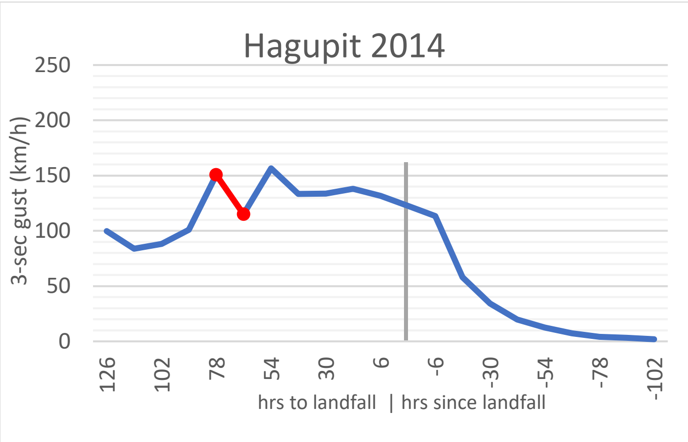


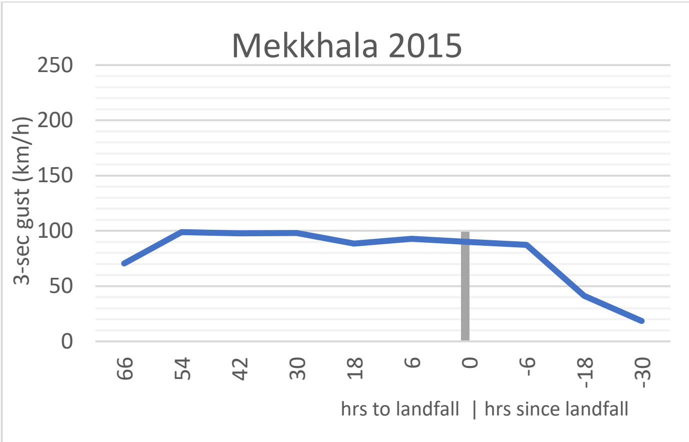


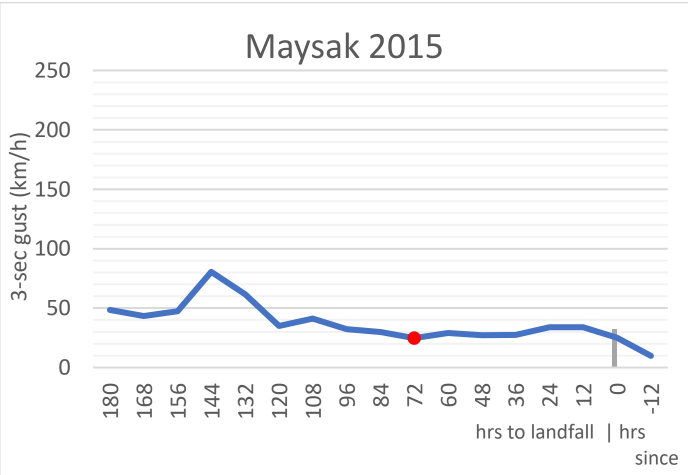


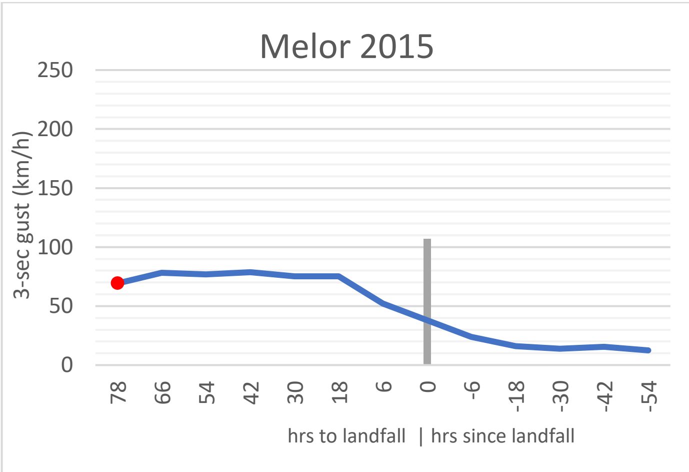

Haiyan 2013
3-sec gust (km/h)
250
200
150
100
50
0
96 84 72 60 48 36 24 12 0 -12 -24 -36 -48 -60 -72 -84
hrs to landfall | hrs since landfall

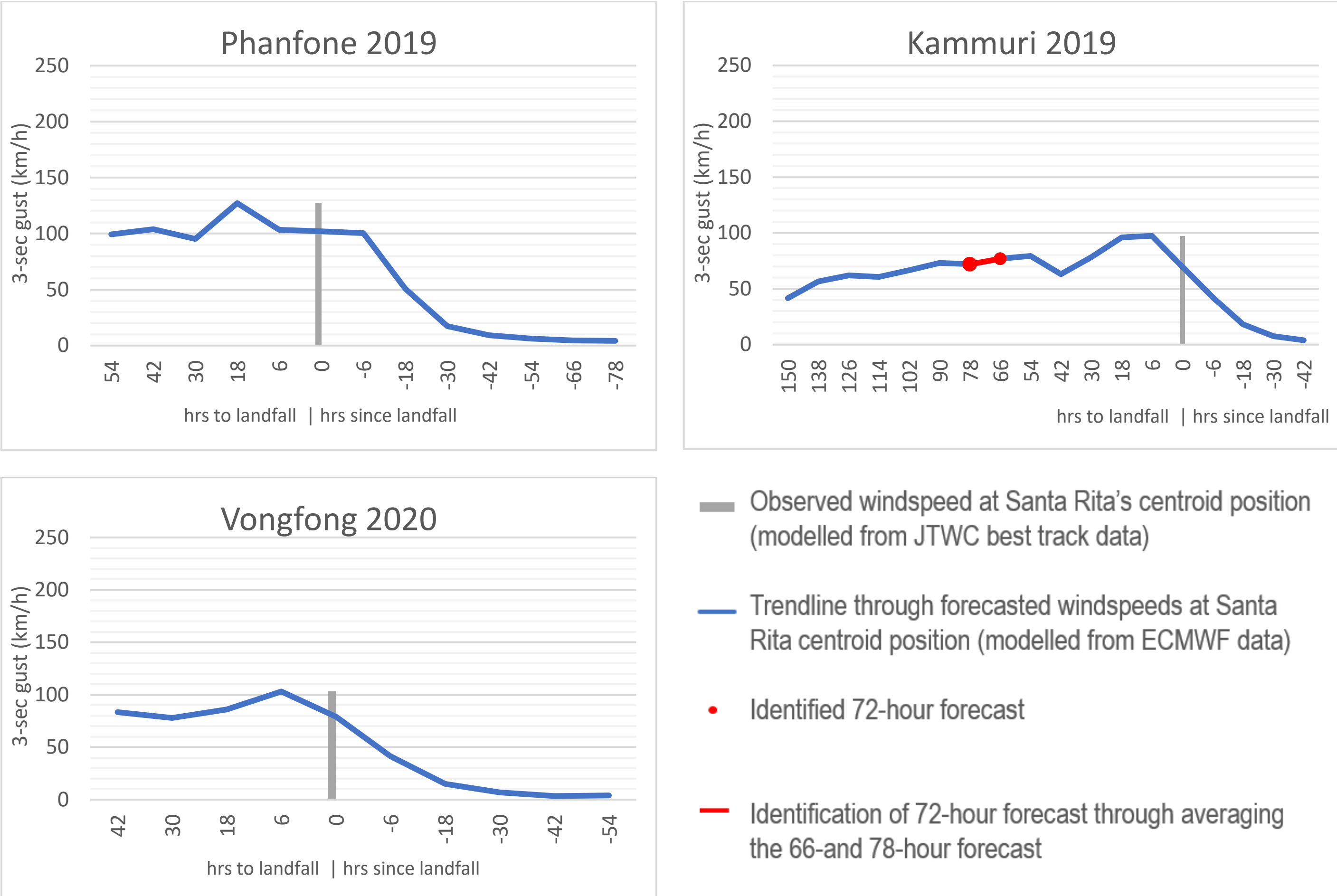

Rammasun 2014
3-sec gust (km/h)
250
200
150
100
50
0
72 60 48 36 24 12 0 -12 -24 -36 -48 -60 -72 -84 -96
hrs to landfall | hrs since landfall


Hagupit 2014
3-sec gust (km/h)
250
200
150
100
50
0
126 102 78 54 30 6 -6 -30 -54 -78 -102
hrs to landfall | hrs since landfall


Mekkhala 2015
3-sec gust (km/h)
250
200
150
100
50
0
66 54 42 30 18 6 0 -6 -18 -30
hrs to landfall | hrs since landfall


Maysak 2015
3-sec gust (km/h)
250
200
150
100
50
0
180 168 156 144 132 120 108 96 84 72 60 48 36 24 12 0 -12
hrs to landfall | hrs
since


Melor 2015
3-sec gust (km/h)
250
200
150
100
50
0
78 66 54 42 30 18 6 0 -6 -18 -30 -42 -54
hrs to landfall | hrs since landfall


Phanfone 2019
250
200
150
100
50
0
3-sec gust (km/h)
54
42
30
18
6
0
-6
-18
-30
-42
-54
-66
-78
hrs to landfall | hrs since landfall
Kammuri 2019
150
138
126
114
102
90
78
66
54
42
30
18
6
0
-6
-18
-30
-42
Vongfong 2020
Observed windspeed at Santa Rita's centroid position (modelled from JTWC best track data)
Trendline through forecasted windspeeds at Santa Rita centroid position (modelled from ECMWF data)
Identified 72-hour forecast
Identification of 72-hour forecast through averaging the 66-and 78-hour forecast

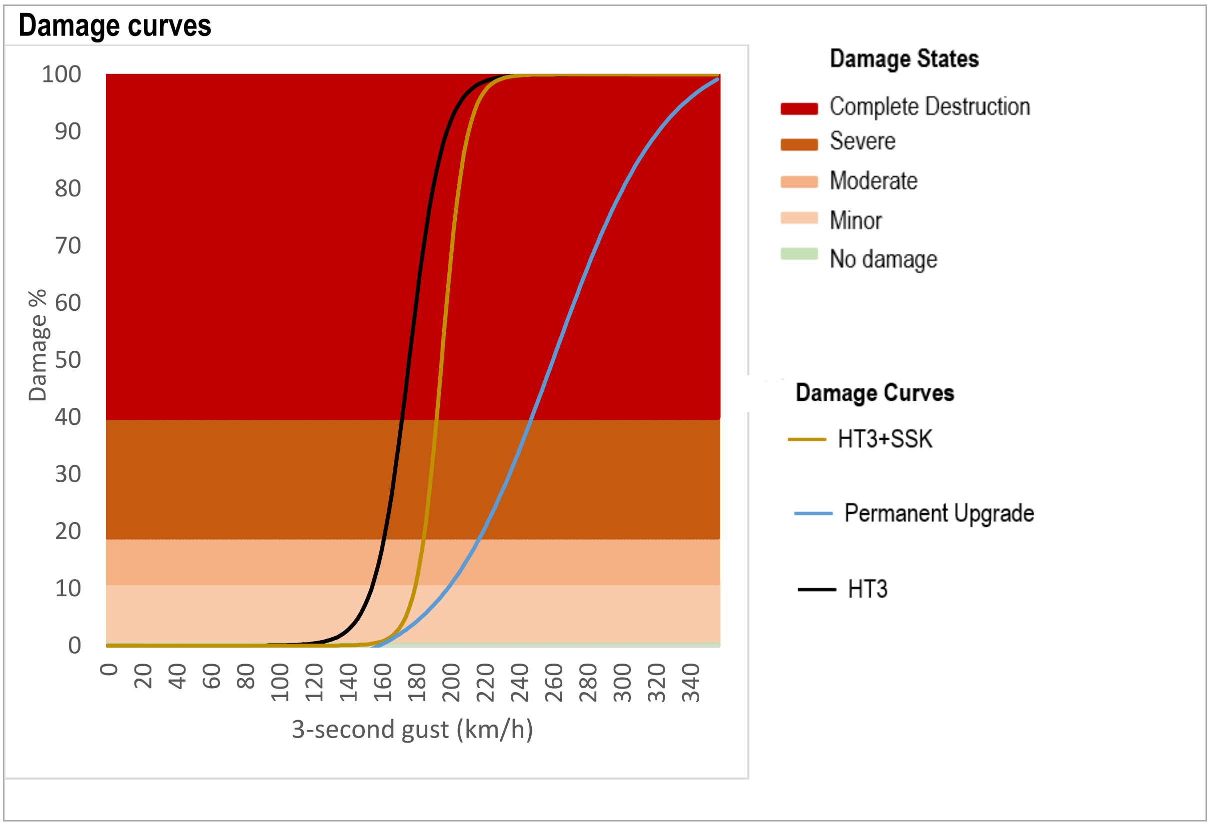
E. Baseline scenario

The values used as part of the baseline scenario: 1. Wind hazard metrics, 2. Physical vulnerability, 3. Event-based losses, 4. Trigger threshold

1. Wind hazard metrics:

Event	Observed windspeed (3 sec. gust, km/h)	Forecasted wind speed at 72 hours (3 sec. gust, km/h)
Utor	131	No 72-hour forecast
Fengshen	169	No 72-hour forecast
Son-Tihn	70	No 72-hour forecast
Bopha	40	101
Haiyan	184	156
Rammasun	92	22
Hagupit	162	133
Mekkhala	93	No 72-hour forecast
Maysak	32	25
Melor	107	74
Phanfone	133	No 72-hour forecast
Kammuri	85	74
Vongfong	121	No 72-hour forecast

2. Physical vulnerability



3. Event-based losses

Damage State	Measure taken	**Total event-based losses (€)**
No damage	Doing nothing	**0**
	Forecast-based Action	**117**
	Permanent upgrade	**0**
Minor damage	Doing nothing	**340**
	Forecast-based Action	**457**
	Permanent upgrade	**638**
Moderate damage	Doing nothing	**510**
	Forecast-based Action	**627**
	Permanent upgrade	**956**
Severe damage	Doing nothing	**680**
	Forecast-based Action	**2191**
	Permanent upgrade	**2487**
Complete destruction	Doing nothing	**1700**
	Forecast-based Action	**3192**
	Permanent upgrade	**4463**

4. Trigger threshold: 130 km/h

F. Global sensitivity analysis results

The number of years after which the permanent upgrade starts outweighing Shelter Strengthening Kit distribution as part of Forecast-based Action (FbA). Both A and B explore all different combinations of over-and underestimating event-based losses and vulnerability. However, A makes use of the wind-hazard metrics as per the baseline scenario, while B makes use of the wind-hazard metrics explored as part of the local sensitivity analysis (section 5.6.2), namely adding 14% intensity to both observed and forecasted windspeeds. A cell shaded in red implies the balance was modelled to occur after 25 years (which is the lifetime of a PU). N.a. implies that the balance would not be found.

A. Global sensitivity analysis: wind-hazard metrics baseline scenario

Assumptions:

Wind-hazard metrics (hazard): as in baseline scenario (main)

Vulnerability: all combinations of over-and underestimation, and baseline scenario (main)

Event-based losses: all combinations of over-and underestimation, and baseline scenario (main)

B. Global sensitivity analysis: wind-hazard metrics plus 14% intensity

Assumptions:

Wind-hazard metrics (hazard): as plus 14% intensity to observed and forecasted windspeeds

Vulnerability: all combinations of over-and underestimation, and baseline scenario (main)

Event-based losses: all combinations of over-and underestimation, and baseline scenario (main)

				PERMANENT UPGRADE								
	HAZARD			main	main	main	main	main	main	main	main	main
		Event-based losses		main	main	main	overestimated	underestimated	overestimated	underestimated	overestimated	underestimated
			Vulnerability	main	overestimated	underestimated	main	main	overestimated	overestimated	underestimated	underestimated
	main	main	main	19	26	15	12	27	15	44	11	20
	main	main	overestimated	7	8	6	5	9	5	10	5	8
	main	main	underestimated	n.a	n.a	100	262	n.a	n.a	n.a	55	194
	main	overestimated	main	30	54	21	19	49	26	159	15	29
	main	underestimated	main	14	17	11	9	19	11	26	8	15
	main	overestimated	overestimated	10	11	9	7	13	8	16	6	11
	main	underestimated	overestimated	5	6	5	4	7	4	8	4	6
	main	overestimated	underestimated	n.a	n.a	254	n.a	n.a	n.a	n.a	100	3467
FbA	main	underestimated	underestimated	558	n.a	62	84	n.a	n.a	n.a	38	100

				PERMANENT UPGRADE								
	HAZARD			plus 14%	plus 14%	plus 14%	plus 14%	plus 14%	plus 14%	plus 14%	plus 14%	plus 14%
		Event-based losses		main	main	main	overestimated	underestimated	overestimated	underestimated	overestimated	underestimated
			Vulnerability	main	overestimated	underestimated	main	main	overestimated	overestimated	underestimated	underestimated
	plus 14%	main	main	6	9	6	4	9	5	13	4	0
	plus 14%	main	overestimated	5	6	5	4	7	4	9	3	0
	plus 14%	main	underestimated	9	13	8	6	12	8	24	6	0
	plus 14%	overestimated	main	9	15	9	6	13	9	30	6	0
	plus 14%	underestimated	main	5	6	5	3	6	4	9	3	0
	plus 14%	overestimated	overestimated	7	10	7	5	10	6	17	5	0
	plus 14%	underestimated	overestimated	4	5	4	3	5	3	6	3	0
	plus 14%	overestimated	underestimated	13	30	12	9	20	13	124	8	0
FbA	plus 14%	underestimated	underestimated	6	9	6	4	9	5	13	4	0