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Prioritization Framework for Robust Climate Change Adaptation Investments: Supporting Transport Infrastructure Decision-Making Under Uncertainty

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Prioritization Framework for Robust Climate Change Adaptation Investments: Supporting Transport Infrastructure Decision-Making under Uncertainty

by

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Prioritization Framework for Robust Climate Change Adaptation Investments: Supporting Transport Infrastructure Decision-Making under Uncertainty

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Espinet, Xavier (Ph.D., Civil, Environmental and Architectural Engineering)

Prioritization Framework for Robust Climate Change Adaptation Investments: Supporting Transport Infrastructure Decision-Making under Uncertainty

Thesis directed by Professor Paul S. Chinowsky

Considering climate change is an imperative for planning, creating and sustaining resilient civil infrastructure systems. However, there exist significant barriers to the understanding and implementation of climate change considerations, including the inherent uncertainty in climate change model projections. This severe uncertainty makes planning, designing and maintaining infrastructure a highly complex task. This is due to the challenge of determining the most likely changes relative to historic design standards. At the same time, traditional cost-benefit analysis to determine alternatives for climate adaptation engineering projects and designs may no longer be valid. The high level of uncertainty associated with climate projection and climate impact assessment requires a new methodology to prioritize alternatives and support decision-making of proactive climate change adaptation investments.

This dissertation seeks to address these challenges in three ways: first, it is demonstrated that is possible to determine specific, quantifiable vulnerability impacts, adaptation options and cost-benefit solutions for civil infrastructure based upon specific climate scenarios. Secondly, it presents the metric of "regret" as a viable option to be incorporated into traditional cost-benefit analysis in order to deal with the severe uncertainty of climate models. Finally, this dissertation introduces a novel method for calculating a "robust" decision rooted in existing decision theory and uncertainty. It presents a framework used for robust decision making that provides guidance about the most low-regret adaptation options for resilient road infrastructure design. The methodology presented in this dissertation is ready to use for practitioner, engineers and planners who are considering proactive climate adaptation projects and investments. Two case studies are elaborated to illustrate and demonstrate the capabilities of the proposed framework. These case studies use investment on the road network in two distinct geographic locations - North East Mexico and Kenya – to demonstrate the applicability of this framework in different contexts.

The interdisciplinary nature of this dissertation relates it to numerous fields of engineering and science, including transport engineering, infrastructure systems, risk and uncertainty engineering, project management and finance, and environmental planning and economics. This dissertation provides a clear framework to support decision makers to prioritize robust proactive adaptation investments for their individual infrastructure assets under the complexity and uncertainty of climate change.

---- Translate into Spanish ----

Guía para la priorización de inversiones proactivas y robustas para la adaptación al cambio climático: Soporte a la toma de decisiones bajo incertidumbre en infraestructura del transporte

Considerar el cambio climático es indispensable durante el planeamiento, la construcción y el mantenimiento para asegurar sistemas de infraestructura civil resilientes. Existes pero barreras significativas para entender e implementar las consideraciones del cambio climático, incluyendo la incertidumbre inherente en las proyecciones de los modelos climáticos. Esta severa incertidumbre hace del planeamiento, diseño y mantenimiento de infraestructuras una tarea altamente compleja. Esto se debe al reto de determinar los cambios más probables respecto a los estándares de diseño históricos. Al mismo tiempo, los análisis tradicionales de coste y beneficios para priorizar alternativas en proyectos de ingeniería relacionado con la adaptación al clima pueden haber dejado de ser válidos. El alto grado de incertidumbre asociado con las proyecciones climáticas y las evaluaciones de impacto climático requiere de una nueva metodología para priorizar alternativas y dar soporte a la toma de decisiones de inversiones proactivas de adaptación al cambio climático.

Esta tesis pretende abordar estos retos de tres maneras distintas: primeramente se demuestra que es posible cuantificar vulnerabilidades e impactos, determinar estrategias de adaptación y desarrollar análisis de *coste y beneficios para infraestructuras basados en proyecciones climáticas. Seguidamente, se presenta el concepto de "arrepentimiento" como una opción viable pare ser incorporado en el tradicional coste-beneficio y tratar con la alta incertidumbre de los modelos climáticos. Finalmente, esta tesis introduce un método novedoso para calcular decisiones "robustas" basado en existente teoría de la decisión e incertidumbre. Se presenta una guía que da soporte a la toma de decisiones y permite obtener los diseños para adaptar carreteras al cambio climático que minimizan el arrepentimiento de la inversión. La metodología presentada en esta tesis esta lista para ser usada por ingenieros, planificadores y profesionales que están considerando proyectos e inversiones proactivas de adaptación al cambio climático. Dos casos de estudio han sido elaborados para ilustrar y demostrar las capacidades de la metodología propuesta. Estos casos de estudio usan inversiones en la red de carreteras de dos localizaciones distintas – Noreste de México y Kenia – demostrando la aplicabilidad de esta metodología en contextos diferentes.*

La interdisciplinaria naturaleza de esta tesis abraca numerosos campos de ingeniería y ciencia, incluyendo ingeniería del transporte, sistemas de infraestructura, ingeniería de riesgo e incertidumbre, financiación de proyectos y planificación y economía medioambiental. Esta tesis presenta una metodología para dar soporte a la toma de decisiones y priorizar inversiones proactivas y robustas de adaptación de sistemas de infraestructura bajo la complejidad e incertidumbre del cambio climático.

DEDICATION

If a man will begin with certainties, he shall end in doubts, but if he will be content to begin with doubts, he shall end in certainties

~ Francis Bacon

Més ens val la incertesa i el risc d'ara mateix,que l'enyor o l'angoixa

~ Miquel Martí i Pol

¿Qui sap si trist o somrient
acull son hoste?
¿Qui sap si mor sobtadament,
sota la brosta?
Qui sabrà mai aquest matí
a què em convida!
I és camí incert cada camí,
n'és cada vida!

~ Josep Carner

Sólo él sabía entonces que su aturdido corazón estaba condenado para siempre a la incertidumbre

~ Gabriel García Marquez

'Your act was unwise' I cried 'as you see by the outcome' He calmly eyed me: 'When choosing the course of my action' said he, 'I had not the outcome to guide me'

~ Ambrose Briece

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Chapter 1 INTRODUCTION

1.1 PROBLEM STATEMENT

Climate Change poses a unique threat to our society. Uncertainty and risk associated with climate change impacts economic, social, political, and environmental sectors in every region of the world (IPCC 2014a). These sectors cover a wide range of industries from agriculture to tourism (Hamilton et al. 2005; Nelson et al. 2014), biodiversity to coastal erosion (Thuiller 2007; Zhang et al. 2004), and private property to public infrastructure (Heltberg et al. 2009; Larsen et al. 2008). Although every region of the world will be affected by climate change in the future, the specific risks and uncertainties are geographically diverse, making it difficult to establish guidelines and frameworks that could be applied to each of these communities.

The magnitude of this global problem has not been accepted by all governments, but many countries are now introducing significant policies on mitigation strategies to reduce the causes of climate change, mostly related to emissions of CO2 (Betsill 2001). Introduction of adaptation (defined as any action designed to reduce the vulnerability to, and consequences of, climate change) is still in the formative stages, however for many of these policymakers (Clar et al. 2013; Dewulf 2015; Hallegatte 2009).

Most climate change research in the past has focused on mitigation strategies for dealing with climate change. Recently, more and more climate change research institutions are recognizing that adopting adaptation strategies is equally important (Füssel 2007; Pielke et al. 2007). However, research in the area of adaptation to climate change still lags behind studies of climate change mitigation. This thesis focuses on expanding the knowledge of the less studied topic of adaptation strategies. Of specific interest to this study is the Transport Infrastructure sector, which is key to fostering future social and economic growth of countries, regions and communities (EEA 2014).

It is imperative to adopt climate change adaptation action in infrastructure planning in order to reduce potential consequence future climate impacts. Climate change will exacerbate existing vulnerabilities on road infrastructure, causing increased degradation rates (Koetse and Rietveld 2009; Meyer and Weigel 2011; Neumann et al. 2014). This may have a direct impact on communities as transportation infrastructure is crucial for trade, commerce, and community functions including commuting to work and school (Erath et al. 2009; Ochia 1990). This is especially evident in economically developing communities, where road infrastructure quality and quantity is positively related to economic and social growth (Calderón and Servén 2004; Esfahani and Ramírez 2003). This critical role makes the question of transportation infrastructure vulnerability and degradation a top concern for public and private entities as well as planners at all levels (Jenelius et al. 2006).

However, a complex challenge while planning proactive infrastructure adaptation designs is the high level of uncertainty associated with climate change impacts (Dessai et al. 2007; Jones 2000). Climate scientists are unable to define with certainty what standards should be used while building infrastructure in order to secure their performance to future climate impacts (Lisø 2006). This uncertainty is a challenge for design engineers and decision-makers because it makes it difficult to understand the true magnitude of the problem. It creates additional complexity during the process of reaching agreement on the most appropriate adaptation strategy or policy, often leading to misinterpretations and misleading decisions (Corotis 2012; Fankhauser and Soare 2013; Pittock et al. 2001).

Within this complexity, there is an increasing agreement between researchers and practitioners that there is a need to move from traditional cost-benefit approaches to new costing methods while designing climate adaptation projects. At the same time, there is a recognized need to incorporate a full range of climate projections while calculating cost and benefits to properly reflect the uncertainty of the problem (Dessai et al. 2004; Fankhauser and Soare 2013; Hallegatte 2009; Watkiss et al. 2014).

In order to solve part of this complexity, conceptual, integrated approaches for adaptation to climate change in transportation sector has been successfully presented by different agencies and governments across the world, with broad consensus for a general adaptation framework (EEA 2014; UNFCCC 2011; US DOT 2012). However, there remains a lack of practical guidance for how a transportation practitioner should approach each of the steps in these conceptual models. Particularly, climate change poses a challenge to prioritizing adaptation strategies, because traditional cost-benefit analysis optimization fails to appropriately address the deep uncertainty of future scenario (Dessai and Hulme 2007; Lempert and Collins 2007).

This research is motivated by the problems stated above and aims to investigate how uncertainty can be better dealt in decision-making, specifically for the prioritization process of adaptation investment strategies to climate change impacts on transportation infrastructure.

1.2 RESEARCH QUESTIONS

This thesis seeks to answer the following questions in order to expand the knowledge base on adaptation strategies and uncertainties, and to offer a potential framework helping policymakers to deal more effectively with climate change decision-making:

- How can uncertainty on climate change impact assessments be incorporated into transport planning? Can a framework for incorporating uncertainty be developed to assist in addressing this area of concern?
- Would considering uncertainty allow transport governance agencies to make more holistic and efficient decisions?

1.3 CONTRIBUTION

The interdisciplinary nature of this dissertation relates it to numerous fields of engineering and science, including transport engineering, infrastructure systems, risk and uncertainty engineering, transport planning, environmental planning, regional planning, environmental modeling and transport policy. The academic contribution of this thesis to the above fields will come from achievement of the following goal:

- Increase the awareness of the impact of climate change on civil infrastructure and the need for adaptation designs and investments among transportation planners and engineers
- Provide a clear framework to incorporate the uncertainty of future climate change impacts during proactive infrastructure adaptation planning and design
- Help transportation decision-makers choose robust adaptation investments for their individual infrastructure assets

1.4 GUIDE FOR READERS

This dissertation is divided into eight chapters. This first chapter has served to state the problem, the research questions and the overall contribution of the thesis. 0 includes a review of current literature and existing work, separated into three sections. Section One*, Holistic Infrastructure Planning for Climate Change*, identifies the threats of climate change to the infrastructure sector and the need for holistic, long-term planning to address the challenges of a future changing climate. Section Two, *Transport Infrastructure Adaptation*, a broad literature review discussing the specifics of climate change adaptation, beginning with a general perspective and concluding with specific examples that address adaptation in transportation sector. The third section, *Decision-Making under Uncertainty of Climate Change*, addresses the issue of uncertainty and risk in the context of climate change scenarios. The final section, *Integrated Approaches, Existing Frameworks and Support Tools*, reviews existing government and academic integrated approaches for dealing with climate change adaptation and uncertainty. The *Point of Departure* for developing the methodology of this thesis follows the literature review.

Chapter 3 introduces the proposed methodology and details each step of the framework. It describes the equations and formulas utilize in this dissertation. This chapter comprises all the equations and formulas used in Chapter 4 -Chapter 6. Most of them are reintroduced and placed again accordingly with the data and results that are being presented in each of the following chapters. Chapter 4 -Chapter 6 are written as standalone pieces, and have become separate journal publications. Chapter 4 and Chapter 5 are under review by two distinct transportation journal while Chapter 6 has been recently accepted for publication. There may be then some content repetition between those chapters and the remaining of the dissertation.

Chapter 4 presents the impacts and cost of climate change on the road infrastructure of Mexico. The Infrastructure Planning Support System (IPSS), a tool developed by Dr. Chinowsky's research group, is used to quantify impacts of climate change for this study. The results reinforce the need to incorporate forward-looking planning to reduce vulnerability by increase road infrastructure resilience to the future weather changes and provide quantified information for decision makers to consider. – *Submitted at Transport Policy on 09/03/2015 – Under Review*

Chapter 5 presents the metric of "regret" as a viable option to be incorporated into cost-benefit analysis in order to deal with the severe uncertainty of climate models. It uses a real future investment to upgrade a major road corridor in Kenya and South Sudan that is part of the Programme for Infrastructure Development in Africa (PIDA) to illustrate the methodology. It concludes that unplanned expenditure could be minimized if the traditional cost-benefit analysis is expanded to include a regret analysis as proposed in this chapter. – *Submitted at Transport Research Record on 07/31/2015 – Under Review*

Chapter 6 introduces a novel method for calculating a "robust" decision rooted in existing decision theory and uncertainty. It presents the framework used for robust decision making and provides guidance about the most low-regret cost-benefit adaptation options for resilient road infrastructure design. A case study of a province in Mexico illustrates the application of this robust framework to actual road transportation planning. – *Submitted at ASCE-ASME Journal for Risk and Uncertainty in Engineering Systems on 04/01/2015 – Accepted for publication on 10/09/2015*

The contribution of the frameworks and the results presented in the dissertation are discussed in Chapter 7. This chapter includes an extensive discussion on decisions under constrained budget, including some possible alternative to the proposed framework and suggesting visualization options to support decision-makers. It includes as well a discussion of the limitations of this research, future lines of work and next steps and a section - *Final Thoughts* - where different points of this research are evaluated and discuss as the benefits of the proposed framework to current decision-making. Finally Chapter 8 summarizes the main findings of this research as serves as a conclusion chapter for this thesis.

Chapter 2 LITERATURE REVIEW – FOUNDATION

2.1 HOLISTIC INFRASTRUCTURE PLANNING FOR CLIMATE CHANGE

Climate change has been at the forefront of global discussions since the founding of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1988. While the early work of the IPCC focused on creating and understanding the science of global climate change and mitigation, a prominent shift has been made recently to include vulnerability assessments, adaptation options, and the financing of climate-resilient projects (IPCC 2014a). The IPCC's Fifth Assessment Report (AR5), concludes that "warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased" (IPCC 2007). Increased CO_2 emissions, among other causes of climate change, have triggered noticeable consequences such as hotter summers and changing extreme weather patterns.

Transportation systems, including road infrastructure, are vulnerable to adverse and extreme weather conditions (EEA 2014; Nemry and Demirel 2012; NRC 2008). This vulnerability is reflected in maintenance planning and cost-benefit analysis to determine acceptable levels of cost and risk in designing and maintaining infrastructure (Neumann et al. 2011; UNFCCC 2011). As increased risks associated with a changing future climate become more apparent, subsequently there is a rising awareness of the need to address potential impacts at the policy level today (Berkhout et al. 2006; Bruin et al. 2009; Burton et al. 2002).

Climate change poses high levels of uncertainty for decision makers, particularly in terms of medium and longer-term transportation planning, because transportation infrastructure is one of the most susceptible sectors in the civil infrastructure realm (Bollinger et al. 2014; Meyer et al. 2010). This is important because transportation systems are the foundation upon which economic growth, commerce, and social activities rely and therefore holds implications for other areas, including urban planning, health, and disaster preparedness (Erath et al. 2009; Schweikert et al. 2014a). Additionally, a large climate-related extreme event may cause a set of adverse reactions along an entire transportation system, posing particularly severe impacts in densely populated areas (Koetse and Rietveld 2009).

Predictions for significant levels of climate changes pose challenges to engineering design, maintenance scheduling, and disaster preparedness plans, mainly because current standards, design practices and building codes are based on historical weather patterns that will be obsolete with the future changing climate (Lisø 2006). New transportation projects and old infrastructure must consider climate change, as it will lead to an increase in maintenance budgets (Schweikert et al. 2014b), to investments diverted for climate change repair, and to disruption of system functionality, all contributing to negative impacts on transit. (Bruin et al. 2009; Hambly et al. 2013; Keener 2013; McBeath 2003).

There is an increased recognition of the potential severity of climate change impacts on transportation infrastructure and small steps are being taken to address these issues. The World Bank is a leading advocate of proactive planning, particularly in Latin America (McAndrews et al. 2012). A number of recent literature have addressed the issue in location-specific case studies (Savonis et al. n.d.; Suarez et al. 2005) and in broader frameworks (Meyer and Weigel 2011), as well as in quantitative modeling (Schweikert et al. 2014c). Two outcomes from this work that drive the incorporation of climate change into projects today is first the recognition that reducing risks to future climate impacts may have immediate benefits to already known weather hazards and second the assertion that projects implemented today may need to adapt to climate change within their design lifetimes (NRC 2008).

There are several world-wide well-established and comprehensive reports that discuss climate change, vulnerabilities, and adaptation and governance strategies. The most significant such reports are summarized below.

The IPCC Fifth Assessment Report, is a scientific research-based, and internationally agreed-upon report published by the United Nations Intergovernmental Panel for Climate Change in 2014. The IPCC has been promoting awareness on climate change science, impacts and vulnerabilities since its founding in 1988. The latest report is an extended document divided into three working groups: physical science, adaptation and mitigation. The report states that there is "high agreement" (although "limited evidence") that climate change will negatively affect transport infrastructure. These negative impacts from climate change include freeze-thaw cycles, temperature extremes, and precipitation (Arent et al. 2014). Additionally, the report includes discussion of road infrastructure in guidance sections related to vulnerability reduction, disaster risk management, and urban resilience (Revi et al. 2014). It contains as well a special chapter based on location that addresses particular potential regional impact and vulnerabilities, to identify where the adaptation investment should be directed first (IPCC 2014b).

In the European Union (EU), the European Council, the highest level of governance in the EU, passed in October of 2014, the "2030 Climate and energy policy framework" that addresses energy and climate policies for the next decade (European Council 2014). In 2010, the Directore-General of Climate Action was established by the European Commission, with the task of addressing sector-specific action plans to deal mainly with mitigation climate change and reduction of GHG emission. At the same time, the European Environmental Agency published at the end of 2014 a report that presents a wide range of successful adaptation strategies across the EU from the transportation sector. The report summarizes the main concept from each successful strategy needed to develop a resilient transportation system (EEA 2014).

In the United States, President Obama announced the creation of the Climate Change Action Plan in 2013 that states the work that the federal government is taking to prepare the US for the future impacts of climate change. The National Climate Assessment addresses planning for the transportation sector in particular (Melillo et al. 2014). The Federal Highway Administration (FHWA), signed an order in December of 2014 stating that *"It is FHWA policy to integrate consideration of climate and extreme weather risks into its planning, operations, policies and programs."* The FHWA has published several reports including the

"Climate Change and extreme weather vulnerability assessment framework" and the "Building Climate Resilient Transportation" to address climate change vulnerabilities in transportation in the US and to help state and local agency understand climate change impacts and appropriate responses. Additionally, the FHWA has been conducting a series of Climate Resilience pilots programs since 2011, to support Department of Transportation (DOT) and Metropolitan Planning Organizations (MPO) agencies around the country increase resilience and build transportation capacity in the face of a changing climate.

A private organization, the Rockefeller Foundation, has also invested a significant effort in the past year in building resilience in urban areas around the world to prepare them for the impacts of climate change. The Rockefeller Foundation seeks to address all major issues through which potential climate change may disrupt cities around the world. In particular, reports by the Foundation point out the importance of protecting transportation infrastructure as key for recovery and prosperity.

While uncertainty is a part of routine decision-making, the potential changes in climate pose challenges on an order of magnitude that lack any historical precedent and are unaccounted for in existing policies (Baynham and Stevens 2013; Picketts et al. 2013). Other fields, including water management (Guo 2006; Mailhot and Duchesne 2010; Murphy et al. 2011) recognize the potentially large risk created by climate change; practitioners in these areas are actively engaging in measures to incorporate climate risk into current policies. Learning from these policies, it is clear that there is a need for new approaches to planning, managing and designing road infrastructure to account for climate change uncertainty.

Building upon lessons learned in the water management approach to incorporating climate change uncertainty, and the needs expressed by transportation fields, it is clear that there is a desire from decision-makers to address climate change to reduce risk, life-cycle cost (including unplanned maintenance and repair), and the degradation rates of roads, which are increasing beyond historical precedent (Füssel and Klein 2006). Incorporating potential future climate conditions into current decision-making will support a more holistic, forward-looking approach and ultimately more climate-resilient road infrastructure designs (EEA 2014; Meyer et al. 2010; Meyer and Weigel 2011).

Several existing studies demonstrate how proactive investment in transportation infrastructure is equivalent to or lower than life-cycle cost estimates, while also improving the performance of the infrastructure to climate stress throughout its lifetime (Chinowsky et al. 2014b; Schweikert et al. 2014b). These cost savings are usually due to retrofit or repair needs for infrastructure that are unable to withstand future damages because they were built to historical climate standards. While uncertainty in climate modelling limits the ability of planners to invest with perfect foresight, the recognition of changing future weather variability and incorporation of flexible design and adaptation options today should be a consideration for transportation decision makers (NRC 2008).

2.2 TRANSPORT INFRASTRUCTURE ADAPTATION

Adaptation strategies, are defined for this dissertation, as the wide ranges of action taken in order to moderate the adverse effects of climate change targeting the specific vulnerabilities of a system (Füssel 2007; Füssel and Klein 2006). Adaptation of transportation infrastructure is imperative to minimize impacts and damages of climate change and to build a robust and resilient system against the uncertain future environment (NRC 2008; UNECE 2013).

To properly understand the issue of climate change adaptation investment and policies, four main question need to be answered: where, when, who and how (Fankhauser et al. 1999; Fankhauser and Soare 2013). These questions refer to where is there a need to adapt, when such adaptation measures should be taken, who is responsible for carrying out the adaptation and how institutions should adapt.

Scientists, researchers and practitioners widely agree that the first question to answer before implementing any adaptation investment or policies is the “where” or the location of potential impacts. The first step even before thinking about adaption, is studying local vulnerabilities and identifying regions, communities or neighborhoods where climate change poses a significant threat relative to other locations (Füssel 2007; Meyer et al. 2010). Identifying vulnerable locations will help decision-makers to decide in what areas to undertake adaptation measures (Burton et al. 2002; Klein et al. 1999). There are already a variety of tools and studies that help engineers and decision-makers to identify civil systems vulnerabilities (Kollat et al. 2012). In the absence of industry tools, academics and researchers can help policymakers recognize local risks and locate potential damages of future climate.

Once the question of where adaptation should occur has been addressed, the next problem is finding the when, or the most appropriate time to adapt. There is disagreement with respect to this question among researchers and academics, although there is general consensus that adaptation measure should be put in place quickly to avoid maximum potential damages (Fankhauser et al. 1999; Füssel 2007). However, there is a continued discussion of waiting to adapt, which is based on two principals, finding the time when benefits are maximized and finding the time when uncertainties are minimized, so that more accurate decisions can be made (Tsvetanov and Shah 2013; Yohe and Neumann 1997).

The third question, of who should adapt, tries to identify the main stakeholders needed to implement efficient adaptation strategies. Most scholars agree that government agencies must guide the process of adaptation by creating policies and laws that encourage autonomous initiatives about adaptation (Fankhauser, Smith, and Tol 1999). Public-Private-Partnerships and insurance companies could also be important allies to promote climate adaptation measure, as they have large incentives to support adaptation measures that reduce future risk in their properties (Shardul and Samuel 2008). The success of climate change adaptation projects and policies to climate change will come, however, with involvement at all levels of decision-making, from federal government to individual, including through regional and local authorities (Bruin et al. 2009; Lisø 2006).

The last question, the how, falls on the hand of the practitioners, design engineers and decision makers. Once the location and the time have been identified, potential adaptation project designs can be prioritized according to engineering standards and rules of economic efficiency, this represents a complex problem of multi-objective optimization (Füssel 2007; Kasprzyk et al. 2013). There are a large number of examples of civil infrastructure engineering adaptation projects, especially in the field of water resource management and flood protection, that discuss the optimal design to protect communities and infrastructure from climate change (Hall et al. 2006; Zhou et al. 2012; Špačková and Straub 2015).

One of the most used methods for prioritization is the concept of Pareto optimality. It has gained popularity to deal with the complex multi objective that engineers deals while designing for climate change adaptation. A Pareto optimal solution is defined as a solution that can not improve in one objective without degrading at least another one (Pareto 1906). In engineering Pareto optimal solution has been widely use with a similar definition that the traditional socio-economics one (Reed et al. 2013). This concept has resulted helpful to prioritize engineering design strategies (Rafiq 2000) and specially has become popular to optimize adapt strategies to climate change (Cui et al. 2013) including civil engineering project (Špačková and Straub 2015; Woodward et al. 2014). At the same this same concept has been traditionally use in transportation engineering and planning problems, in order to optimize and prioritize investment, as pavement improvements or highway rehabilitation projects (Bai et al. 2012; Fwa et al. 2000; Wu et al. 2012).

There are few examples, however, of how to design adaptation projects for transport infrastructure, limited to only a few studies on pavement management and coastal transportation routes (Cechet 2005; Mills et al. 2009; Suarez et al. 2005). These studies of adaptation are mostly limited to academic research, suggesting that a knowledge gap still remains between academia and practitioners; there are few real-world examples of climate change adaptation engineering projects (Kirshen et al. 2002; Meyer and Weigel 2011).

Much of the discussion of "how" relies on the economics of climate change adaptations, meaning the economic indicators for the feasibility and efficiency of adaptation strategies to climate change. The goal of the following section is to identify all potential indicators and then select the course of economic analysis that is most well-established and supported by the expert and academics. The literature review of economic analysis focuses on civil infrastructure (including, but not limited to transportation) system adaptation strategies for mitigating the impact of future climate and weather hazards.

2.2.1 ECONOMICS OF ADAPTATION

Academic study of the economics of climate change began in the early 1990s with interest to compute the total cost of climate change on a global scale, for justification of mitigation measures and strategies. Since then, there has been an extensive debate of how to calculate this global impact, such as finding results as a percent of national GDP or as a percent of the total amount of lost global GDP (Lempert 1999; Tol 2012, 2003). This debate is not directly related to the aim of this thesis, as it focuses on the economics of mitigation rather than the economics of adaptation. However, reviews of this literature have been useful to identify major issues on general economics of climate change, including the discounting debate (Weitzman 1998), the treatment of extreme weather events versus progressive climate change, and deep uncertainty in economic analysis (Azar and Lindgren 2003; Rabl and Zwaan 2009). These issues are going to be discuss at the end of this section.

According to (Stewart et al. 2014), experts generally agree to calculate benefits from the adaptations investment strategies based on the reduction of expected damage and they use net present values (Benefit minus Cost) to prioritize options. Examples of this approach can be seen in flood-related adaptation measures (Hall et al. 2006; Aerts and Botzen 2013; Rojas et al. 2013; Woodward et al. 2014; Špačková and Straub 2015), in cost-benefit analyses of water management infrastructure as sewer and dam sizing, and in dealing with uncertainty of climate change (Nassopoulos et al. 2012; Zhou et al. 2013).

Quantifying the monetary cost of climate change for the built environment has some case studies on adaptation analysis of buildings and, in particular, high wind impact projected by climate change (Stewart et al. 2014; Stewart and Deng n.d.). This economic analysis is based on a stochastic approach, using probability damage functions and associating repair cost to each of associated damage stage. In this approach, the benefits of adaptation are computed as a reduction of damage provided by the adaptation measure built. This method follows a scenario-based analysis, where each climate projection is considered equally likely to occur.

Apart from buildings, most of the example of economics of adaptation of climate change has focused either on sea level rise impact analysis (Kirshen et al. 2012; Neumann et al. 2011; Tsvetanov and Shah 2013), flooding protection costing exercises (Aerts and Botzen 2013; Su and Tung 2013) or water management projects as dams, or sewer systems (Nassopoulos et al. 2012). Academic literature on the economics of adaptation of transport infrastructure is still a small field. Some studies have focused on risk assessments of climate change for transportation infrastructure, but do not provide costs of impacts or adaptation (Wu et al. 2013).

Few of them had actually provide specific climate change costing impacts of transportation infrastructure. There has been some work focused on pavement performance, calculating increase of maintenance and repair cost due to change on temperature and precipitation patterns (Arndt et al. 2011; Mills et al. 2009). At the same time, another study focus on the increase on frequency of flooding event and the consequent repair of culvert and road drainage costing (Lennon and Dorney n.d.). There has been some economic study to address climate change vulnerability on bridges due to increased flooding and faster deterioration of bridges piles (Flint et al. 2014; Wright et al. 2012). Finally, a few other large scale costing exercises have studied range of transportation infrastructure, including paved road and dirt roads and bridges, with numerous assumptions and simplifications (Larsen et al. 2008; Neumann et al. 2014), or entire national high capacity road network (Cechet 2005).

Civil infrastructure is mostly managed by public agency, federal, state or local government, and review of government reports, white papers, and EU “green papers” provides real-world context for this research. There has been particular governmental interest of late for developing new approaches for climate change adaptation.

In Europe, several countries have produced individual reports to studying the importance of climate change adaptation benefits. The Netherland Environmental Assessment Agency published a brief policy report in March of 2014, identifying the benefits and costs of climate change. The definition of benefits and cost are similar to the majority of methodologies mentioned above (Hof et al. 2014).

The German Federal Government through the German Federal Enterprise for International Cooperation, GIZ, published a framework in 2007 to asses adaptation project prioritization, similar to the one later developed by the UNFCC. The GIZ framework identifies possible economic indicators and discusses the effectiveness of each of them. This framework did not touch on uncertainty, but did identify the Net Present Value, NPV, as the best measure to rank adaptation projects (GTZ 2007). In 2013, the GIZ published an updated version of their first report. Similar to the first one, the presented the multiple ways of prioritizing adaptation projects. In this report, they discussed the issue of uncertainty and added the use of Multi-Criteria Decision Analysis as an option for decision-making option if it is not possible to monetize costs and benefits. (GIZ 2013a). That same year, the German Government partnered with the Mexican Government to apply the methodology suggested in the report to climate change adaptation projects in Mexico (GIZ 2013b).

With the objective of summarizing all the different methodologies for assessing costs and benefits of climate change adaptation, in 2011 the UNFCC created a report based on papers and workshops in different countries about costing climate change adaptation strategies. This report provides several case studies and lessons learns with the intent of providing governments and agencies with a holistic overview of the whole prioritization process (UNFCCC 2011).

In 2011, the Australian Government’s Department of Energy published a framework for costing adaptation strategies based on Cost-Benefit Analysis and Net Present Value. It encourages use of climate change scenarios to find expected values (AECOM Australia 2012) .

Most of the afore-mentioned research on climate change adaptation costing analysis is limited to a small number of possible climate projections all employing scenario-based analysis (Nassopoulos et al. 2012; Stewart et al. 2014; Towler et al. 2012). Some other costing efforts have been made based on the value of expected climate change projections (Kirshen et al. 2012; Špačková and Straub 2015). If information from all possible climate projections is available, decision-makers may not be inclined to use the strategy that maximizes the expected value of climate change cost (Su and Tung 2013). Rather, decision-makers may want to use all climate projections to estimate the reduction of damages and so have a better understanding of all possible outcomes and consequences (Rojas et al. 2013).

A few remaining challenges with climate change adaptation economics still must be discussed. The issue of discounting cost is a recurring debate about the economics of climate change. The discussion began at the end of the 20th century with economists seeking to quantify the benefits of environmental projects or policies, in terms of global climate change, nuclear waste disposal, or ground water pollution metrics (Weitzman 1998). *The Economics of Climate Change: the Stern Review* (Treasury 2007) suggested using a near-zero discount rate for cost of climate change to produce favorable result for any mitigation strategy. The debate on discount rates for climate change and extreme weather events moves beyond economics into the fields of philosophy, ethics, politics and even physiological science (Carson and Roth Tran 2009; Corotis 2009; Dasgupta 2008). Other opinions suggest that near-zero discount rate work against intergenerational justice and agent-relative ethics, as investment place premiums on future generations (Beckerman and Hepburn 2007; Lind 1995), which is in consistent with new market rules about the potential of losing efficiency and equity on investment (Nordhaus 2007). Calculations that include a discount assure that mitigation and adaptation policies provide future benefits that are at least as beneficial as productive activities today. Based on these debates, some economists believe that economics of adaptation to climate change do not belong within traditional economics theory, and should incorporate ethics and philosophy into their process (Broome 2008).

There is a large field of adaptation economics literature that instead of considering the impacts of progressive climate change, focuses on mitigation strategies to reduce vulnerability of extreme weather events (Bonstrom and Corotis 2014; Bouwer et al. 2014). Although the timing and frequency of occurrence of extreme hazards differs from progressive climate change, the economic strategies used to study these events are similar to the climate change adaptation infrastructure investments problem. Studying these methodologies suggests benefits from reducing vulnerabilities (Bjarnadottir et al. 2014; Rose et al. 2007) and incorporating uncertainty into estimates for direct future cost.

Moving from traditional cost-benefit approaches to setting priorities for adaptation projects, there is a clear need for advanced climate change adaptation costing methods that incorporate the full range of climate projections to properly reflect the uncertainty of the problem. (Dessai et al. 2004; Fankhauser and Soare 2013; Hallegatte 2009; Watkiss et al. 2014; Weitzman 2009). The issue of uncertainty leads to the next section, describing advances in decision-making under uncertainty of climate change.

2.3 DECISION-MAKING UNDER UNCERTAINTY OF CLIMATE CHANGE

“Engineering design is sometimes thought of as a ‘game against nature.’” Ian Jordaan uses this presents this idea in his book Decision under Uncertainty (Jordaan 2005) to connect the decision in engineering design problems with the common probabilities problems defined in game theory. Jordaan provides a simple discussion of decision-making and game theory principles through an analogy of every-day decision-making. For a person living in Calgary, Alberta, each morning he needs to decide whether to wear a coat before leaving home. There are two possible actions, wearing the coat or not wearing the coat, and there are two states of nature, that the morning will be cold or the morning will be warm. Actions and States of Nature are common terms used in theory of games. In Jordaan’s analogy, the choice of the person in Calgary has four possible consequences, referred to as utilities, depending on the combination of the action taken and the state of nature that occurs. All decision-making is based on the values of such utilities and the fact that states of nature possess uncertainty.

The person getting dressed in Calgary has the exact same problem as any engineer designing an adaptation project for climate change. The engineer has a wide range of possible actions, such as using different types of binder for asphalt of the new highway, but an even broader spectrum of states of nature to consider, defined in this context as future climate variables. When adapting to climate change, engineers are engaged in a “game” with the nature as the opponent, just as Jordaan. This section of the literature review therefore describes traditional decision theory and game theory to understand the fundamental principles that have led to modern decision-making under uncertainty.

Decision theory and game theory was developed almost fifty years ago, by mathematicians, statisticians, and economists (Luce and Raiffa 1957; Savage 1951; Wald 1971) through the concepts of utilities and, more specifically, pay-off tables. A pay-off table is a matrix composed of utilities; the matrix's columns are states of nature, while the rows are the possible actions to choose (Benjamin and Cornell 1963; Jordaan 2005).

The pay-off table provides information about each of the actions, but after building this table there remains a need for criteria to determine which of action is most desirable. The traditional criterions indecision theory are maximax, maximin and minimax, each based on the "risk attitude" of the decision-maker. Maximax correlates to an optimistic risk-attitude, because it is the most desirable action for maximizing benefits. Maximin refers to the pessimist attitude, because it chooses the action with maximum benefits and assumes that the least favorable state of nature occurs (Wald 1971). Finally, the minimax criterion connects to the opportunist risk attitude, as the action that minimize losses. In the early 20th century, Van Neumann defined the concept of minimax and it was identified as the optimal criterion for a zero-sum game (Neumann and Morgenstern 1944). The minimax concept was refined by Savage in the mid-century, using regret instead of losses, redefining it as the criterion that minimizes the worst regret from each state of nature (Savage 1951).

Implementation of the three criterions presented here is often referred to as decision-making under ignorance (Ellsberg 2001; Hansson 1994; Resnik 1987). This label describes any decision-making when there is information about the states of nature but a lack of knowledge about the probabilities with which each of them occur.

These criterion, together with decision theory and game theory, are widely used among practitioners and engineering and it is still taught around the world as part of decision-making under uncertainty around the world (Hansson 1994; Resnik 1987). However, climate change poses a unique threat to this traditional theory, because uncertainty increases in each step of the climate modelling process (Wilby and Dessai

2010). The states of natures, or changes in climate, which may occur in the future are almost unpredictable and each of potential state carries a deep and severe uncertainty.

Deep uncertainty in climate change impact assessments has been a highly discussed topic for almost 20 years among economist, mathematicians and scientist (Fankhauser et al. 1999; Jones 2000; Lempert et al. 2004; Yohe and Neumann 1997). Deep uncertainty describes a scenario when decision-makers cannot agree on the prior probabilities and interdependencies of system model inputs (Lempert et al. 2004). Severe uncertainty has been defined similarly as a situation where there a large lack of information expressed as a non-probabilistic information gap (Ben-Haim 2000). The term deep uncertainty seems to be more commonly used in the literature than severe uncertainty despite having almost the same definition (Brown et al. 2011; Kasprzyk et al. 2013; Nassopoulos et al. 2012). Climate change poses a particular challenge for prioritization of adaptation investments due to the deep uncertainty of projected costs and benefits (Dessai et al. 2007; Dessai and Hulme 2007). This uncertainty makes it very difficult for decision makers to know the true magnitude or nature of the problem and then to choose the standards or thresholds to adapt their infrastructure.

Deep uncertainty can be dealt with using "robust decision-making," described as the strategies with lower regret (Dessai and Hulme 2007; Gupta and Rosenhead 1968). Robust decision-making practices will perform better that optimization techniques under situation when probabilities of state of nature are not well understood, as optimization can prioritize option with higher values of potential regret (Lempert and Collins 2007; Rosenhead et al. 1972).

The notion of robust decision-making first appeared in the context of operations management and systems modelling (Ben-Haim 2001; Rosenhead et al. 1972), where the robust option is least sensitive to the uncertainty of outcomes. More recently, the idea of robustness has been applied to climate change impact assessment (Dessai and Hulme 2007; Hallegatte 2009) and to decision-making for adaptation strategies (Lopez et al. 2014; Moody and Brown 2013), especially in the context of water management (Brown et al.

2011; Lempert and Groves 2010). Robustness can be defined as the property of an action or a decision that is insensitive to uncertainty, or in other words that the outcome is invariable to different future scenarios.

There has yet to be an example in the literature applying the robust decision-making process for transportation planning climate change adaptation projects. Robustness has been used in other contexts in the realm of transportation engineering, but only while dealing with transportation networks and traffic engineering, mainly in route optimization problems (Huynh and Walton 2008; Yan et al. 2013).

As introduced in the previous sections of this chapter, prioritization climate change adaptation options is a recent and complex problem, which involves combined aspects numerous different academic fields, such as economics, engineering, planning, and even behavioral sciences. One of the examples of type of theories that could help to integrate all this field onto the prioritized problem in climate change circumstances is the *Prospect Theory* developed during the 70's to capture the behavior of decision-makers with events with lower probability of occurrence and high consequences (Kahneman and Tversky 1979).

There is a need for simple frameworks and general methodologies that could help decision makers to more clearly understand this highly challenging problem of prioritize climate change adaptation investments. The next section explores some of the existing frameworks and integrated approaches to address this issue.

2.4 INTEGRATED APPROACHES, EXISTING FRAMEWORKS AND SUPPORT TOOLS

Integrated approaches are commonly used to address complex problems such as climate change (Berkhout et al. 2006; Jaroszweski et al. 2010; Rothman and Robinson 1997; Tyler and Moench 2012). Integrated approaches consider multiple sectors and their interactions to tackle the problem. In one of the first published articles on climate change policy implications, Morgan et al. (1999) stated that an integrated assessment approach is ideal for addressing issues related to climate change adaptation because it allows for the synthesis of disparate knowledge, inclusion of uncertainties, and the ability to create a baseline allowing for current and future assessment and discussion. "Thoughtful analysis" is cited as the "only real approach we have to improve the quality of our understanding" (Morgan et al. 1999).

There are two distinct integrated approaches to deal with climate change: top-down and bottom-up (Leal-Arcas 2011; Tuladhar et al. 2009). On the mitigation side of climate change, top-down approaches come from high-level policy plans, with economic sectors as units for modeling and evaluating mitigation policies. Bottom-up describe the reverse of this, modeling strategies at an individual scale and then aggregating them to find regional outcomes for mitigation policies. The Kyoto Protocol provides an example of top-down mitigation policy (Leal-Arcas 2011), where the policy was developed and agreed-upon multilaterally and then applied at the nation level. Application of the two strategies to adaptation, not mitigation, to climate change allows for similar definitions.

Top-down adaptation approaches use downscale modeling to identify vulnerable areas. Once these areas are identified and possible climate risk to communities or infrastructure is located and then addressed with the appropriate adaptation strategy. The information in this approach cascades from one step to the next, from the highest to lowest. Each step of the model add a new degree of uncertainty, so at the final stage the impact results possess a dramatic range of uncertainty (Mastrandrea et al. 2010; Wilby and Dessai 2010). Top-down approaches have been the most common way of addressing climate change risk assessment for many years (Klein et al. 1999; Mastrandrea et al. 2010) as the traditional method for to understanding climate change impacts (Burton et al. 2002).

The bottom-up approach meanwhile, begins where the top-down leaves off. It consider a specific sector, infrastructure or community, where the adaptation may be implemented. The approach identifies all possible vulnerabilities through local and community-specific base knowledge, and then links these vulnerabilities to the projected climate models (Brown et al. 2011; Dessai et al. 2005). Bottom-up approaches are used to reduce social vulnerability at a household or individual scale (Heltberg et al. 2009), to increase resiliency on private properties and reduce damage to well-being, such as on nutrition, income, or wealth, from possible climate change impacts (Watkiss and Hunt 2011). In the context of climate change planning, the top-down adaptation approach is referred as a scenario-driven or scenario-based approach while the bottom-up method is referred to as a vulnerability-based approach (IPCC 2014a).

These two general approaches can be applied to economic, political, and infrastructure sector decision-making. Recent efforts to modify the general approach hold consequences for the transportation sector, allowing practitioners and decision makers in transportation agencies to easily apply the approach for their sector assets. In particular, the Federal Highway Administration, FHWA, published a conceptual model to assess vulnerabilities and risk climate change effects on transportation infrastructure (US DOT 2011). Figure 2.1 summarizes the conceptual model developed by FHWA, which based on five main steps: identify assets, gather climate information, analyze vulnerability, prioritize adaptation strategies, and monitor resources. This FHWA report doesn't include details of how to handle all the steps of the model only addressing the green ones. Late on 2012 FHWA published a new and more extensive climate change vulnerability assessment framework that has remained as the current framework of reference for the US Department of Transportation (US DOT 2012). This framework includes a similar conceptual diagram as the previous one but again it do not address the issue of prioritizing climate change adaptation investment. It explicitly states that not many agencies have conducted this task and that it remains as a task for the near future. "Not many agencies have conducted these analyses [Identifying, Analyzing and Prioritizing Adaptation Options] to date. As such, the FHWA anticipates making this section of the framework more robust based on experience with the second round of pilots." (US DOT 2012 pg. 36)

At the same time, Meyer and Weigel developed a conceptual model similar to FHWA for climate change adaptation approach for highway infrastructure based on a six-step model (Meyer and Weigel 2011). Both of these two models are scenario-based, top-down, approaches. Of interest for practitioners is that the Meyer and Weigel framework identifies a wide range of stress-specific adaptation strategies to highway maintenance based on previous research and studies. Other types of transportation assets, as bridges, pipelines or railroads, however, have different responses to specific climate change variables, the adaptation will differ substantially from one asset to another (Rowan et al. 2013). This conceptual model was later refined and expanded to give specific examples for how to address each of the steps (Armstrong et al. n.d.).

It includes a number the important economic indicators to consider in the prioritization step and importance of incorporating uncertainty as well.

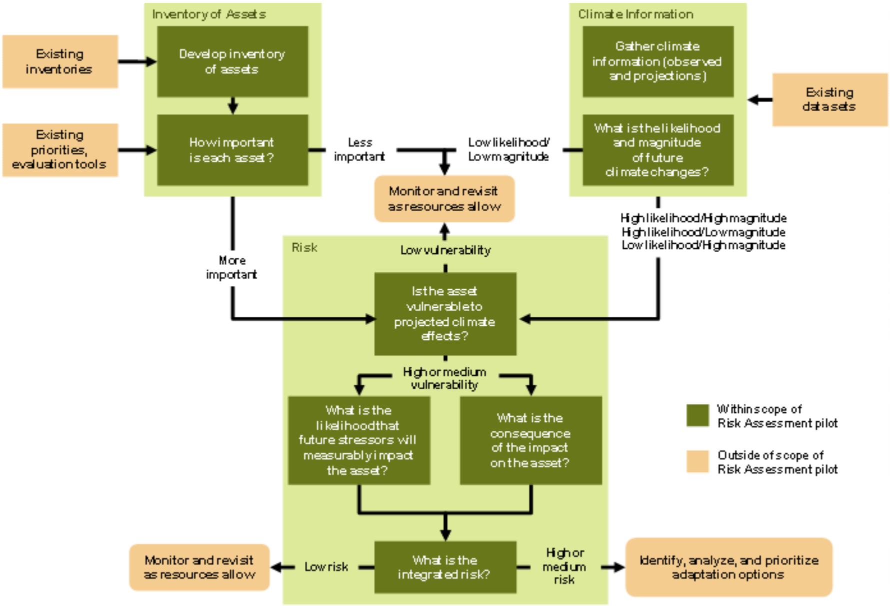


Figure 2.1: Conceptual Model for Assessing Vulnerabilities – US DOT 2011

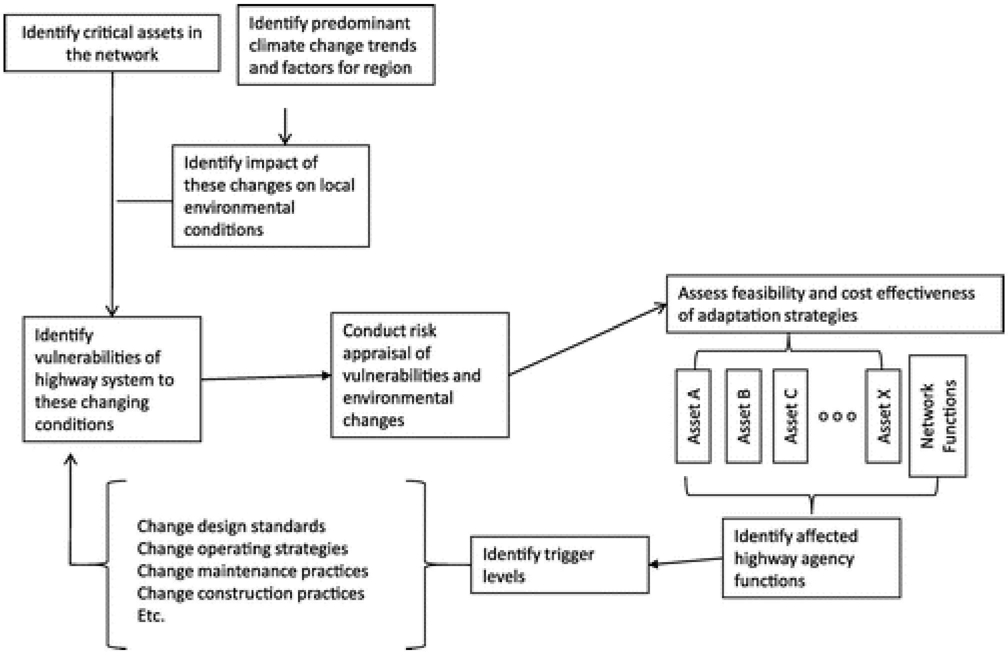


Figure 2.2: Management Approach to vulnerabilities of transportation facilities to climate change - Meyer and Weigel 2011

The US-based approaches of the FHWA and Meyer and Weigel both share similarities with other transportation assets frameworks developed in other parts of the world. Many frameworks in the United States, the United Kingdom, and New Zealand include top-down approaches for application by regional governments. All of these national-level frameworks are composed of an identification stage, a vulnerability stage, and a feedback mechanism, each differs slightly in risk assessment. This stage is optional in the U.S., but is required in the U.K. and New Zealand (Hirsch and Kunstman n.d.).

All the conceptual models and framework described above identify the need to prioritize and optimize the best adaptation strategy for reducing vulnerabilities. Neither the FHWA nor the Meyer and Weigel conceptual model addresses specifically how to find and select the optimal or most efficient strategy. The challenge of selecting an optimal strategy is highly complex because it carries deep uncertainty, as introduced in the previous section.

Multi-Criteria Decision Analysis can be a useful tool for prioritizing project investments for infrastructure development subject to deep uncertainty (Lambert et al. 2012) and prioritizing different adaptation strategies to climate change (Bruin et al. 2009). Some difficulties can arise, however, when assigning weights or scores to each of the strategies, as they are based on stakeholder subjectivity and opinions (Lambert et al. 2013).

The Robust Decision Making Method (Lempert et al. 2006), *RDM* , and the Info-Gap Method (Ben-Haim 2001), introduced in the previous section, are two different methodologies that each seek to address the problem cost-benefit optimization in the context of deep or severe uncertainty. These two approaches share similarities, with both representing uncertainty as a set of multiple possible scenarios and with a joint goal of identifying the most robust strategy or least sensitive to uncertainty. However, they treat losses and gains differently, take different approaches to address imprecise probabilities, and they conduct the analysis in different orders. Although these differences may appear insignificant they can in fact lead to markedly different robust adaptation strategies (Hall et al. 2012). It is left to individual decision-makers to select which of these two methodologies they believe to be most appropriate for treating the problem of prioritization of adaptation strategies under uncertainty of climate change. Despite their benefits, neither of this two approaches have ever been applied to transportation-specific problems of adaptation to climate change.

2.5 POINT OF DEPARTURE

This research builds upon existing literature and conceptual frameworks to investigate how uncertainty can be better dealt with decision-making, specifically for the prioritization process of adaptation investment strategies to climate change impacts on transportation infrastructure.

Conceptual, integrated approaches for adaptation to climate change in transportation sector has been successfully presented by different agencies and governments across the world, with broad consensus for a general adaptation framework. However, there remains a lack of practical guidance for how a transportation practitioner should approach each of the steps in these conceptual models. Particularly, climate change poses a challenge to prioritizing adaptation strategies, because traditional cost-benefit analysis optimization fails to appropriately address the deep uncertainty of future scenario.

This thesis expands the current general framework and decision-making approaches for climate change and transport adaptation. Most of the topics researched in the literature review section fall into two different categories, related either to climate change adaptation or to decision-making theory. The different topics covered in the literature have been broken into six main sub-themes, which are displayed visually in Figure 2.3. The horizontal axis is decision-making theory and the vertical is climate change adaptation. Topics located on the right side of the graph focus mainly on decision-making theory while topics higher along the vertical are considered to have a stronger focus on general climate change adaptation. *Classic decision-making theory* and *robust decision-making* are located on the bottom right part of the figure, indicating literature that is considered to contribute directly to general decision-making theory but do not specifically address climate change adaptation issues. At the top left of the figure, *governmental adaptation guidelines* indicates expanding knowledge on climate change adaptation that does not incorporate any information about decision-making theory. Literature that covers both climate change adaptation and decision-making theory are compiled in the subjects of *economics of adaptation*, *qualitative and quantitative approaches*. This dissertation departs from these middle ground topics that cover both climate change adaptation and decision-making theory. This research expands upon previous literature to present a new methodology for optimizing and prioritizing adaptation investments by addressing and incorporating deep uncertainty of future climate scenarios, based on robustness and non-regret approaches.

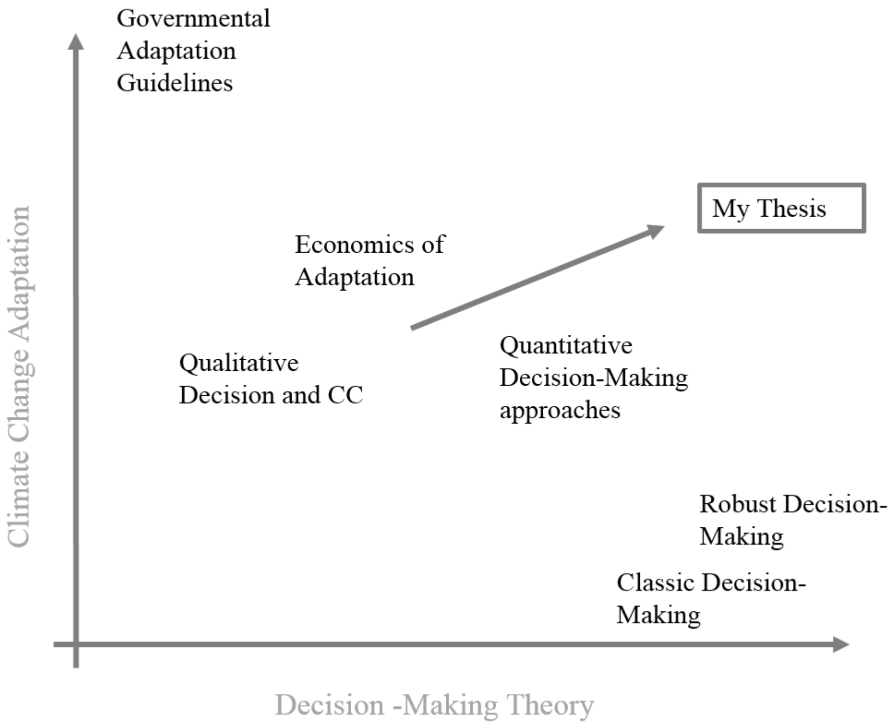


Figure 2.3: Point of departure Diagram

Chapter 3 METHODOLOGY

The methodology proposed for this research introduces uncertainty and decision-making theory into the field of climate change adaptation. Using these established fields of study, this project will examine the potential for developing a framework to address uncertainty in climate change impacts on the transportation sector.

The proposed framework follows a five stage approach (Figure 3.1). The first step identifies infrastructure design adaptation strategies. The second step quantifies the costs and benefits of possible adaptation strategies. The third step calculates economic indicators for each of the strategies based on perfect future climate foresight. The fourth step compares each strategy across all possible climate scenarios; It builds a three-dimensional matrix that is foundation for helping decision makers choose an adaptation strategy. The fifth and final step of the framework will lead to robust decisions based on the matrix built in step four and explores the regret between strategies and between possible future scenarios. The end-result of this framework is providing a range of adaptation strategies from among the strategies identified in step one that show a more robust behavior so decision-makers can choose among strategies that would have a potential lower regret.

Although this thesis explores road-specific design adaptation strategies to climate change, the proposed framework is flexible enough to be applied to adaptation strategies for any type of infrastructure system. The following sections detail each step of the proposed methodology.

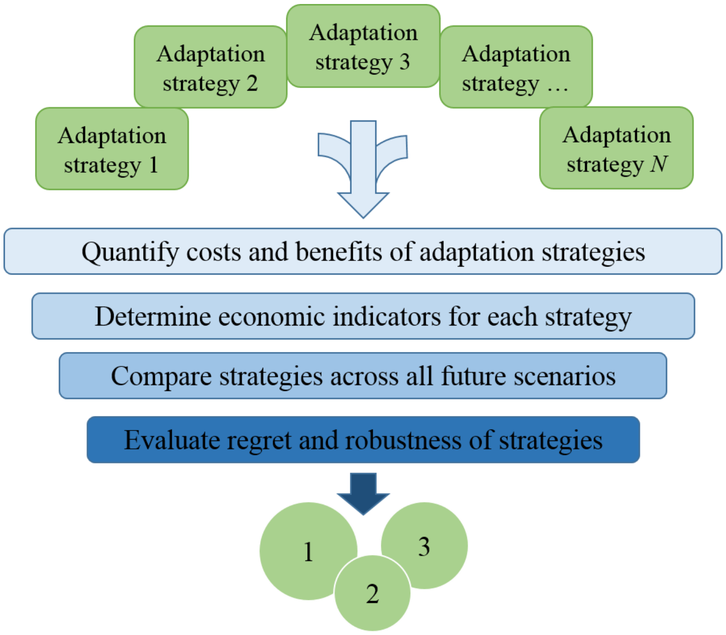


Figure 3.1: Proposed Five-step methodology to identify best adaptation strategies to climate change

3.1 VULNERABILITIES AND DESIGN-SPECIFIC ADAPTATION STRATEGIES

The first step of the proposed methodology is to identify vulnerabilities of the infrastructure due to future climate. Most of the national reports described in the literature review include region-specific vulnerabilities to future climate. After locating vulnerabilities, infrastructure managing agency need next to identify an engineering design-specific adaptation strategy to address each set of vulnerabilities.

A few tools have been developed to help policy makers and planners identify transportation vulnerabilities to climate change and undertake wider decision-making. Notably, the *Climate Change Adaptation Tool for Transportation* (CCATT) is designed to help assess climate change and transportation. However, as a barrier to routine use, CCATT requires detailed inputs from local administrators, complicating and the ease of its implementation (Oswald and McNeil 2013). Additionally, the MAGICC/SCENGEN model focuses on changes in temperature, precipitation and other climate phenomena, but it is not designed to connect these changes to impacts on the built environment (UCAR 2007). The *Infrastructure Planning Support System*, a novel tool developed by the authors, bridges the gap between the two other tools, and is useful to identify regional and local vulnerabilities in transportation systems (Schweikert et al. 2014c). The relevance of this tool for transportation planners and decision-makers will be detailed in the following section.

Once local vulnerabilities have been identified, most transportation engineering professionals, practitioners, and academics can develop specific design alternatives to address the impact of climate change, stemming from increase of temperature, precipitation, freeze-thaw cycle or increased frequency of extreme events like flooding or storms (Meyer and Weigel 2011; Rowan et al. 2013).

Discussion with several transportation firms and practitioners established that for simplification, only three main vulnerabilities will be studied, temperature, precipitation and flooding. For each of these impacts, a set of design specific adaptation strategies are selected. In order to address the impact of increased temperature on road infrastructure different actions can be taken such as applying surface rejuvenation spray to restore surface by applying cutback binder, constructing dense seals, or adopting base bitumen binders with higher softening points (Nemry and Demirel 2012; US DOT 2015; Verhaeghe et al. 2012). In the case of greater precipitation, adaptation actions can include adding wider paved shoulders to improve surface drainage, increasing base strength (thickness and/or quality), or increasing frequency of the resealing cycle, among others (NRC 2008; US DOT 2014; Verhaeghe et al. 2012). Finally, to combat the impacts of flooding, adaptation could include increase the flood design return period or increasing the size of culverts (US DOT 2014). For each of these adaptation strategies, it is crucial for infrastructure managers to provide an approximate cost and schedule.

3.2 COSTS AND BENEFITS OF ADAPTATION

The methodology to obtain costs and benefits of adaptation to climate change is conducted through a four-step process. First, the projected climate scenarios are identified for the geographical area of study. Second, the impact of each model on the road stock is evaluated. In the third step, the costs for each scenario are determined. Finally these cost are compiled and summarized to provide recommendation for road planning in response to the future environment and climate change. The four steps of this methodology exist in a single software tool created with different algorithms to generate each step. This innovative software is called the Infrastructure Planning Support System, or IPSS, and was created by the Institute for Climate and Civil Systems (iCliCs) Research Group at the University of Colorado at Boulder. IPSS is a computer-based tool that includes six areas of analysis including climate change, environmental and social impact to provide a holistic vision and a road long term planning capability. It has been used to quantify the impact of climate change on transport infrastructure in African Countries, (Chinowsky et al. 2014b), in Asia (Chinowsky et al. 2012a) and a nation-wide studies in both roads and bridges (Chinowsky et al. 2013b), and several comparative studies of different countries around the world (Schweikert et al. 2014b).

In the following section this tool is described in more detail, along with the four steps of the methodology introduced above. This tool has been refined and updated to be used in this dissertation. However the development of this tool is out of the scope of this thesis, and it has been merely used in the present dissertation as a tool to obtain vulnerability and adaptation costs.

3.2.1 IPSS AS A PLANNING TOOL

IPSS was developed from technical and engineering research to evaluate the impact of climate change and the consequents cost on the transport infrastructure. The IPSS system combines quantitative and qualitative analysis methods to develop the projected fiscal cost, in addition to social impacts and improvements for the current transport infrastructure. This thesis uses the part of IPSS that quantifies on the impact of climate change onto road system. The climate change module of IPSS is an original tool because it represents one of the first times that future climate projections have been incorporated into processes for transport planning and maintenance scheduling of road networks.

The climate analysis is developed in IPSS through three main steps. In the first, IPSS determines the projected climate change in the specific region of study. As a default IPSS used projected climate data from climate models agreed in both the Coupled Model Intercomparison Project phases 3 and 5, CMIP3 and CMIP5, and approved by the IPCC Assessment Report Fourth and Fifth, AR4 and AR5. A list of CMIP model used in this thesis can be found in *Appendix 1*. IPSS is flexible in that additional climate models can be added for region-specific climate projections. After selection of the climate model, the projected climate values are then compared with historical climate trends to obtain outcomes for future changes. For this study, analysis in IPSS assessed the impacts from two climate variables, maximum average monthly temperature, and maximum monthly cumulative precipitation. IPSS is capable of identifying climate changes at a CRU (climate research unit) scale, which is a global grid network of 50 by 50 kilometers developed by the University of East Anglia (Mitchell et al. 2004).

The second step of the process is to evaluate the impact of the future climate variations on the infrastructure system of study. Material-specific stress-response equations and material climate threshold information are used in this step to identify the damage incurred on the infrastructure by each of the climate variables. The iCliCs research group developed the material stress-response equations based on a previous transportation consulting projects and material science reports, combined with historical data and lab testing. In this study these equations express the response of the road materials under the three climate variables, precipitation, temperature and flooding. After evaluating the projected damage, the third step of IPSS is to quantify this damage by placing a monetary value on it. The monetary cost of climate change comes from the assumption that transport infrastructure managers are going to repair and increase their maintenance costs in order to maintain the design life of the road. Detailed stress-response equation and detailed methodology of IPSS can be reviewed in previous work by the authors (Chinowsky and Arndt 2012; Schweikert et al. 2014c).

The final and fourth step is to process, compile, and summarize the large amount of data generated during this analysis. As a default, IPSS calculates the fiscal cost incurred from increasing repair and maintenances on the current road infrastructure. The iCliCs group has developed two additional metrics for a comprehensive analysis of the infrastructure vulnerabilities. Apart from the above-mentioned *Total Fiscal Cost*, which is a purely economic measurement of the impact of climate change, IPSS provides the *Kilometers Damaged*, which is the total amount of paved inventory that is estimated to be damaged by climate change. The third metric is the *Opportunity Cost*. This last metric represents the number of kilometers of new paved road inventory that could be built with the money spent on repairing the climate change damages. The amount of potential new roads is then compared to the total existing paved road inventory in the region of study to compute a measurement of lost opportunity, due to climate change, for expansion of the current infrastructure. This last metric is particularly meaningful when different regions are compared, since it provides a relative cost. Comparison of these relative costs helps to identify the most vulnerable areas in a region, even if they have a small road inventory and a subsequent small total fiscal cost. These three metrics provide a holistic picture of the impact of climate change and the specific vulnerabilities of road infrastructure in the different areas of study.

IPSS computes annual estimates for the three metrics for each of the climate models incorporated into the analysis, over the length of the chosen period of study. To make the results from IPSS most understandable and useful for transportation planners, the tool determines both cumulative cost for the period of analysis and a decadal average cost. In most cases IPSS reports the damages on those time scale for models of the 5th, 50th and 95th percentiles of outcome, representing the low-severity scenario, the median value and the damage predicted for an extreme climate change. Results also are shown from all of the range of climate models as boxplots or probability density functions, to better understand risk and uncertainties associated with the analysis.

3.3 ECONOMIC ANALYSIS OF ADAPTATION STRATEGIES

The third step of the framework is to identify economic indicators based on future climate perfect foresight. As each of the climate models predicts a different impact and vulnerability, a different economic value will be obtained for each of the climate scenarios.

In the previous step, the cost of each alternative, the amount of damage reduction and the remaining repair after adaptation was obtained. It is crucial to accurately describe each formulation of these costs with appropriate indexing as the intent is to expand these formulas into a large number of alternatives and climate scenarios. With appropriate notation it will be easier to create algorithms to work with large amounts of data. To perform the economic evaluation, the costs and benefits for each alternative must be obtained. Following previous literature the cost and benefit in present value are calculated as follows, where CA_i, DR_{ij}, R_{ij} are denoted as the costs for adapting, damage reduction, and the remaining repair for adaptation strategy *i* at year *j*:

$$C_i = \frac{CA_i}{(1+r)^n} + \sum_{j=1:m} \frac{R_{ij}}{(1+r)^j}$$

$$DR_i = \sum_{j=1:m} \frac{DR_{ij}}{(1+r)^j}$$

i: adaptation strategy

n: year of schedule adaptation

m: final year of period analysis

r: discount rate

From here, the Net Present Value can easily be calculated as:

$$NPV_i = C_i \;\;;$$

The damage reduction is not used in the total computation of the net present value but its definition is going to be useful in the following sections. Net Present Values is going to be used in this dissertation as the economic indicator for ranking project investments. The next step of the framework incorporates all of the adaptation strategies together to compare them between different climate scenarios.

3.4 COMPARISON ACROSS ALL FUTURE SCENARIOS

In the previous step, the Net Present Values of each strategy for all different climate scenarios were obtained, producing as many outcomes for NPV as there are climate scenario for each strategy. Even for the same strategy, values of NPV may differ highly as they are directly influenced by the projected climate change impact and the subsequent adaptation. To define these Net Present Values, denote *k* as the scenario for which the adaptation strategy has been design, and then NPV_i^k, as the Net Present Value of Strategy *i* designed for climate model *k*. The model we are designing the strategy for will be called design climate scenario in the rest of this dissertation.

Another dimension to the problem needs to be added, in order to compare among strategies. As mentioned above, decision makers choose for which climate scenario they want to adapt. Most likely the climate scenario that will actually happen will differ from the one that was adapted for. In this case, define l as the climate scenario that could happen. Then, $NPV_i^{k\,l}$ will refer to the Net Present Value of strategy i designed for climate k, now assuming that scenario l occurs.

The fourth step of the framework consists of integrating the decision-making process along all possible climate scenarios. A pay-off table will be built based on NPV, to facilitate the integration and comparison of the different adaptation strategies. For each strategy i, a two dimensional matrix is constructed where the rows are each of the scenarios that the strategy is designed for, denoted as k, and the columns are the scenarios that actually happen, denoted as l. In the diagonal of the matrix, when $k = l$, the values of NPV are the ones obtained in the previous step of the framework and are equivalent to having perfect foresight about the strategy to choose and the climate scenario that will occur.

To calculate the values outside the diagonal we need to make a differentiation between two different possible outcomes. Decision makers can overestimate the projected impact of climate and then over-design the infrastructure, or they can underestimate the climate change, assuming a less severe climate projection, which could result in a design that does not reduce all possible impacts. The severity of a climate projection will be measured by the total vulnerability cost, in dollar value, define in this section as R - the total projected additional maintenance and repair due to future climate projections -. In order to express this difference using the variables defined above, this analysis assumes that if climate change is overestimated, then the risk reduction predicted will be larger than the real risk reduction. Conversely, if climate change is underestimated, then the risk reduction assumed will be smaller than the real risk reduction. The table below summarize these definitions:

Table 3.1: Summary of Definition of Different Cases of Climate Comparison

Design climate scenarios, k, more severe than real climate scenarios, l.	overdesign	$DR_i^k > DR_i^l$
Design climate scenarios, k, less severe than real climate scenarios, l.	under-design	$DR_i^k < DR_i^l$
Design climate scenarios, k, equal to real climate scenarios, l.	perfect foresight	$DR_i^k = DR_i^l$

The calculation of NPV for each of the three assumptions above differ slightly and are defined as follows. The values in the first quantity represent the total benefits. The components of the second quantity are the initial cost of adaptation plus the cost of the remaining impacts that have not been addressed.

Table 3.2: Notation for Net Present Value Comparison across Scenarios

$NPV_i^{k\,l} = \left(\frac{CA_i^k}{(1+r)^n} + \sum_{j=1:m} \frac{R_{ij}^l}{(1+r)^j}\right)$	$DR_i^k > DR_i^l$
$NPV_i^{k\,l} = \left(\frac{CA_i^k}{(1+r)^n} + \sum_{j=1:m} \frac{R_{ij}^l}{(1+r)^j} + \sum_{j=1:m} \frac{\Delta DR_{ij}^{l-k}}{(1+r)^j}\right)$	$DR_i^k < DR_i^l$
$NPV_i^{k\,l} = NPV_i^k$	$DR_i^k = DR_i^l$

Now the components of the pay-off matrix are $NPV_i^{k\,l}$ with k, l = 1, 2…, c with c equaling the total number of climate scenarios. This payoff matrix is the same kind of matrix employed in traditional and elementary decision theory (Benjamin and Cornell 1963; Jordaan 2005). Using the traditional terms, the states of nature will be the climate scenarios that actually happen while the actions are both the possible strategies and designs. The suggested pay-off matrix is an expansion of the traditional pay-off matrix, but with the introduced of another dimension. Another action is introduced: the climate change for which we are going to design the strategy. Now, the pay-off table contains dimensions *i* and *k* as actions, and *l* states of nature. See Figure 3.2 to exemplify the three dimensional pay-off table.

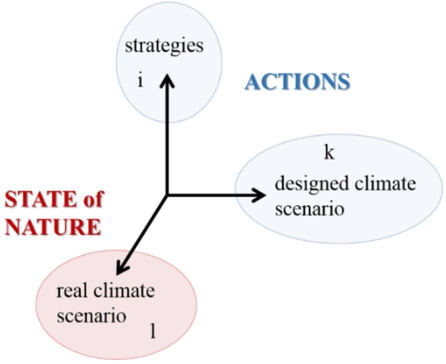


Figure 3.2: Diagram of three dimensional pay-off table

From this matrix, the analysis can apply the classic criterions from decision-making theory, Maximax, Maximin, and Minimax, introduced in the literature review. All these criterion can be expanded to accommodate the third dimension of the problem. All these criterions have been defined when the net present values is calculated as benefit minus cost. In the case presented in this dissertation we calculated net present values as a sum of cost and we do not include benefits. Therefore the prioritization exercise needed to obtain the option that minimized the total NPV instead of the traditional way of maximizing benefits. This is the reason why the following definitions of the decision-making theory criterions have been modified from the traditional definitions.

Maximax criterion, often called the maximum of maximums or the best of the best, looks at the best projected state under each action and then chooses the action with the largest value. This criterion represents an optimistic point of view. Notation for maximax criterion is expressed as:

$$\min_{i}(\min_{k}(\min_{l}(NPV_{i}^{k\,l})))$$

Maximin criterion, often called the maximum of the minimums or the best of the worst, looks at the worst projected state under each action and then chooses the action with the largest value. This criterion represents a pessimistic point of view. Notation for maximin criterion is expressed as:

$$\min_i(\min_k(\max_l(NPV_i^{k\,l})))$$

Minimax criterion is often called the minimum of the maximum. This criterion is based on opportunistic loss or regret, not the direct payoff values as the other criterion. An opportunistic lost matrix, OLM, is created to allow use of this criterion. The OLM states can be calculated from the states of the POM minus the maximum payoff of each state. Then:

$$OLM_i^{kl} = NPV_i^{kl} - (\min_k(NPV_i^{kl}))$$

The minimax criterion looks then at the largest opportunity loss from each action and choses the smallest loss among all of these. It is said that these criterion represents a cautious attitude (Hansson 1994). Notation for the minimax criterion is expressed as:

$$\min_i(\min_k(\max_l(OLM_i^{kl})))$$

After this step of the framework, the best adaptation strategy can then be found for each of the attitude or criterions described above. This new methodology developed a three dimensional pay-off table that allows decision makers to incorporate high flexibility into the process for selecting the best strategies. The three criteria above can be used if one of the dimensions is removed or blocked. Assuming that the decision maker is only interested in a specific adaptation strategy, dimension *i* will not be consider, making the outcome the best climate scenario to design for given this strategy. On the other hand, if decision makers have chosen the climate scenario for which they want to design, they can again use this methodology to identify the strategy that will be most favorable to a specific climate scenario, blocking dimension *k*.

The next step of the framework evolves from classic decision-making theory to incorporate the concept of robustness and regret. It expands the methodology to identify strategies with low sensitivity to uncertainty and discuss issues of probabilities in the climate projections.

3.5 ROBUST DECISION-MAKING UNDER UNCERTAINTY

Other common criteria in decision-making are expected values of net present values. The expected value of the NPV of an adaptation strategy can be calculated from the traditional equation of probability theory of expected value. The sample of scenarios is a discrete sample, so summation is used instead of integration:

$$E\left[NPV_i^k\right] = \sum_{l=1:c} NPV_i^{kl} * P(L = l)$$

As presented in the literature review, there is significant work using the expected value of future costs and benefits to rank and prioritize adaptation strategies and find the optimal value based on maximizing benefits. However, as mentioned earlier, assigning probabilities to climate models and future projection is challenging and most of the times can be misleading if not done appropriately. Given that there is large disagreement about the possible probabilities of climate scenarios (Brown et al. 2011; Dessai and Hulme 2004; Groves and Lempert 2007), the resulting expected values should be treated carefully.

Robustness has recently gained academic popularity as the optimal criteria for investments with deep uncertainty. Robustness, as described in the literature review, is the property of being less sensitive to uncertainty. In the climate change adaptation problem, the robust strategy will be the one with less variances among all possible scenario.

In the previous section, the regret matrix was obtained and defined as the OLM, opportunistic loss matrix. Using this matrix identifies the most robust strategy. The regret for each combination of actions, strategy and design, can be treated as a random sample, and so different statistics can be obtained for each strategy, such as the mean, standard deviation and percentile values. In order to properly compare between strategies, a relative regret value will be calculated, as a percentage of the expected values. The denominator is the expected cost, so when the real climate is the same as expected *l*=*k*. The relative regret is denoted as follows:

$$OLM_i^{kl}(\%) = \frac{NPV_i^{kl} - (\min_k(NPV_i^{kl}))}{NPV_i^{kk}}$$

To visualize robustness, boxplots of the regret will be display across the strategies. Boxplots, together with the statistical values, will allow the decision-makers to select the most robust strategy. This project suggests the use of a deviation from zero that can be defined similarly to the notation of standard deviation, where *c* is the total number of climate models and RI_i is the robustness indicator for strategy i. This indicator shows the average distance of the regret from zero. Low values of the robustness indicator signify a regret distribution closer to zero, indicating a strategy that has low sensitivity to uncertainty. High values of the robustness indicator will result from a strategy with a wide regret distribution, that it is highly dependent on the future climate and uncertainty.

$$RI_i = \sqrt{\left(\sum_{k,l=1:c} \left(OLM_i^{kl}\right)^2\right)/c}$$

The strategy with the lowest value of the robustness indicator will be selected as the most robust strategy. The three dimensional matrix again can allow the decision-maker to incorporate flexibility. The matrix can find the most robust combination of strategy and design, or used separately to obtain the most robust design for a specific strategy or the most robust strategy based in a predetermined design. In this methodology, it is suggested to first find the most robust strategy based on all possible design and projected climate scenarios. Once the strategy has been selected, find the corresponding most robust design standards.

3.6 SOFTWARE PACKAGE

As part of the work in this dissertation, all the steps in the proposed methodology have been compiled in a software coding package using MatLab language. This software package uses costing inputs to provide regret analysis and robust decision-making. It include different plotting module to display the data calculated in the analysis.

Compiling the methodology in a software package allow to use and run this methodology for large amount of climate projection and large areas of analysis with multiples infrastructure assets. The package is flexible enough to allow different number of climate projections for each run, different area size and inventory and even number of adaptation to investigate. It facilitates performing sensitivity analysis and multiple case studies.

The systems requires cost inputs. It requires the information at a yearly basis for total damage, the adaption cost and the total damage reduction divided by stressors (precipitation, temperature and flooding) and by each climate projections. It requires as well specific parameters, as the discount rate and the last year of the analysis.

The package provides a high number of data table for total net presents values, projected regret, and regret analysis for each combination of adaptation strategy. At the same time provide multiple visualization option, figure, graphs and table to assist the user in understating all adaptation options and support decision-making. The visualization options are divided in three modules; *Basic Plots, Basic Regret,* and *Regret Scatter Plots*. Following Figure 3.3, Figure 3.4 and Figure 3.5 are example of graphs provided by each module.

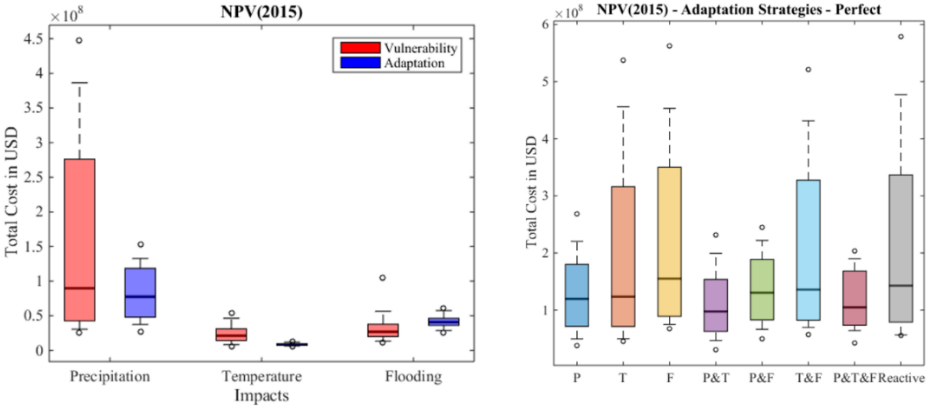


Figure 3.3: Example of graphics from the Basic plots module

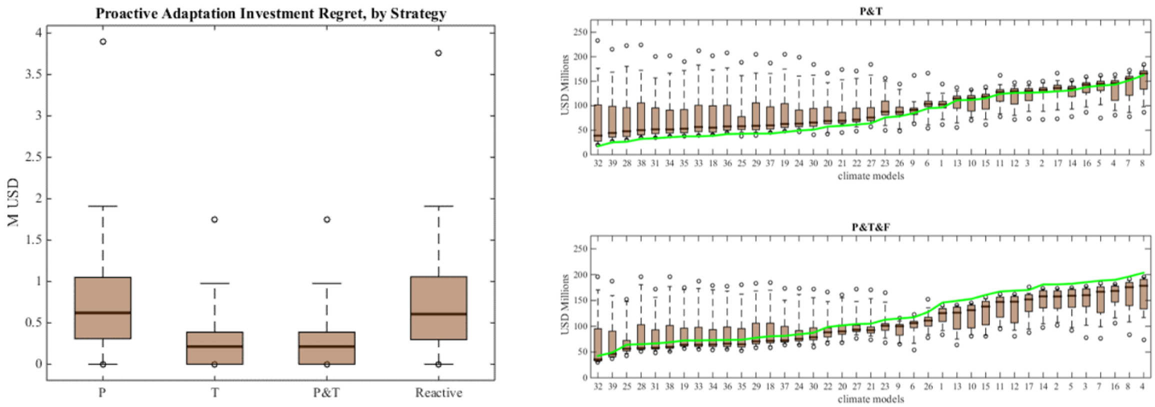


Figure 3.4: Example of graphics from the Basic Regret plots modules

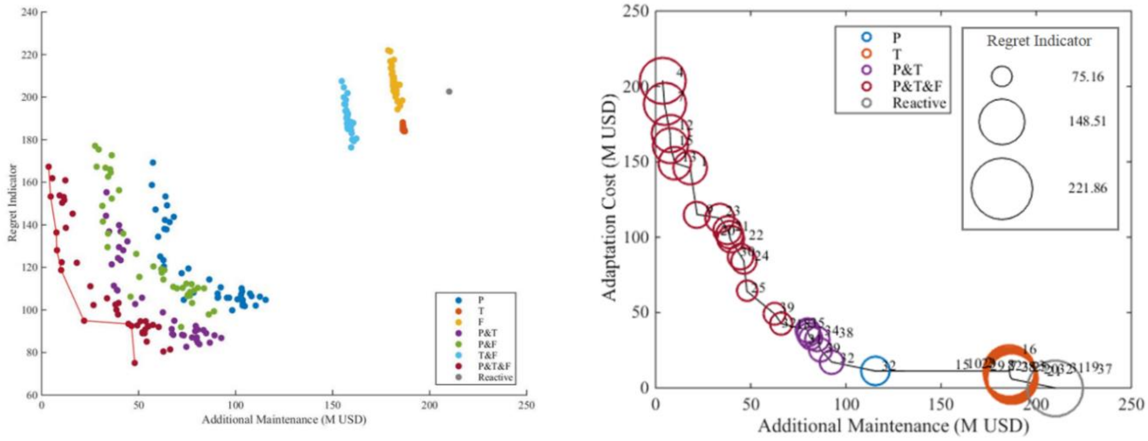


Figure 3.5: Example of graphics from Regret Scatter plots module

3.7 SENSITIVITY ANALYSIS

The selection of most robust adaptation strategy is based on several assumptions made at the beginning of the methodology. Among others, the most sensitive assumptions anticipated to be critical are the discount rate and the year when adaptation occurs. For the first iteration of the process, a zero discount rate will be considered and the time of adaptation will be set as the present, or today. Considering this pair of assumptions will clearly modify the outcome of this analysis. It may be relevant to compare and analyze the sensitivity of both parameters.

To investigate the sensitivity, different runs of the analysis will be performed using different discount rates, for the same set of adaptation strategies and the same problem parameters. The results will be compared and analyzed to determine the sensitivity of the discount rate and its implications for the methodology. At the same time, using a single discount rate, different adaptation starting times will be assumed, and again the best strategies based on each of the times will be compared and discussed.

Chapter 4 QUANTIFYING VULNERABILITY

This chapter is a journal paper manuscript submitted at Transport Policy on 09/03/2015 and currently under review. It presents the impacts and cost of climate change on the road infrastructure of Mexico. The Infrastructure Planning Support System (IPSS), a tool developed by Dr. Chinowsky's research group, is used to quantify impacts of climate change for this study. The results reinforce the need to incorporate forward-looking planning to reduce vulnerability by increase road infrastructure resilience to the future weather changes and provide quantified information for decision makers to consider.

4.1 INTRODUCTION

Transportation infrastructure is crucial for trade, commerce, and community functions including commuting to work and school (Erath et al. 2009; Ochia 1990). This is especially evident in economically developing communities, where road infrastructure quality and quantity is positively related to economic and social growth (Calderón and Servén 2004; Esfahani and Ramírez 2003). Additionally, roads are one of the main capital assets of any country, and so one of the largest portions of national and regional budgets and investments (Fernald 1999; Neumann et al. 2014). This critical role makes the question of transportation infrastructure vulnerability and degradation a top concern for public and private entities as well as planners at all levels (Jenelius et al. 2006).

Road vulnerability, understood as the potential of a road to lose serviceability or accessibility due to a hazard event, can be defined as a function of both risk and resiliency (Berdica 2002; Nicholson and Du 1997). Risk normally refers to the probability that an event with negative consequence will occur. Resiliency is used similarly in different studies and tends to describe the potential to efficiently recover from an external strain. The concept of resilience could be transferable to roads as, for example, the potential of recover serviceability after a strain to the transportation system. In particular, road vulnerability is recognized to have direct negative outcomes on economic, environmental and/or societal conditions (Berdica 2002; Taylor and D'Este 2007).

Many previous studies, including *Berdica* 2002 and *Taylor and D'Este* 2007, recommend incorporating "sustainable" infrastructure planning in order to reduce potential vulnerabilities. In particular, a highlight from most of these studies is a recommendation that for incorporating sustainability it is crucial to identify these vulnerabilities in the early stages of the planning process (Berdica 2002). Sustainable infrastructure planning is most often referred as a holistic planning process, that incorporates life-cycle assessments with the inclusion of projected future cost from maintenance and repairs due to hazard and weather related events (Dasgupta and Tam 2005; Frangopol and Liu 2007; Koetse and Rietveld 2009).

At the same time, many recent studies are indicating that climate change can exacerbate vulnerabilities on road infrastructure, causing increased degradation rates (Koetse and Rietveld 2009; Meyer and Weigel 2011; Neumann et al. 2014). Climate change impacts can lead to an increase in the variability of weather patterns and changes in the frequency and severity of extreme events. These impacts have been characterized as an additional strain in the transportation system, based on the definition of 'risk' presented above (Berdica 2002; Erath et al. 2009).

However, despite this increased recognition of the potential severity of climate change impacts on transportation infrastructure, only small steps are being taken to address these issues. The World Bank is starting to advocate for proactive planning, particularly in Latin America (McAndrews et al. 2012). Recent literature has addressed the issue in location-specific case studies (Savonis et al. n.d.; Suarez et al. 2005) and in broader frameworks (Meyer and Weigel 2011), as well as in quantitative modelling (Schweikert et al. 2014c).

These previous works form a solid base for the necessity of incorporating climate change impacts into all phases of transportation planning with the purpose of reducing risks to future projected climate changes. An additional benefit is that the inclusion of these projected impacts onto the life-cycle costing and planning of road systems can substantially reduce financial costs from increased vulnerabilities, rehabilitation and additional maintenance (NRC 2008). It is recognized that decision-makers seek to address climate change in order to reduce risk, life-cycle cost (including unplanned maintenance and repair), and degradation rates of roads, which are increasing beyond historical precedent (Füssel and Klein 2006). Incorporating potential future climate conditions into current decision-making will support a more holistic, forward-looking approach and ultimately more climate-resilient road infrastructure designs (EEA 2014; Meyer et al. 2010; Meyer and Weigel 2011).

Several existing studies demonstrate how proactive investment in transportation infrastructure is equivalent to or lower than life-cycle cost estimates, and also improves the performance of the infrastructure under climate stress throughout its lifetime (Chinowsky et al. 2014b; Schweikert et al. 2014b). These cost savings are usually due to retrofit or repair needs for infrastructure unable to withstand future damages, because they were built to historical climate standards. While uncertainty in climate modelling limits the ability of planners to invest with perfect foresight, the recognition of changing future weather variability and incorporation of flexible design and adaptation options today should be a consideration for transportation decision makers (NRC 2008). One method for doing so, the modelling system IPSS (*Infrastructure Planning Support System*), is explained and explored throughout the remainder of this chapter.

The first section of this chapter reviews the current state of literature and work done regarding climate change mitigation and adaptation in Mexico. Specifically, this first section focuses on efforts in Mexico to prepare the country against future impacts of climate change through adaptation strategies. The second section explains the methodology used in this study to calculate road vulnerabilities and the engineering approach based on incorporating life-cycle engineering onto transportation planning. In the third section, the regional impacts of the transportation system are analyzed, including a discussion of risk and uncertainty during road planning. The chapter concludes by discussing the importance of incorporating long-term transportation planning to increase resilience and reduce vulnerabilities of regions and communities who rely on road transportation.

4.2 BACKGROUND

The future projected changes in climate for Mexico include increased average temperatures, increased extreme low temperatures and both severe flooding and drought (IPCC 2014b). These predicted climate change impacts could result in severe and widespread changes, including: the replacement of tropical forests with savannahs, an increase in arid vegetation, potential species extinction, loss of costal vegetated wetlands, diminished agricultural production, increased disparity between social classes, a drier environment across portions of the country, increased droughts and simultaneous increases in the intensity of rain and tropical cyclones (Ibarrarán et al. 2009; IPCC 2014b; NCCS 2013).

Driven by the country’s awareness of climate impacts, the Mexican Government has demonstrated commitment, a long-term vision, and political will to addressing climate change by implementing national policies and by taking a leading role in several rounds of global negotiations to address climate change (Schafer 2013). Notably, in 1994, Mexico joined the United Nations’ Framework Convention on Climate Change (UNFCCC) and in 2005 signed the Kyoto Protocol. Based on these commitments, the country preceded to create several laws and guiding documents to help direct efforts in mitigating and adapting to climate change.

A key effort was the 2005 creation of the *Interministerial Commission on Climate Change*. The group is responsible for establishing and creating strategies to address climate change. Out of this commission came the creation of the *National Strategy on Climate Change* (ENACC) in 2007 and the *Special Climate Change Program* (PECC) in 2009 (Sosa-Rodriguez 2013). Other programs were created to support these bodies, including the *Energy Saving and Efficient Use Program* and the *Renewable Energy Development Program*, both established in 2009 (Sosa-Rodriguez 2013).

All the aforementioned efforts were focused on reducing carbon emission, through national efforts to mitigate the anthropogenic causes of climate change. In 2014, the Ministry of the Environment and Natural

Resources (SEMARNAT) released the *Special Climate Change Program 2014-2018,* an important step towards policy-level acknowledgement of potential adaptation needs and strategies (PECC 2014).

The PECC is one of the policy planning instruments developed after the General Climate Change Law (LGCC 2012) was passed in 2012. The PECC complements the previous existing mitigation policies and develops a set of adaptation strategies and guidelines to address the impact of climate change, reducing vulnerabilities of population, ecosystems and productive sector and increasing resiliency of strategic infrastructure.

The *Adaptation Plan* created by the PECC is divided into three stages. The first stage (2008 to 2012) assesses the country's vulnerability to climate change and conducts an economic evaluation of priority measures. The second stage (2013 to 2030) focuses on strengthening adaptation capacities, and the third stage (2030 to 2050) is designed to consolidate the capacities already established in stages one and two. The aim of the *Adaptation Plan* has specific reference to infrastructure:

> "[Focus on how to] Reduce vulnerability of population and productive sectors and increase its resilience and the resistance of strategic infrastructure. The objective seeks to consolidate and modernize actions and instruments to reduce social vulnerability, favouring prevention and risk management over disaster reconstruction." *PECC 2014-2018 pg.33*

The *National Climate Change Strategy* launched in 2013 by the Mexican Federal Government (NCCS 2013), also includes the importance of adapting infrastructure to future impacts of climate change. The document reinforces the need to incorporate climate change criteria into the planning and building of new strategic infrastructure (such as communications, transportation, and energy). Adaptation is highlighted as best being achieved at the local level; the design of measures to be developed will depend on the region and context of implementation. The document encourages local and regional governments to follow a preventive approach, where adaptation is prioritized based on investments that reduce vulnerability, in contrast to measures that merely address damages once they have occurred (NCCS 2013).

Based on this review of current policy approaches towards addressing climate change in Mexico, this chapter seeks to provide guidance for road adaptation that aligns with the current call by both the *National Climate Change Strategy* and the *Special Program for Climate Change*. This study presents an innovative approach for road infrastructure assessment and proactive adaptation strategies using climate modelling and future life-cycle analysis of impacts. Specifically, this chapter presents a first estimate of cost projections due to future climate impacts for the primary road systems and reveals vulnerabilities due to the projected weather changes.

4.3 METHODOLOGY

The methodology for this study uses a four-step process. First, a range of future climate scenarios are identified for Mexico. Second, the impact of each model on the existing road infrastructure is evaluated. In the third step, the costs are determined based upon the impact of climate change for each scenario using the IPSS system. Finally, these costs are summarized to provide useful information for planning the road infrastructure to withstand the future environment and changes in climate.

The results of this study are obtained using the *Infrastructure Planning Support System* (IPSS). This tool combines both quantitative and qualitative methods of analysis to develop the projected total fiscal cost of climate change impacts on road infrastructure. Additional capabilities that were not utilized in this study include assessment of building infrastructure, social impacts, environmental considerations, and analysis of future growth scenarios (Chinowsky et al. 2014a; Schweikert et al. 2014a). This study focuses on the quantitative aspects of modelling, which results in outputs to compare the total fiscal cost of the impact of climate change scenarios on the state road infrastructure. These comparisons are accomplished using technical and engineering research incorporated into IPSS to evaluate the impact of climate change and the consequents cost on the transport infrastructure(Schweikert et al. 2014c).

IPSS performs its climate impact analysis in three steps. First, IPSS determines the projected climate change on the specific region of study. As a default it uses CMIP 3 or CMIP 5 (*Coupled Model Intercomparison*

Project Phase 3 and 5) climate models approved by the Intergovernmental Panel for Climate Change 4th and 5th Assessment Reports, respectively (IPCC 2007, 2013). The flexibility of IPSS during this step leaves room for any climate model data with region-specific climate projections to be added. The projected climate values are then compared with historical climate trends to obtain the future changes. This study used two climate variables: maximum average monthly temperature and maximum monthly cumulative precipitation. Projected changes in these variables were mapped at the Climate Research Unit (CRU) grid level, a global map of approximately 0.5° resolution grid. The climate change projections utilized in this study were analyzed with data from 22 General Circulation Models (GCMs) approved by the IPCC. These data include the available A1, A1B and B1 projections for each GCM, representing different scenarios of future developments in technology and population growth, described in the IPCC AR4 report (IPCC 2007 p. 200). In total 54 scenarios are used in this study. Each model contains projected changes in temperature and precipitation that represent a range of potential climate futures.

The second step of the process is to evaluate the impact of the future climate variations on the infrastructure. Material-specific stress-response equations and materials information are used to identify incurred damage to infrastructure by each climate variable. These equations have been previously published and greater detail can be found in: (Chinowsky and Arndt 2012; Chinowsky et al. 2012b). Once future projected damage is determined, the third step of IPSS is to quantify this damage according to relevant construction and maintenance costs.

The third step utilizes two metrics to evaluate climate change impacts: *total fiscal Cost*, which is an economic measurement of the impact of climate change; and *opportunity Cost*. Opportunity cost is a metric adopted by the authors to represent the number of kilometers of new, secondary paved road inventory that could be built with the money spent on repairing the climate change damages, relative to existing paved road infrastructure (Chinowsky et al. 2011). This metric is particularly applicable when comparing impacts between different regions, as it provides a relative cost. Particularly, the opportunity cost can be used to identify the most vulnerable areas in terms of damage to infrastructure even if two areas have vastly differing inventories of road infrastructure and therefore cannot be compared on a fiscal cost basis.

IPSS provides these metrics annually for 2015-2050 for each of the climate models used in the analysis. In order to make this data more useful for transportation planners, summary costs are used to convey results. The total cumulative cost (for 2015-2050) and the decadal average cost are used. Generally, because 54 separate CMIP3 models were used in this study, only the results from three models—representing the 5th, 50th and 95th percentiles—were used. These represent the lower, median, and upper projection of damage models. Additionally, it presents results of an analysis using all 54 climate models and presents an approach to understand risk and uncertainties.

These metrics are used to provide a picture of the impact of climate change and the specific vulnerabilities of the road infrastructure in Mexico. One of the reasons why Mexico has been chosen for this study case is its particular geographic location that gives Mexico one of the most diverse climate systems in the world. Most climate models suggest serious consequences of climate change in Mexico, with a general shift to warmer and drier condition.

Mexico has a total length of more than 377,000 kilometers of roads infrastructure, with 38% of them paved. The roads in Mexico are managed by different entities; the federal government, the State governments and a portion of them are privately managed through concession contracts (SCT 2014).

For the study only the primary road infrastructure has been modelled. This includes a portion of the total paved road inventory in each of the states summing to a total of 23,000 kilometers of primary paved road analyzed corresponding to a 15% of the total paved inventory of Mexico.

4.4 RESULTS

The results have been divided into three sections. In the first section, values of the projected climate change in Mexico are presented for the models used in this study. In the second section, the total fiscal costs, and opportunity costs are summarized and presented as a useful metric to identify vulnerabilities of the road infrastructure. Finally, the third section presents and discusses the risk and uncertainty associated with each of these costs.

4.4.1 PROJECTED CLIMATE CHANGE IN MEXICO

Table 4.1 summarizes the climate change impacts from low severity and high severity climate scenarios, represented as the 5th and 95th percentile from the ensemble of 54 CMIP3 models. The data is presented as a regional average in 5 regions of Mexico, North East, North West, Central, South East (Peninsula) and South West. The changes are projected for a decadal average for 2040-2050.

The models are consistent in predicting a general warming on all the regions of the country. The increase on the average temperature for the warmer month ranges from 1.2-3.7 degrees Celsius in all the regions, with lower warming in the Northwest, and a higher increase in the Northeast and Central regions. The precipitation models have a greater variance, with some predicting drier conditions, while a few predict increases in precipitation. The North East will see a smaller change in precipitation patterns while the Central Region is projected to have greater changes that will likely result in a drier future environment.

Table 4.1: Regional projected climate change by 2050. Projected climate by 5th and 95th percentile, equivalent at low and high severity climate change.

Climate Change 2040 - 2050	**Temp. Change (Celsius)**		**Precip. Change (mm)**	
	5th	95th	5th	95th
North East	1.4	3.8	-20	17
North West	1.4	2.7	-12	14
Central	1.5	2.9	-31	30
Península	1.3	2.7	-17	1

South West	1.2	2.5	-35	-3

4.4.2 VULNERABILITY OF MEXICO PRIMARY ROADS

Road infrastructure vulnerabilities to climate change are presented and summarized in Table 4.2. These vulnerability values represent the cumulative impact from 2015-2050. The impacts displayed in Table 4.2 are shown by two climate projections, the 5th and the 95th percentile models, representing low and high impact models. Columns 3 and 4 are the projected incremental total fiscal cost of maintenance and repair necessary to maintain the functionality of roads during their lifespan when projected climate changes cause damages. Columns 7 and 8 the opportunity cost for each State.

Table 4.2: Vulnerability of Primary Roads by federal states. Cumulative impact on the period 2015-2050. Vulnerability shown by the 5th and 95th percentile model equivalent at low and high severity climate change.

Cumulative 2015-2050		**Cost (USD M)**		**Opportunity Cost**	
State	Kilometers of Primary Road	5th	95th	5th	95th
Aguascalientes	184	11.1	30.3	6.2%	17.0%
Baja California	1,103	14.0	163.6	1.3%	15.3%
Baja California Sur	723	9.5	146.9	1.4%	21.0%
Campeche	518	35.4	242.7	7.1%	48.4%
Chiapas	758	13.1	108.9	1.8%	14.8%
Chihuahua	55	3.4	17.6	6.5%	33.1%

Coahuila	30	15.5	41.6	54.0%	145.1%
Colima	164	0.1	3.3	0.1%	2.1%
Distrito Federal	131	0.2	0.2	0.2%	0.2%
Durango	392	39.9	126.7	10.5%	33.4%
Guanajuato	850	42.5	165.1	5.2%	20.1%
Guerrero	1,195	103.5	269.9	8.9%	23.3%
Hidalgo	672	16.5	80.8	2.5%	12.4%
Jalisco	1,696	67.6	236.1	4.1%	14.4%
Michoacán	1,654	46.0	190.8	2.9%	11.9%
Morelos	226	12.7	30.8	5.8%	14.1%
México	863	8.5	29.1	1.0%	3.5%
Nayarit	493	4.4	42.4	0.9%	8.9%
Nuevo León	411	66.1	184.6	16.6%	46.3%
Oaxaca	989	56.8	139.8	5.9%	14.6%
Puebla	1,050	27.4	73.8	2.7%	7.3%
Querétaro	344	6.2	37.7	1.9%	11.3%
Quintana Roo	534	20.6	225.8	4.0%	43.6%
San Luis Potosí	1,298	183.7	525.6	14.6%	41.8%
Sinaloa	420	16.1	61.1	4.0%	15.0%
Sonora	1,907	15.9	129.2	0.9%	7.0%

Tabasco	228	17.3	84.2	7.8%	38.2%
Tamaulipas	1,400	179.8	580.3	13.3%	42.8%
Tlaxcala	161	1.9	0.5	1.2%	0.3%
Veracruz	1,268	69.7	267.9	5.7%	21.8%
Yucatán	480	40.2	202.6	8.6%	43.5%
Zacatecas	820	166.9	421.2	21.0%	53.0%

This study projects a total fiscal cost for Mexico of \$1.3 – 4.8 billion USD cumulative cost for 2015-2050 time period. For the lower impact models (5th percentile) the costs range from \$0.2 million USD in some states, including Colima and Distrito Federal, to as high as \$100 million USD in San Luis Potosi and Tamaulipas. For the 95th percentile model, these costs range from \$0.2 million USD in Distrito Federal and Tlaxcala and up to \$550 million USD in San Luis Potosi or Tamaulipas. The higher cost in San Luis Potosi and Tamaulipas comes from having a large road inventory and being severely impacted by climate change. These results show on the map in Figure 4.1 reveals that two of the most impacted states, San Luis Potosi and Tamaulipas are located in the Northeastern part of the country.

Figure 4.1: Total fiscal cost mapped in USD Millions at states level for the 95th percentile models.

The other metric, opportunity cost, displays these results in a metric for making comparisons between regions. As detailed in the methodology section, opportunity cost is a variable relative to the amount of road inventory. It represents the amount of new road that could be built if money was not diverted to repair roads damaged buy climate change. The geographic variance is high, with states as Nayarit or Sonora with impact below 1%, while analysis Zacatecas and Coahuila shows more than 20% for the least severe climate change model (5th percentile). For the highest impact models (95th percentile), opportunity cost ranges from less than 1% in Tlaxcala and Distrito Federal to more than 50% in Zacatecas and more than 100% in Coahuila.

The first metrics could be of special interest for state and local road agencies as they show information on how local budget will be increased and modified in the future due to climate change. Additionally, opportunity cost could help making national level comparisons of states to identify regions in the country where climate change will have a higher impact. The results of this study indicate that greater attention and funding is needed in states like Zacatecas or Coahuila as they are two of the states that will suffer the most from future climate change impact.

The results for the opportunity cost displayed in Table 4.2 are compared on the maps in Figure 4.2. The map on the left is the opportunity cost for the 5th percentile model while the map in the right is the 95th percentile. Both maps use the same scale from 0% opportunity cost (no impact from climate change) to over 50%. In addition to the information from Table 4.2, Figure 4.2 also shows the geographic clustering of the most vulnerable areas. States in the Northeast and the peninsula are projected to be the most vulnerable. When looking at the least severe climate projection map (5th percentile) the magnitude of the impact is lower but a similar conclusion can be drawn based on location: the most vulnerable infrastructure to climate change is located in the Northeastern states.

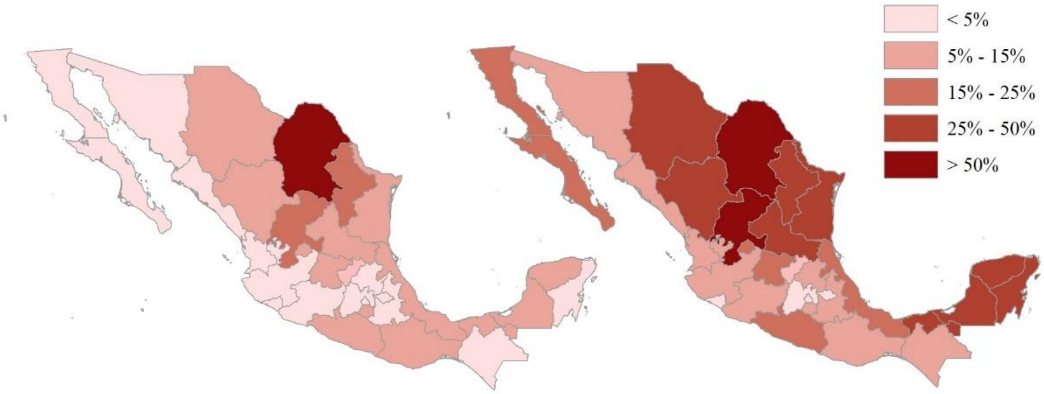


Figure 4.2: Opportunity Cost mapped at states level for the 5th (left) and 95th (right) percentile models.

4.4.3 RISK AND UNCERTAINTY ON TRANSPORT PLANNING DECISIONS

Planning for the future environment has a notable challenge associated with the uncertainty of climate change models (Pittock et al. 2001; Schneider 2001). Climate modelers agree upon the uncertainty of their own models, which are built based on a lot of assumptions and unpredictable variables. It is therefore of great importance that planner and decision makers understand the uncertainty and risk associated with each of their decisions (Dessai et al. 2007; Jones 2000; Mastrandrea et al. 2010). To provide a more holistic picture of the spread of potential impacts projected by the 54 CMIP3 climate scenarios used in this study, box plots are graphically detail the range of outcomes.

In the previous sections only two possible outcome were discussed, the projection representing the least severe change (5th percentile) and the most dramatic change (represented by 95th percentile results). In between these two outcomes there lies a large range of different potential outcomes. It should be noted that each of these 54 scenarios is equally likely to occur (Dessai et al. 2007).

Figure 4.3 presents box plot graphics of both total fiscal cost and opportunity cost. Because of the large amount of data, only information for five of the 31 states is shown. These five states are the ones with higher opportunity cost across all Mexican states. The middle line represents the median value, the box limits are the 25 and 75th percentile results, and the whiskers reach maximum and minimum values.

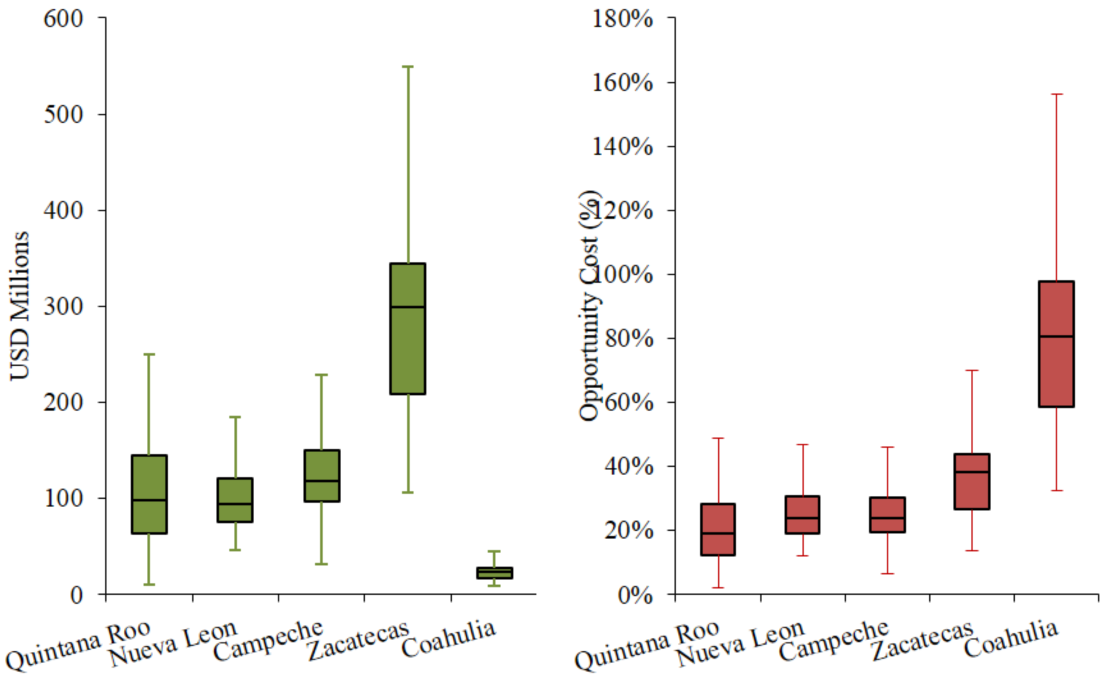


Figure 4.3: Box and whiskers representation of uncertainty of total fiscal cost (right) and opportunity cost (left) for five states. The whiskers show maximum and minimum values, the limits of the box are the 25 and 75th percentile and the middle line represents the median value.

The graph of total fiscal cost on the left on Figure 4.3 shows the variability and uncertainty of the results from the impacts of climate change. The first three States, Quintana Roo, Nueva Leon and Campeche, all have a median cost of around $100 million USD. However, in the peninsula states of Quintana Roo and Campeche, the total fiscal cost varies from several million dollars to more than $250 million USD; more than twice the median cost. Conversely, Nueva Leon has a similar median cost, but less variability. Zacatecas has one of the largest costs from climate change and also shows a huge variability, with a minimum impact around $100 million USD and a maximum impact that almost reaches $600 million USD.

Similar conclusions can be extracted from the graph on the right. The opportunity cost shows larger variability on the two states in the Peninsula and less uncertainty in Nueva Leon. Coahuila shows the largest relative impact of climate change. However, Coahuila's relative impact is highly uncertain, as shown in the boxplot graphic, creating an additional planning challenge.

4.5 LIMITATIONS

This study is designed as a high-level assessment of the vulnerability—in terms of increased maintenance and repairs—of the existing road networks in Mexico to the impacts of climate change through 2050. There are several limitations to the current approach. A main source of uncertainty comes from the data used for analysis. Inherently, future climate modelling is uncertain (IPCC 2013 p. 20). However, the authors seek to reduce this risk as much as possible by utilizing all available models that are approved by the IPCC to provide a range of analysis for future climate changes. These models are sorted to provide a small representative sample, in the form of lower and higher end cost projection models (5th and 95th percentiles, respectively).

A key limitation of the modelling approach used in this study is the assumption of 'perfect foresight' for projecting the costs of climate damages and repairs. The approach used in this study posits that the repair is done at the time when the damage occurs, assuming that this will account for all climate-related damages projected that year. It is highly unlikely that the projected changes will occur exactly as modelled. However, without better modelling information, this approach presents one approach to understanding climate impacts.

A final key limitation of this study is that analysis was limited to looking at incremental changes in climate (precipitation and temperature) on existing road infrastructure. It therefore does not account for sea level rise, flooding, other extreme events, or growth of infrastructure. While all of these are within the capabilities of the IPSS tool to analyze, the scope of this study was limited by the available input data and therefore focuses on outputs from the climate models including precipitation and temperature.

4.6 CONCLUSION

This study quantitatively modelled the potential impacts of climate change on the primary road infrastructure networks in Mexico. The focus of this study was the long-term changes in precipitation and temperature that affect the engineering design criteria for roads. Changes in precipitation and temperature over time cause damages to the integrity of the road network. Such damages can greatly increase the financial burden associated with maintenance and repairs and can reduce the usefulness of the road due to increased construction periods. Due to limitations in available data, this study does not account for important climate change related factors including sea level rise, flooding, and other extreme events.

The metrics used in this study are total fiscal cost of damages and repairs between 2015 and 2050, and a metric adapted by the authors called opportunity cost. The total fiscal cost metric relates the total damage to the roads in financial dollars while the opportunity cost presents a relative metric for more accurately comparing areas with different road inventories.

These findings show that the North East region of Mexico, including the San Luis Potosi and Tamaulipas states, are highly vulnerable to climate change in terms of both financial costs and relative impacts, with a projected increase in total fiscal cost between 2015 and 2050 that ranges from 184-526 million USD and 180-580 million USD respectively. The state of Coahuila is particularly vulnerable compared to its neighbors, with an opportunity cost that ranges from 54% - 145%.

This study represents an important first step in moving climate change rhetoric and political commitments in Mexico toward sustainable action. The quantitative modelling used in this chapter highlights the importance of considering climate change in present day financial budgets. A logical next step in this research is to explore the opportunities for proactive adaptation investment strategies to reduce the damages over the life-cycle of the road.

Planning our roads and infrastructure to the current and future impacts of climate change is imperative for road infrastructure that forms the backbone of many fundamental economic and social community functions. Additionally, proactive investments to reduce future damages can save critical funds by preventing wasted money on repairs that could have been avoided.

Chapter 5 EXPANDING BENEFIT-COST ANALYSIS

Chapter 5 This chapter is the manuscript of a journal paper submitted at Transport Research Record on 07/31/2015 and currently under Review. It presents the metric of "regret" as a viable option to be incorporated into cost-benefit analysis in order to deal with the severe uncertainty of climate models. It uses a real future investment to upgrade a major road corridor in Kenya and South Sudan that is part of the Programme for Infrastructure Development in Africa (PIDA) to illustrate the methodology. It concludes that unplanned expenditure could be minimized if the traditional cost-benefit analysis is expanded to include a regret analysis as proposed in this chapter

5.1 INTRODUCTION

The *Northern Multimodal Corridor* is a critical infrastructure corridor in Eastern Africa. This transport corridor links the landlocked countries of Uganda, Rwanda, Burundi, South Sudan and the eastern part of Democratic Republic of Congo with Kenya's maritime port in Mombasa (African Development Bank et al. 2011). These countries rely on the corridor to engage with overseas trade including imports and exports, which is vital to their economic development and growth. The Programme for Infrastructure Development in Africa (PIDA) has identified the Northern Multimodal Corridor as one of the top investment priorities and is thus designating more than a billion USD to modernize and upgrade the road network (African Union et al. 2012).

The PIDA project is led by the African Union Commission, in partnership with the African Development Bank and the UN Economic Commission for Africa. The Programme is a long-term infrastructure plan (2012-2040) that provides guidance to create a more cohesive and integrated system of infrastructure - including transport, ITC, water and energy - throughout the African Continent (African Union et al. 2012).

A focus of the PIDA plan is incorporating potential damage that climate change can cause within the African infrastructure system into the design and budgeting process. From this focus, a proactive adaptation approach is being considered on all new investments and projects (African Development Bank 2011; African Union 2014). This inclusion follows from demonstrations that incorporating climate change conditions into current decision-making improves the likelihood of creating a more sustainable infrastructure that then leads to more climate-resilient transportation systems (Meyer et al. 2010; Rowan et al. 2013).

In particular, studies have demonstrated that failing to incorporate climate change into the design of transport infrastructure can significantly increase life-cycle cost estimates and exacerbate vulnerabilities to climate stressors throughout the infrastructure lifespan (Erath et al. 2009; Venner and Zamurs 2012). In contrast, proactive adaptation can result in economic savings, usually from reducing the need for repair and maintenance due to using design standards that consider future climate estimates (Schweikert et al. 2014b, 2015).

However, a complex challenge while estimating the cost and benefits of adaptation strategies is the high level of uncertainty associated with climate change impacts (Dessai et al. 2007; Jones 2000). Climate scientists are unable to define with certainty what standards should be used while building infrastructure in order to secure their performance to future climate impacts (Lisø 2006). This uncertainty is a challenge for design engineers and decision-makers because it makes it difficult to understand the true magnitude of the problem. It creates additional complexity during the process of reaching agreement on the best adaptation strategy or policy, often leading to misinterpretations and misleading decisions (Fankhauser and Soare 2013; Pittock et al. 2001).

Within this complexity, there is an increasing agreement between researchers and practitioners that there is a need to move from traditional cost-benefit approaches to new costing methods while designing climate adaptation projects. At the same time, there is a recognized need to incorporate a full range of climate projections while calculating cost and benefits to properly reflect the uncertainty of the problem (Dessai et al. 2004; Fankhauser and Soare 2013; Hallegatte 2009; Watkiss et al. 2014).

This chapter presents a method to bridge this need for greater understanding of uncertainty in infrastructure design by expanding the traditional cost-benefit analysis for adaptation strategies to climate change. The method incorporates the deep uncertainty of climate projections into the decision process and introduces the concept of regret as a viable metric for incorporating into costing methods. The methodology is illustrated using data from the Northern Multimodal Corridor PIDA Project. The background section explores many traditional ways that decision-making theory deals with uncertainty and expands on how this theory has been updated to accommodate the uncertainty of climate change. This section is followed by the methodology. A portion of the Northern Multimodal Corridor has been selected to illustrate the methodology, in particular the part of the corridor that includes the countries of Kenya and South Sudan, the two largest components of this corridor. The Results section summarizes the findings on these two countries and discusses the implications for decision-makers and investment agencies. Finally the chapter finishes with a discussion of the limitations on the methodology and overall conclusions from the research.

5.2 BACKGROUND

In the past 10 years, there has arisen a need to standardize costing methods for climate adaptation projects. Globally, different institutions and agencies have produced several frameworks and guidelines to asses these projects. In Europe, several countries have produced individual reports that explore new methods for costing adaptation design alternatives. The Netherlands Environmental Assessment Agency published a policy report that identifies the benefits and costs of climate change (Hof et al. 2014). The German Federal Government through the German Federal Enterprise for International Cooperation, GIZ, published a framework in 2007 to assess adaptation project prioritization, similar to the one later developed by the UNFCCC. (GTZ 2007). Elsewhere, the Australian Government's Department of Energy released a framework for costing adaptation strategies based on Cost-Benefit Analysis and Net Present Value that states the importance of incorporating a full range of climate change models into their traditional costing methods (AECOM Australia 2012) .

With the objective of summarizing many of the different methodologies for assessing costs and benefits of climate change adaptation, the UNFCCC released a summary report based on chapters and workshops in different countries about costing climate change adaptation strategies. This report provides several case studies and lessons learned with the intent of providing governments and agencies with a holistic overview of the whole prioritization process (UNFCCC 2011).

As government entities have expanded their exploration of this area, there has been some work from researchers and academics to explore and expand traditional costing methods to incorporate climate change uncertainty. Most of these examples have focused either on sea level rise (Kirshen et al. 2012; Neumann et al. 2011; Tsvetanov and Shah 2013), flood protection (Su and Tung 2013), or water management projects such as dams or sewer systems (Nassopoulos et al. 2012).

Few of these studies have focused on transportation infrastructure. There has been some work focused on pavement performance, calculating the increase of maintenance and repair cost due to changes in temperature and precipitation patterns (Chinowsky et al. 2013a; Mallick et al. 2014; Mills et al. 2009). There have been some economic studies to address climate change vulnerability on bridges due to increased flooding and faster deterioration of bridges piles (Flint et al. 2014; Wright et al. 2012). Finally, a few large-scale costing exercises have studied a range of transportation infrastructure in the US, including paved and dirt roads and bridges, with numerous assumptions and simplifications and all of them compiled in the latest EPA CIRA report (EPA 2015).

Most of the afore-mentioned research on climate change adaptation costing analysis is limited to a small number of possible climate projections, all employing scenario-based analysis (Mills et al. 2009; Nassopoulos et al. 2012). Additional costing efforts have been based on the value of expected climate change projections (Kirshen et al. 2012; Mallick et al. 2014).

The difficulty in any of these efforts is balancing the need to understand the range of potential climate outcomes with the need to minimize information uncertainty in the decision-making process. One way of dealing with the large range of outcomes and the uncertainty associated with them is incorporating the concept of regret in the costing exercises (Dessai and Hulme 2007; Gupta and Rosenhead 1968). “Regret” - sometimes called *opportunistic loss*- has been a well-studied concept in decision-making theory, developed in the early 20st century and is defined as the difference between the best possible outcome and the given outcome (Neumann and Morgenstern 1944; Savage 1951). The use of regret has been successfully applied to climate change impact assessment (Dessai and Hulme 2007; Hallegatte 2009) and to decision-making for adaptation strategies especially in the context of water management (Brown et al. 2011; Lopez et al. 2014). However, there has not yet been an example of incorporating this term in transport infrastructure design.

This chapter presents the use of a regret analysis as one viable alternative to traditional cost-benefit approaches to deal with the uncertainty of climate change on transportation planning and design. The chapter uses the Kenya and South Sudan context within the Northern Multimodal Corridor as a specific example. The area covered in this partial corridor analysis is 2,850 of the total 5,165 kilometers, with 1,450 in Kenya and 1,400 in South Sudan.

5.3 METHODOLOGY

The research undertaken in this study uses 39 separate climate scenarios from the ensemble of CMIP5 approved by the IPCC 5th Assessment Report (IPCC 2013). These models are used to estimate the potential impact and financial regret on the infrastructure in the time period 2015-2050. The impacts are determined based on three climate factors: precipitation, temperature, and flooding. Proactive adaptation and reactive adaptation strategies are analyzed for each climate scenario by utilizing the impact and adaptation methodology from the IPSS tool (Schweikert et al. 2014c).Each scenario is analyzed individually over the entire road and time period. Additionally, a discussion of potential impacts is presented to illustrate the ramifications on the lifespan of potentially impacted roads, if no adaptation actions are taken.

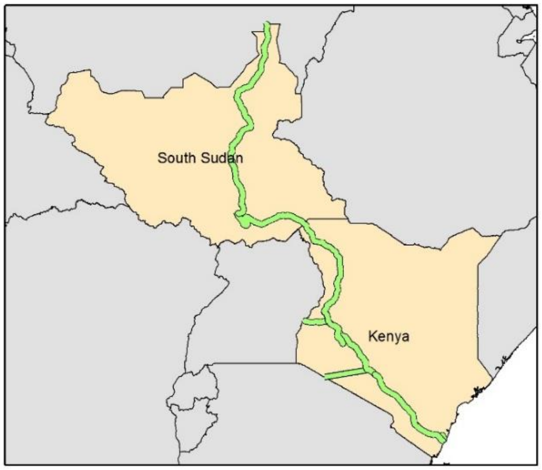


Figure 5.1: Northern Multimodal Corridor in South Sudan and Kenya

In this analysis, proactive adaptation refers to changing the design standard for new construction or rehabilitation operations based on projected climate impacts over the design lifespan of a road. Reactive adaptation refers to conducting additional maintenance to retain the intended design lifespan as climate impacts are incurred each year. This analysis approach makes particular sense in terms of the PIDA project, where the research and analysis is performed before construction begins; allowing proactive investment strategies in construction to be a viable option for the corridor. Finally, climate impacts refer to reductions in design lifespan that occur due to projected climate changes. In this case, the reductions in lifespan are allowed to occur and new construction does not include any changes to specifications. This case is included for completeness although studies have repeatedly demonstrated that this is the least viable option from a capital expenditure perspective (Schweikert et al. 2014b, 2015). This perspective is thus not included in the regret analysis.

The additional illustration provided in this summary is the potential regret that is introduced for each climate scenario at the country level in the Corridor Programme. For this analysis, the proactive adaptation and reactive adaptation numbers are calculated for each scenario using a discount rate of 3% to calculate present value costs. These values are then used to determine potential regret for each scenario. In summary, the method for determining this regret incorporates the following steps:

1. *Adaptation Costs*: For each climate stressor (precipitation, temperature, and flooding), a decision is made for adaptation for each climate scenario. This decision is based on the proactive and reactive adaptation cost projections for each scenario. Where proactive adaptation is projected to cumulatively cost less in financial terms when compared with the reactive strategy, proactive adaptation is taken. Otherwise, a reactive strategy is taken.
2. *Regret Costs*: Once the investment strategies for each climate are developed, a cross-impact matrix is developed to determine the potential regret costs for each stressor under each scenario. In this analysis, the potential regret for each of the scenarios is calculated by determining the regret if the "expected" scenario is compared against the occurrence of a different actual scenario. The amount of this regret is dependent on the strategy suggested in each of these scenarios and the projected adaptation and maintenance costs for each of the scenarios. The costs are separated into two categories: wasted resources that represent potential overspending and unexpected impacts, which are costs incurred from underspending. The conclusion of this step results in a regret cost matrix for each stressor.
3. *Regret Percentage*: Once the regret costs are determined, a second set of matrices are developed that provide an indication of the percent overspending or underspending that may occur for each of the projected strategy and climate interactions. Once again, these percentages provide an indication of the degree of regret that may occur for each scenario.
4. *Total Regret*: The final step of the matrix process is combining the matrices into a total regret matrix. In this process, the cost matrices are added together to provide a total regret for each scenario combination in the matrix. Concurrently, the total cost is compared to the expected cost for each scenario combination. In this manner, a percentage of overspending or underspending is

determined based on the strategy anticipated for each of the individual stressors and the total anticipated regret for each scenario.

5. *Regret Summary*: For each climate scenario, the maximum overspending and the maximum underspending are determined to provide a visual regret scenario potential for each climate scenario.

From these calculations, the decision maker obtains three key information points for each climate scenario based on the concept of regret: the total potential regret variance in terms of present value costs, the total potential overspending percentage, and the total potential underspending percentage. The appropriate adaptation strategy can then be selected by an individual decision maker depending on the chosen criteria.

The following section presents the results for the two countries in the Corridor Programme, Kenya and South Sudan, as an illustration of the regret analysis and the five metrics presented above.

5.4 RESULTS

Climate impacts reduce the projected lifespan of a road. Changes in precipitation, temperature, and/or flooding each have a negative effect on the lifespan. The potential maintenance savings (or extended lifespan) is considered in the adaptation analysis in the sections to follow.

For this analysis, each of the 39 climate scenarios result in a projected reduction in life over the geographic area in which the corridor is planned to be built. This reduction is based on specific impacts from each of the three stressors. Figure 5.2 illustrates the distribution of projected final lifespans that result from climate change impacts. The numbers indicate the potential average lifespan of the roads included in the project compared to an original design lifespan of 20 years. In this analysis, projected lifespan is the maximum lifespan that can be achieved during the period 2015-2050.

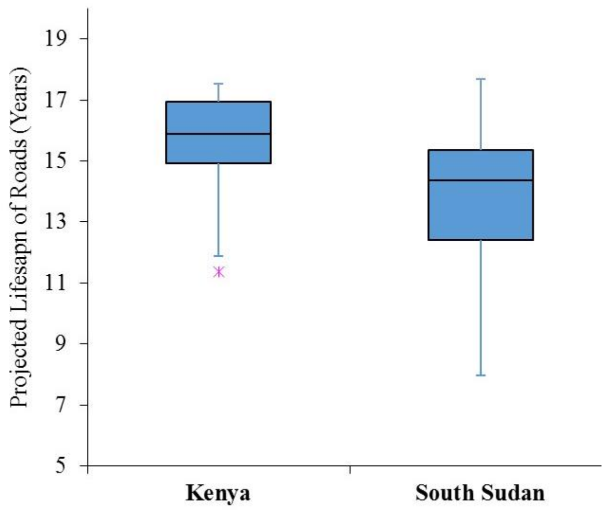


Figure 5.2: Average lifespan of roads from impacts of projected climate change with no adaptations taken. Original lifespan is 20 years.

As illustrated, South Sudan has a greater variation in average lifespan than that seen for Kenya, while as seen below, Kenya has greater costs predicted by most models. Additionally, the lower bounds of the lifespan average for South Sudan is lower than that for Kenya where the 25th percentile for South Sudan being 12.5 years and 15 years for Kenya. Additionally, the median value for South Sudan is lower, 14.5 years, than the median of 16 years for Kenya.

The result of this reduction will be a need for a greater number of road rehabilitations during an overall study period. For example, over a 50 year period of study, the standard number of road lifecycles will be 2.5 with a base of a 20-year lifespan. However, using the 15.5 year lifespan of South Sudan, this increases to 3.2 cycles. Similarly, for Kenya, this increases to 3.1 cycles. This approach has been routinely dismissed as a non-viable option for transportation planners, because maintenance, rebuilding, and new construction schedules are dependent on scheduling plans that often stretch 20 years or more for each planning agency. Disrupting this schedule would have economic impacts for local jurisdictions, planning impacts for transportation agencies, and budgetary impacts for local and regional government agencies.

5.4.1 TOTAL COSTS PERSPECTIVE

The next lens on the potential climate impact on the corridor countries in this example is the perspective of total costs. Here we examine the total costs of a proactive adaptation approach versus a reactive adaptation approach over the length of the corridor within each country. The proactive approach is dependent on perfect foresight, since proactive adaptation depends on knowing the potential climate impacts over the lifespan of the road. As illustrated in Table 5.1, looking at the present value of cumulative costs through 2050 reveals that variance exists between the stressors in terms of potential costs that will be absorbed if the proactive or reactive adaptation strategy is adopted. Of particular note in this summary is the difference in variance between the proactive and reactive adaptation strategies, and the difference in scale of potential costs that can be anticipated between the two strategies.

As illustrated, Kenya sees an overall advantage in taking a proactive approach to adaptation for precipitation and temperature, but sees an overall advantage to taking a reactive approach to adapting to potential flood impacts. South Sudan sees a similar benefit for precipitation and temperature. However, South Sudan also sees an advantage to proactive adaptation for potential flooding impacts.

Table 5.1: Summary table of costs for Kenya and South Sudan broken down by adaptation strategy and stressor

Strategy	**Country**	**Length (KM)**	**Completion**	**Precip**			**Temp**			**Flooding**			**Total**		
				Cumulative Costs Discounted at 3% Through 2050											
				5th	**50th**	**95th**	**5th**	**50th**	**95th**	**5th**	**50th**	**95th**	**5th**	**50th**	**95th**
Proactive Adaptation	Kenya	1480	2020	$ 36.4	$ 50.0	$105.1	$ 4.9	$ 6.3	$ 8.1	$ 36.7	$ 40.4	$ 44.8	$ 78.0	$ 96.7	$158.0
	South Sudan	1376	2030	$ 27.8	$ 33.4	$ 57.1	$ 0.9	$ 1.0	$ 2.3	$ 22.5	$ 24.7	$ 26.5	$ 51.3	$ 59.0	$ 85.9
Reactive Adaptation	Kenya	1480	2020	$ 50.7	$ 69.0	$239.9	$ 12.0	$ 36.5	$ 65.7	$ 10.5	$ 15.2	$ 42.6	$ 73.2	$120.7	$348.1
	South Sudan	1376	2030	$ 77.6	$ 99.3	$297.9	$ 17.3	$ 32.8	$ 79.2	$ 31.8	$ 51.5	$115.2	$126.8	$183.6	$492.3

5.4.2 COST DIVISION BETWEEN STRESSORS

The separation of climate impacts into precipitation, temperature, and flooding allows a further refinement of the adaptation strategies adopted for each climate scenario. Specifically, an optimal adaptation approach can be determined by determining whether a proactive or reactive strategy should be selected for each stressor within each climate scenario. As illustrated in Figure 5.3, the proactive and reactive strategies result in different perspectives for each stressor.

For precipitation, a significant reduction in variance is seen for both South Sudan and Kenya. Similarly, the individual percentiles are reduced for each country. Temperature also sees a reduction in these factors, but not to the extent that is observed for precipitation. Finally, flooding impacts are reduced for South Sudan, but to a much lower degree in Kenya. However, it should be noted that Kenya sees a reduction in variance from proactive adaptation which will assist in the final decision making process.

Overall, Figure 5.3 indicates that precipitation and temperature benefit from a proactive adaptation strategy. However, flooding is dependent on the country being studied. In Kenya, proactive adaptation for flooding provides a benefit in terms of reducing the variance, but the additional cost required to achieve this reduction in variance means that proactive adaptation may not be beneficial. In contrast, South Sudan sees a notable reduction in variance, as well as a reduction in the median and central cost estimates.

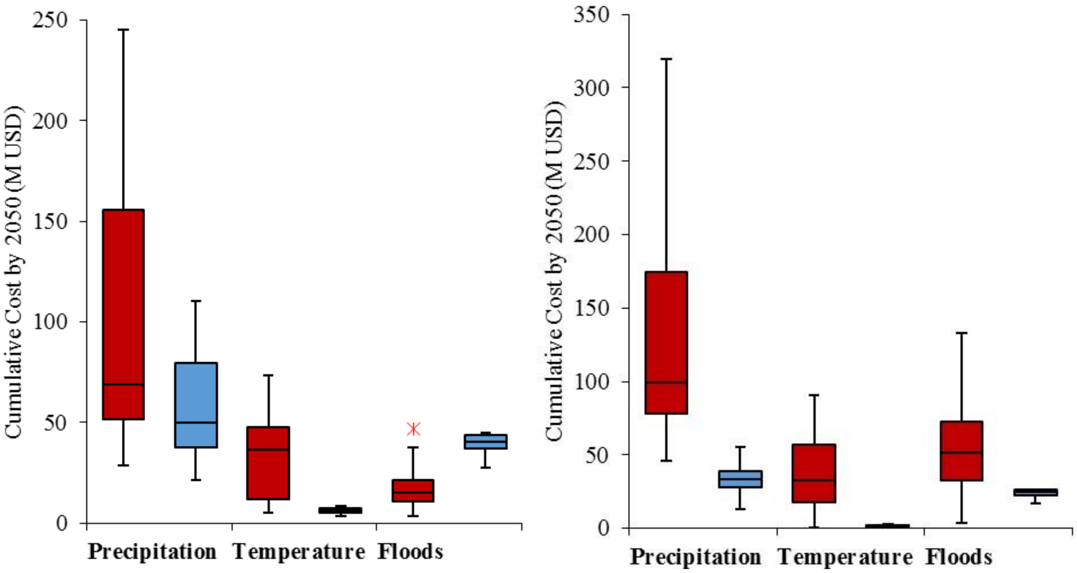
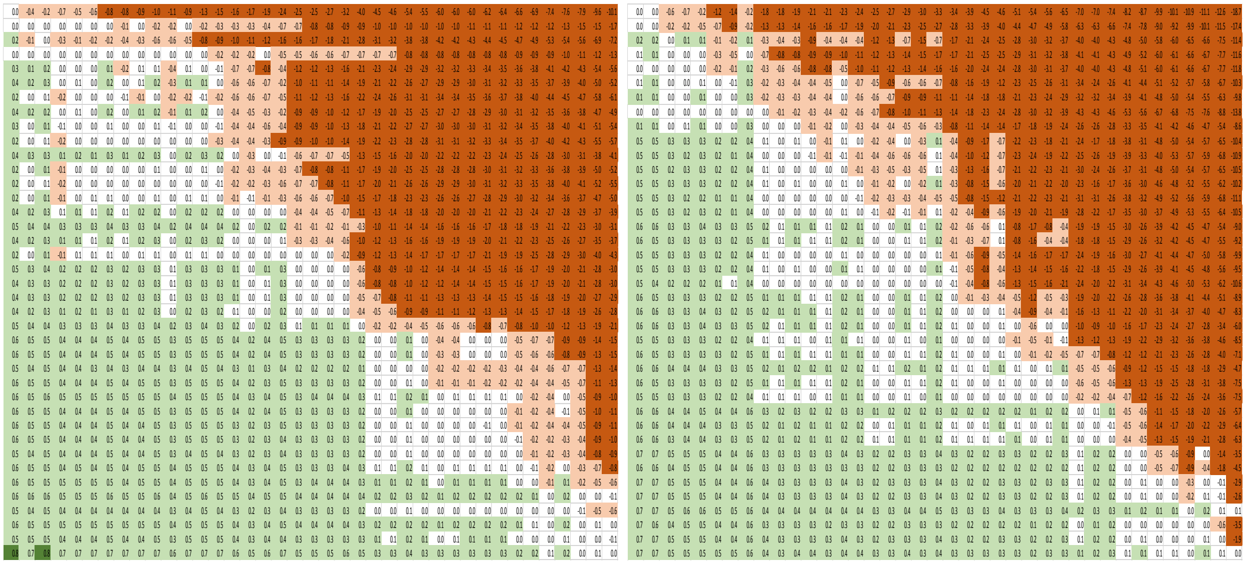


Figure 5.3: Cumulative Costs in Millions – Reactive Maintenance Strategy in Red and Proactive Adaptation Strategy in Blue – Kenya (left) and South Sudan (right)

5.4.3 REGRET ANALYSIS

Based on the total costs obtained for each strategy in each stressor, the results were then analyzed from a regret perspective. This analysis utilizes the methodology introduced in the previous section. The results described in this section provide both an overall regret and a breakdown of the overall into potential overspending (wasted resources) and underspending (unexpected impacts).

As a basis for conducting the regret analysis, the three individual regret matrices were combined into a single total regret matrix (Figure 5.4). This matrix represents the optimal adaptation strategy for each stressor combined into a total regret percentage. Each of the cells in the matrix is the regret value between a chosen model (columns) and the model that may occur (rows). The regret matrix has a diagonal full of zeros, as there is no regret if the model chosen is the same as the one that happens. In this illustration, the dark orange represents combinations where underspending will exceed 80%. The light orange is underspending from 10-80%. The green represents overspending from 10 - 80%. In this case, almost no overspending will exceed 80% so a minimum of dark green exists on the matrix.



0.0	-0.4	-0.2	-0.7	-0.5	-0.6	-0.8	-0.8	-0.9	-1.0	-1.1	-0.9	-1.3	-1.5	-1.6	-1.7	-1.9	-2.4	-2.5	-2.5	-2.7	-3.2	-4.0	-4.5	-4.6	-5.4	-5.5	-6.0	-6.0	-6.0	-6.2	-6.4	-6.6	-6.9	-7.4	-7.6	-7.9	-9.6	-10.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.2	-0.2	0.0	-0.2	-0.3	-0.3	-0.3	-0.4	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1	-1.1	-1.2	-1.2	-1.2	-1.3	-1.5	-1.5	-1.7
0.2	-0.1	0.0	-0.3	-0.1	-0.2	-0.2	-0.4	-0.3	-0.6	-0.6	-0.5	-0.8	-0.9	-1.0	-1.1	-1.2	-1.6	-1.6	-1.7	-1.8	-2.1	-2.8	-3.1	-3.2	-3.8	-3.8	-4.2	-4.2	-4.3	-4.4	-4.5	-4.7	-4.9	-5.3	-5.4	-5.6	-6.9	-7.2
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.2	0.0	-0.5	-0.5	-0.6	-0.6	-0.7	-0.7	-0.7	-0.7	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.9	-0.9	-0.9	-1.0	-1.1	-1.2	-1.3
0.3	0.1	0.2	0.0	0.0	0.0	0.1	-0.2	0.1	0.1	-0.4	0.1	0.0	-0.1	-0.7	-0.7	-0.8	-0.4	-1.2	-1.2	-1.3	-1.6	-2.1	-2.3	-2.4	-2.9	-2.9	-3.2	-3.2	-3.3	-3.4	-3.5	-3.6	-3.8	-4.1	-4.2	-4.3	-5.4	-5.6
0.4	0.2	0.3	0.0	0.1	0.0	0.2	0.0	0.1	0.2	-0.3	0.1	0.1	0.0	-0.6	-0.6	-0.7	-0.2	-1.0	-1.1	-1.1	-1.4	-1.9	-2.1	-2.2	-2.6	-2.7	-2.9	-2.9	-3.0	-3.1	-3.2	-3.3	-3.5	-3.7	-3.9	-4.0	-5.0	-5.2
0.2	0.0	0.1	-0.2	0.0	0.0	0.0	-0.1	-0.1	0.0	-0.2	-0.2	-0.1	-0.2	-0.6	-0.6	-0.7	-0.5	-1.1	-1.2	-1.3	-1.6	-2.2	-2.4	-2.6	-3.1	-3.1	-3.4	-3.4	-3.5	-3.6	-3.7	-3.8	-4.0	-4.4	-4.5	-4.7	-5.8	-6.1
0.4	0.2	0.2	0.0	0.1	0.0	0.2	0.0	0.1	0.2	-0.1	0.1	0.2	0.0	-0.4	-0.5	-0.3	-0.2	-0.9	-0.9	-1.0	-1.2	-1.7	-1.9	-2.0	-2.5	-2.5	-2.7	-2.7	-2.8	-2.9	-3.0	-3.1	-3.2	-3.5	-3.6	-3.8	-4.7	-4.9
0.3	0.0	0.1	-0.1	0.0	0.0	0.1	0.0	0.0	0.1	-0.1	0.0	0.0	-0.1	-0.4	-0.4	-0.6	-0.4	-0.9	-0.9	-1.0	-1.3	-1.8	-2.1	-2.2	-2.7	-2.7	-3.0	-3.0	-3.0	-3.1	-3.2	-3.4	-3.5	-3.8	-4.0	-4.1	-5.1	-5.4
0.2	0.0	0.1	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	-0.4	-0.4	-0.3	-0.9	-0.9	-1.0	-1.0	-1.4	-1.9	-2.2	-2.3	-2.8	-2.8	-3.1	-3.1	-3.2	-3.3	-3.4	-3.5	-3.7	-4.0	-4.2	-4.3	-5.5	-5.7
0.4	0.3	0.3	0.1	0.2	0.1	0.3	0.1	0.2	0.3	0.0	0.2	0.3	0.2	0.0	-0.3	0.0	-0.1	-0.6	-0.7	-0.7	-0.5	-1.3	-1.5	-1.6	-2.0	-2.0	-2.2	-2.2	-2.2	-2.3	-2.4	-2.5	-2.6	-2.8	-3.0	-3.1	-3.8	-4.1
0.2	0.0	0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	-0.2	-0.3	-0.4	-0.3	-0.7	-0.8	-0.8	-1.1	-1.7	-1.9	-2.0	-2.5	-2.5	-2.8	-2.8	-2.8	-3.0	-3.1	-3.2	-3.3	-3.6	-3.8	-3.9	-5.0	-5.2
0.2	0.0	0.1	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.2	-0.3	-0.6	-0.7	-0.7	-0.8	-1.1	-1.7	-2.0	-2.1	-2.6	-2.6	-2.9	-2.9	-3.0	-3.1	-3.2	-3.3	-3.5	-3.8	-4.0	-4.1	-5.2	-5.5
0.2	0.0	0.1	-0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	-0.1	-0.1	-0.1	-0.3	-0.6	-0.6	-0.7	-1.0	-1.5	-1.7	-1.8	-2.3	-2.3	-2.6	-2.6	-2.7	-2.8	-2.9	-3.0	-3.2	-3.4	-3.6	-3.7	-4.7	-5.0
0.4	0.2	0.3	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0	-0.4	-0.4	-0.5	-0.7	-1.1	-1.3	-1.4	-1.8	-1.8	-2.0	-2.0	-2.0	-2.1	-2.2	-2.3	-2.4	-2.7	-2.8	-2.9	-3.7	-3.9
0.5	0.4	0.4	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0.2	0.4	0.4	0.4	0.2	0.0	0.2	0.2	-0.1	-0.1	-0.2	-0.1	-0.3	-1.0	-1.1	-1.4	-1.4	-1.6	-1.6	-1.6	-1.7	-1.8	-1.8	-1.9	-2.1	-2.2	-2.3	-3.0	-3.1
0.4	0.2	0.3	0.1	0.1	0.1	0.2	0.1	0.2	0.3	0.0	0.2	0.3	0.2	0.0	0.0	0.0	0.1	-0.3	-0.3	-0.4	-0.6	-1.0	-1.2	-1.3	-1.6	-1.6	-1.9	-1.9	-1.9	-2.0	-2.1	-2.2	-2.3	-2.5	-2.6	-2.7	-3.5	-3.7
0.2	0.0	0.1	-0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-0.9	-1.2	-1.3	-1.4	-1.7	-1.7	-1.7	-1.7	-2.1	-1.9	-1.9	-2.5	-2.8	-2.9	-3.0	-4.0	-4.3
0.5	0.3	0.4	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.3	0.3	0.3	0.1	0.0	0.1	0.3	0.0	0.0	0.0	0.0	-0.6	-0.8	-0.9	-1.0	-1.2	-1.4	-1.4	-1.4	-1.5	-1.6	-1.6	-1.7	-1.9	-2.0	-2.1	-2.8	-3.0
0.4	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.3	0.3	0.3	0.1	0.0	0.1	0.3	0.0	0.0	0.0	0.0	-0.6	-0.8	-0.8	-1.0	-1.2	-1.2	-1.4	-1.4	-1.5	-1.5	-1.6	-1.7	-1.9	-2.0	-2.1	-2.8	-3.0
0.4	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.3	0.3	0.3	0.1	0.0	0.1	0.3	0.0	0.0	0.0	0.0	-0.5	-0.7	-0.8	-1.1	-1.1	-1.3	-1.3	-1.3	-1.4	-1.5	-1.5	-1.6	-1.8	-1.9	-2.0	-2.7	-2.9
0.4	0.2	0.3	0.1	0.2	0.1	0.3	0.1	0.2	0.3	0.0	0.2	0.3	0.2	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	-0.4	-0.5	-0.6	-0.9	-0.9	-1.1	-1.1	-1.2	-1.3	-1.3	-1.4	-1.5	-1.7	-1.8	-1.9	-2.6	-2.8
0.5	0.4	0.4	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0.2	0.3	0.4	0.3	0.2	0.0	0.2	0.3	0.1	0.1	0.1	0.1	0.0	-0.2	-0.2	-0.4	-0.5	-0.6	-0.6	-0.6	-0.8	-0.7	-0.8	-1.0	-1.0	-1.2	-1.3	-1.9	-2.1
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.3	0.5	0.5	0.5	0.4	0.2	0.4	0.5	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	-0.4	-0.4	0.0	0.0	0.0	-0.5	-0.7	-0.7	-0.9	-0.9	-1.4	-1.5
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.3	0.5	0.5	0.5	0.4	0.2	0.4	0.5	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	-0.3	-0.3	0.0	0.0	0.0	-0.5	-0.6	-0.6	-0.8	-0.9	-1.3	-1.5
0.5	0.4	0.5	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.5	0.4	0.3	0.1	0.3	0.4	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.2	-0.2	-0.3	-0.4	-0.4	-0.6	-0.7	-0.7	-1.3	-1.4
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.3	0.5	0.5	0.5	0.4	0.2	0.3	0.5	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.4	-0.4	-0.5	-0.7	-1.1	-1.3
0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.3	0.4	0.5	0.3	0.4	0.4	0.4	0.3	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.1	0.0	-0.2	-0.4	0.0	-0.5	-0.9	-1.0
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.3	0.5	0.5	0.5	0.4	0.2	0.4	0.5	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.4	-0.1	-0.5	-1.0	-1.1
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.3	0.5	0.5	0.5	0.3	0.2	0.3	0.5	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	-0.2	-0.4	-0.4	-0.5	-0.9	-1.1
0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.3	0.5	0.5	0.5	0.3	0.2	0.3	0.4	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.2	-0.3	-0.4	-0.9	-1.0
0.5	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.3	0.4	0.5	0.4	0.3	0.2	0.3	0.4	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.3	-0.4	-0.8	-0.9
0.6	0.5	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.3	0.4	0.5	0.3	0.3	0.3	0.4	0.3	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.1	0.0	-0.1	-0.2	0.0	-0.3	-0.7	-0.8
0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.3	0.4	0.5	0.3	0.4	0.4	0.4	0.3	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0	-0.1	0.1	-0.2	-0.5	-0.6
0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.5	0.5	0.6	0.4	0.5	0.6	0.5	0.5	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.3	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.2	0.0	0.0	-0.1
0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.5	0.4	0.3	0.2	0.3	0.4	0.3	0.3	0.3	0.3	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.5	-0.6
0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.3	0.4	0.5	0.4	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.0	0.2	0.0	0.1	0.0
0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.3	0.5	0.5	0.5	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	-0.1
0.8	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.6	0.5	0.6	0.7	0.5	0.5	0.5	0.6	0.5	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.2	0.0	0.1	0.0

0.0	0.0	-0.6	-0.7	-0.2	-1.2	-1.4	-0.2	-1.8	-1.8	-1.9	-2.1	-2.1	-2.3	-2.4	-2.5	-2.7	-2.9	-3.0	-3.3	-3.4	-3.9	-4.5	-4.6	-5.1	-5.4	-5.6	-6.5	-7.0	-7.0	-7.4	-8.2	-8.7	-9.9	-10.1	-10.9	-11.1	-12.6	-18.7
0.0	0.0	-0.2	-0.2	-0.5	-0.7	-0.9	-0.2	-1.3	-1.3	-1.4	-1.6	-1.6	-1.7	-1.9	-2.0	-2.1	-2.3	-2.5	-2.7	-2.8	-3.3	-3.9	-4.0	-4.4	-4.7	-4.9	-5.8	-6.3	-6.3	-6.6	-7.4	-7.8	-9.0	-9.2	-9.9	-10.1	-11.5	-17.4
0.2	0.2	0.0	0.1	0.1	-0.1	-0.2	0.1	-0.3	-0.4	-0.3	-0.9	-0.4	-0.4	-0.4	-1.2	-1.3	-0.7	-1.5	-0.7	-1.7	-2.1	-2.4	-2.5	-2.8	-3.0	-3.2	-3.7	-4.0	-4.0	-4.3	-4.8	-5.0	-5.8	-6.0	-6.5	-6.6	-7.5	-11.4
0.1	0.1	0.0	0.0	0.0	-0.3	-0.5	0.0	-0.7	-0.8	-0.8	-0.9	-0.9	-1.0	-1.1	-1.2	-1.3	-1.4	-1.5	-1.7	-1.7	-2.1	-2.5	-2.5	-2.9	-3.1	-3.2	-3.8	-4.1	-4.1	-4.3	-4.9	-5.2	-6.0	-6.1	-6.6	-6.7	-7.7	-11.6
0.0	0.0	0.0	0.0	0.0	-0.2	-0.1	0.2	-0.3	-0.6	-0.6	-0.8	-0.8	-0.5	-1.0	-1.1	-1.2	-1.3	-1.4	-1.6	-1.6	-2.0	-2.4	-2.4	-2.8	-3.0	-3.1	-3.7	-4.0	-4.0	-4.3	-4.8	-5.1	-6.0	-6.1	-6.6	-6.7	-7.7	-11.8
0.1	0.1	0.0	0.0	0.1	0.0	-0.1	0.3	-0.2	-0.3	-0.4	-0.4	-0.5	0.0	-0.7	-0.5	-0.9	-0.6	-0.6	-0.7	-0.8	-1.6	-1.9	-1.2	-2.3	-2.5	-2.6	-3.1	-3.4	-2.4	-2.6	-4.1	-4.4	-5.1	-5.2	-5.7	-5.8	-6.7	-10.3
0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.3	-0.2	-0.3	-0.3	-0.4	-0.4	0.0	-0.6	-0.6	-0.7	-0.9	-0.9	-1.1	-1.1	-1.4	-1.8	-1.8	-2.1	-2.3	-2.4	-2.9	-3.2	-3.2	-3.4	-3.9	-4.1	-4.8	-5.0	-5.4	-5.5	-6.3	-9.8
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.3	-0.4	-0.2	-0.6	-0.7	-0.8	-1.0	-1.1	-1.3	-1.4	-1.8	-2.3	-2.4	-2.8	-3.0	-3.2	-3.9	-4.3	-4.3	-4.6	-5.3	-5.6	-6.7	-6.8	-7.5	-7.6	-8.8	-13.8
0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.0	-0.1	-0.2	0.0	-0.3	-0.4	-0.4	-0.5	-0.6	-0.3	-0.8	-1.1	-1.4	-1.4	-1.7	-1.8	-1.9	-2.4	-2.6	-2.6	-2.8	-3.3	-3.5	-4.1	-4.2	-4.6	-4.7	-5.4	-8.6
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.0	0.1	0.0	-0.1	0.1	0.0	-0.2	-0.4	0.0	-0.3	0.1	-0.4	-0.9	-1.7	-0.7	-2.2	-2.3	-1.8	-2.1	-2.4	-1.7	-1.8	-3.8	-3.1	-4.8	-5.0	-5.4	-5.7	-6.5	-10.4
0.5	0.5	0.3	0.2	0.3	0.2	0.1	0.4	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.4	-0.6	-0.6	-0.6	0.1	-0.4	-1.0	-1.2	-0.7	-2.3	-2.4	-1.9	-2.2	-2.5	-2.6	-1.9	-3.9	-3.3	-4.0	-5.3	-5.7	-5.9	-6.8	-10.9
0.5	0.5	0.2	0.3	0.3	0.2	0.2	0.4	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.5	-0.3	-0.5	0.1	-0.3	-1.3	-1.6	-0.7	-2.1	-2.2	-2.3	-2.1	-3.0	-2.4	-2.6	-3.7	-3.1	-4.8	-5.0	-5.4	-5.7	-6.5	-10.5
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.0	0.1	0.0	0.0	0.1	0.0	-0.1	-0.2	0.0	-0.2	0.1	-0.3	-0.8	-1.5	-0.6	-2.0	-2.1	-2.2	-2.0	-2.3	-1.6	-1.7	-3.6	-3.0	-4.6	-4.8	-5.2	-5.5	-6.2	-10.2
0.5	0.5	0.3	0.2	0.2	0.1	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.3	-0.3	-0.4	-0.5	-0.5	-0.8	-1.5	-1.2	-2.1	-2.2	-2.3	-2.1	-3.1	-3.1	-2.6	-3.8	-3.2	-4.9	-5.2	-5.6	-5.9	-6.8	-11.1
0.5	0.5	0.3	0.2	0.3	0.2	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.0	-0.1	-0.2	-0.1	-0.1	0.1	-0.2	-0.4	-0.9	-0.6	-1.9	-2.0	-2.1	-1.9	-2.8	-2.2	-1.7	-3.5	-3.0	-3.7	-4.9	-5.3	-5.5	-6.4	-10.5
0.6	0.6	0.3	0.3	0.4	0.3	0.3	0.5	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	-0.2	-0.6	-0.6	0.1	-0.8	-1.7	-0.8	-0.4	-1.9	-1.9	-1.5	-3.0	-2.6	-3.9	-4.2	-4.5	-4.7	-5.4	-9.0
0.6	0.5	0.3	0.3	0.3	0.3	0.2	0.5	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	-0.1	-0.3	-0.7	0.1	-0.8	-1.6	-0.4	-0.4	-1.8	-1.8	-1.5	-2.9	-2.6	-3.2	-4.2	-4.5	-4.7	-5.5	-9.2
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	-0.6	-0.9	-0.5	-1.4	-1.6	-1.7	-1.7	-2.4	-1.9	-1.6	-3.0	-2.7	-4.1	-4.4	-4.7	-5.0	-5.8	-9.9
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	-0.1	-0.5	-0.8	-0.4	-1.3	-1.4	-1.5	-1.6	-2.2	-1.8	-1.5	-2.9	-2.6	-3.9	-4.1	-4.5	-4.8	-5.6	-9.5
0.5	0.4	0.2	0.2	0.2	0.1	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.4	-0.8	-0.6	-1.3	-1.5	-1.6	-2.1	-2.4	-2.0	-2.2	-3.1	-3.4	-4.3	-4.6	-5.0	-5.3	-6.2	-10.6
0.6	0.5	0.3	0.3	0.3	0.2	0.2	0.5	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	0.0	-0.1	-0.3	-0.4	-0.5	-1.2	-0.5	-0.3	-1.9	-2.0	-2.2	-2.6	-2.8	-3.6	-3.8	-4.1	-4.4	-5.1	-8.9
0.6	0.6	0.3	0.3	0.4	0.3	0.2	0.5	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.1	-0.4	-0.9	-0.4	-0.1	-1.6	-1.3	-1.1	-2.2	-2.0	-3.1	-3.4	-3.7	-4.0	-4.7	-8.3
0.6	0.6	0.3	0.3	0.4	0.3	0.3	0.5	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	-0.6	0.0	0.0	-1.0	-0.9	-1.0	-1.6	-1.7	-2.3	-2.4	-2.7	-2.8	-3.4	-6.0
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	-0.1	-0.5	-0.1	-0.1	-1.3	-1.2	-1.3	-1.9	-2.2	-2.9	-3.2	-3.6	-3.8	-4.6	-8.5
0.6	0.5	0.3	0.3	0.3	0.3	0.2	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	-0.1	-0.2	-0.5	-0.7	-0.7	-0.8	-1.2	-1.2	-2.1	-2.3	-2.6	-2.8	-4.0	-7.1
0.6	0.6	0.4	0.4	0.4	0.3	0.3	0.5	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	-0.5	-0.5	-0.6	-0.9	-1.2	-1.5	-1.5	-1.8	-1.8	-2.9	-4.7
0.6	0.5	0.3	0.3	0.3	0.3	0.2	0.5	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	-0.6	-0.5	-0.6	-1.3	-1.3	-1.9	-2.5	-2.8	-3.1	-3.8	-7.5
0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.4	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-0.2	-0.4	-0.7	-1.2	-1.6	-2.2	-2.6	-2.4	-3.6	-7.5
0.6	0.6	0.4	0.4	0.5	0.4	0.4	0.6	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.0	0.1	0.1	-0.5	-0.6	-1.1	-1.5	-1.8	-2.0	-2.6	-5.7
0.6	0.6	0.4	0.4	0.4	0.3	0.3	0.5	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	-0.1	-0.5	-0.6	-1.4	-1.7	-2.0	-2.2	-2.9	-6.4
0.6	0.6	0.3	0.4	0.4	0.3	0.3	0.5	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	-0.4	-0.5	-1.3	-1.5	-1.9	-2.1	-2.8	-6.3
0.7	0.7	0.5	0.5	0.5	0.4	0.4	0.6	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.0	0.0	-0.5	-0.6	-0.9	0.0	-1.4	-3.5
0.6	0.6	0.4	0.5	0.5	0.4	0.4	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.0	0.0	-0.5	-0.7	-0.9	-0.4	-1.8	-4.5
0.7	0.7	0.5	0.5	0.5	0.4	0.4	0.6	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.2	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.1	0.2	0.2	0.0	0.1	0.0	0.0	-0.3	0.0	-0.1	-2.9
0.7	0.7	0.5	0.5	0.5	0.4	0.4	0.6	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.0	0.1	0.0	0.0	-0.2	0.1	-0.1	-2.6
0.7	0.7	0.5	0.6	0.6	0.5	0.5	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.1	0.2	0.1	0.1	0.0	0.2	0.1	0.1
0.7	0.6	0.4	0.5	0.5	0.4	0.4	0.6	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.6	-3.5
0.7	0.7	0.5	0.5	0.5	0.4	0.4	0.6	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.2	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.0	-1.9
0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.6	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.1	0.2	0.3	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0

Figure 5.4: Regret Matrix – Kenya (left) and South Sudan (right)

5.4.4 Regret Costs

The first regret analysis focuses on the total regret costs anticipated for each climate scenario. As illustrated in the summary charts (Figure 5.5), the total of the potential wasted resources and the unanticipated impacts varies significantly between climate scenarios. In the total regret costs, each bar illustrates the potential overspending plus the potential underspending for each scenario. Thus, a first analysis of the potential total regret indicates that the scenarios provide a distinct difference in terms of potential regret and the magnitude of the regret in each scenario. Additionally, we see that the potential total regret variance for South Sudan is significantly greater than the variance for Kenya. A general trend in both countries is that a more expensive adaptation option (green line in Figure 5.5) will result in less potential regret.

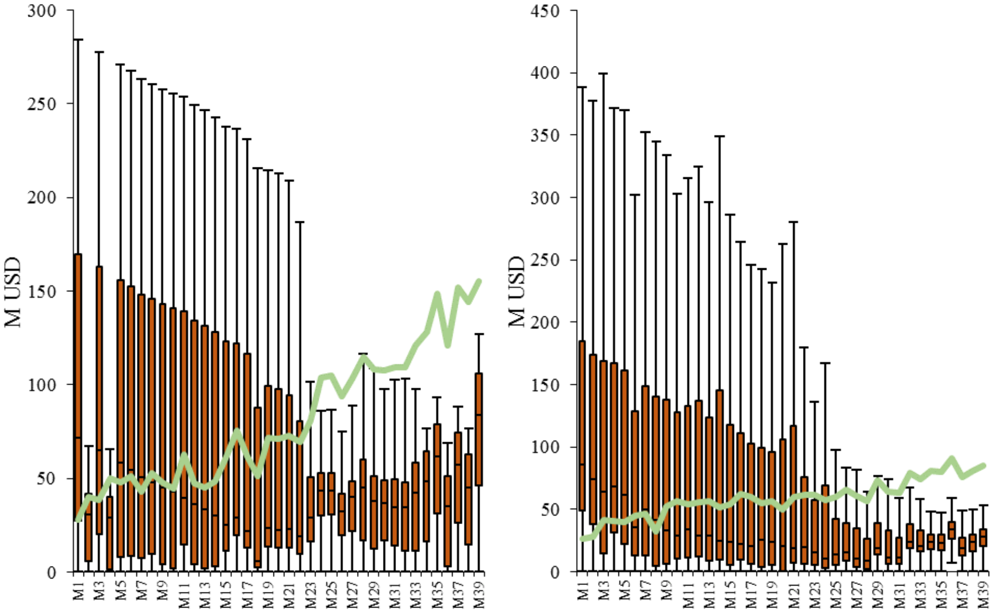


Figure 5.5: Total Regret Distribution per model (in brown) and Total Cost of Adaptation Investments (in green) – Kenya (left) and South Sudan (right)

The next level of regret analysis is the relative percentage of regret that a decision will incur for both potential overspending and underspending. As illustrated in the following graphs (Figure 5.6), the potential for underspending due to unanticipated impacts (values below the zero line) is greater in the majority of cases than the potential for overspending (values over the zero line). However, the variance in the potential to underspend can vary significantly between climate scenarios. Additionally, potential outliers present a greater threat to decisions if the final decision is to take a risk on underspending.

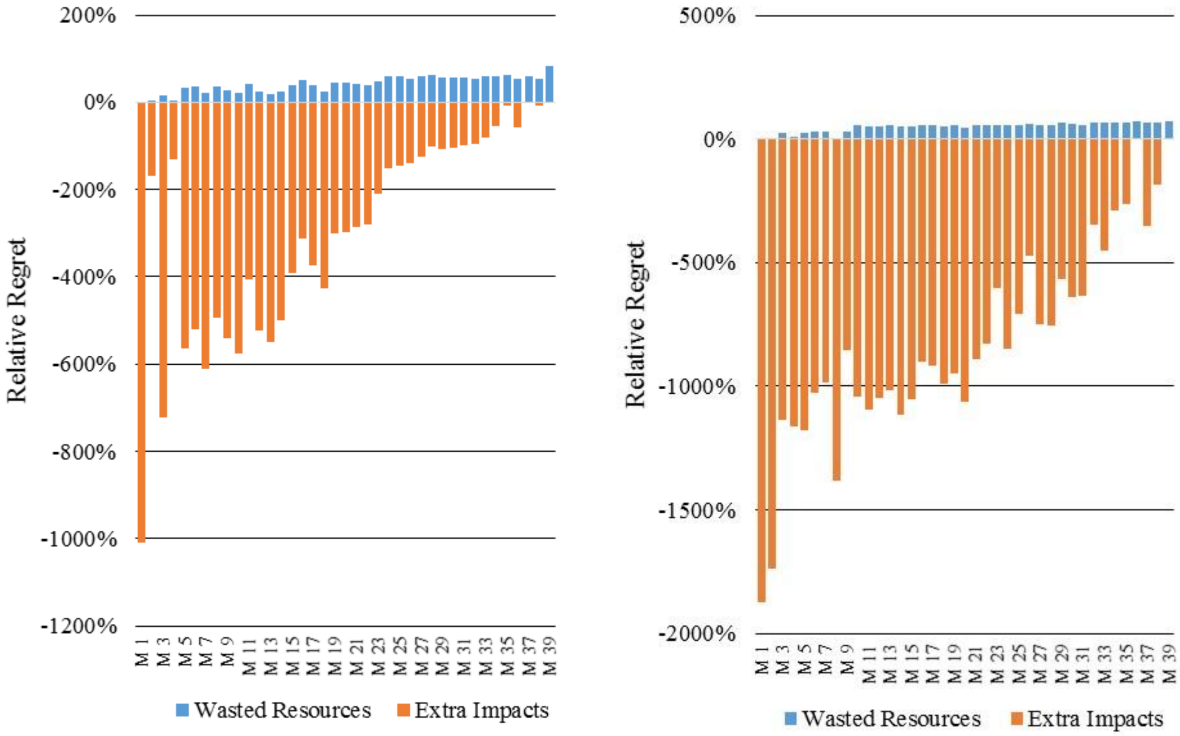


Figure 5.6: Maximum Relative Regret for Extra Expenditure and Wasted Resources – Kenya (left) and South Sudan (right)

5.5 LIMITATIONS

One limitation of this study is the scale on which the regret is calculated. It is assumed for simplification that the decision of which climate model to adapt for is made at a national level. The two areas of analysis cover a wide surface of land and cross multiple sub-national division so the design and planning decision may, in reality, be taken at a regional scale rather than national.

In order to simplify the case study, a large number of assumptions have been made. This study does not deal with the potential of delays in adaptation investment, it solely considers the option of adaptation as the financial cost and construction all occurring and being completed in the year where the construction of the project happens. At the same time, the final results come from investigating three specific climate-stressors: temperature, precipitation and intensity of flooding, and the analysis does not consider other impacts such as sea-level rise, earthquakes, or hurricanes.

This study uses costing results from the IPSS tool. For this analysis, no additional costing parameters were incorporated, including price fluctuations, innovative construction methods, or uncertainty on previous damage states. A key limitation of the modelling approach used in this study is the assumption of ‘perfect foresight’ for projecting the costs of climate damages and repairs. The approach used in this study posits that the repair is done at the time when the damage occurs, assuming that this will account for all climate-related damages projected that year. It is highly unlikely that the projected changes will occur exactly as modelled. However, without better modelling information, this approach presents a reasonable approach to understanding climate impacts. Other limitations of the IPSS tool can be consulted at Schweikert et al. 2014c.

5.6 CONCLUSION

Traditional cost benefit analysis is insufficient to deal with the prioritization of adaptation options to climate change. Climate change poses a complex challenge due to the high level of uncertainty associated with climate impact assessment and models. This challenge requires new methods for costing alternatives. This chapter presents the concept of regret as a viable and ready to use alternative to conduct cost-benefit analysis of proactive adaptation design. This concept has been illustrated using a transport infrastructure project in the countries of Kenya and South Sudan, which is part of the African Continental infrastructure plan PIDA.

This study reveals that the road investments in this region are threatened by future climate impacts. The climate change impacts could incur extra repair and maintenance costs that range from 73-348 MUSD in Kenya and 127-492 MUSD in South Sudan, due to increase of heat, precipitation, and flooding event severity. Proactive Adaptation designs are crucial to reduce life-cycle cost and improve infrastructure performance. This chapter has presented a new metric, regret, in order to determine the most suitable adaptation design from a suite of options.

In particular, the findings demonstrate that the decision of what climate projections to adapt for could result in an extra impact of more than 1,000% over the planned budget, while the maximum overspending is less than 80% of the predicted cost for the case of the Kenya PIDA project. The case of South Sudan is more dramatic with a potential regret that ranges from 2,000% of additional impact to 80% of overspending percentage relative to the projected budget.

These results are an illustration of the critical importance for planners to begin broadening the perspective with which future investment and planning decisions are made. By utilizing the tools and techniques put forward in this chapter, planners can significantly reduce not only the financial cost of climate change, but increase the robustness, resiliency, and integrity of the road infrastructure network in the coming decades.

Chapter 6 ROBUST DECISION-MAKING

This chapter is the manuscript of a journal paper submitted at ASCE-ASME Journal for Risk and Uncertainty in Engineering Systems on 04/01/2015 and accepted for publication on 10/09/2015. It introduces a novel method for calculating a "robust" decision rooted in existing decision theory and uncertainty. It presents the framework used for robust decision making and provides guidance about the most low-regret cost-benefit adaptation options for resilient road infrastructure design. A case study of a province in Mexico illustrates the application of this robust framework to actual road transportation planning.

6.1 INTRODUCTION

Climate Change poses a unique threat to our society. Uncertainty and risk associated with climate change impacts economic, social, political, and environmental sectors in every region of the world (IPCC 2014a). Although it is projected that every region of the world will be affected by climate change in the future, the specific risks and uncertainties are geographically diverse, making it difficult to establish guidelines and frameworks that could be applied uniformly to each of these communities.

The majority of climate change research in the past has focused on mitigation strategies for dealing with climate change causes. Recently, more climate change research is recognizing that adopting adaptation strategies (defined as any action designed to reduce the vulnerability to, and consequences of, climate change) is equally important (Füssel 2007; Pielke et al. 2007). However, research in the area of adaptation to climate change still lags behind studies focused on climate change mitigation. This chapter focuses on expanding the knowledge of the less studied topic of adaptation strategies. Of specific interest to this study is the Transport Infrastructure sector, which is key to fostering future social and economic growth of countries, regions and communities (EEA 2014).

A challenge in the creation of adaptation strategies is the high level of uncertainty associated with climate change impacts (Dessai et al. 2007; Jones 2000; Schneider 2001). Climate agencies are unable to define with certainty in the present what future standards that will need to be adopted in order to adapt infrastructure to the changing climate (Lisø 2006; Meyer and Weigel 2011). This uncertainty makes it difficult for decision-makers and policy-makers to understand the true nature of the problem and then to choose the best strategy to hedge against future weather events, leading to misinterpretations and misleading decisions about climate adaptation policy (Corotis 2012; Fankhauser and Soare 2013; Pittock et al. 2001).

The interdisciplinary nature of this chapter relates it to numerous fields of engineering and science, including transport engineering, infrastructure systems, risk and uncertainty engineering, transport planning, environmental planning, regional planning, environmental modeling and transport policy. The specific goal of the current study is to provide a clear model and framework to represent the uncertainty connected to future climate change adaptation and, using this framework, help transportation decision makers choose the best adaptation strategy for their individual infrastructure assets.

The body of this chapter includes: a review of current literature and existing work, separated into two sections - *Planning for Resilience, Sustainability and Climate Change*, and *Decision Making under Uncertainty of Climate Change*. The second section introduces a proposed methodology for addressing uncertainty in climate change, termed by the author a *Robust-Based Prioritization Framework*. The third section, *Pilot Study Demonstration*, uses the methodology to exemplify how it can be applied to current transportation decisions. Specifically, it uses an example of paved road maintenance in the State of Coahuila in northeast Mexico. The chapter concludes with a discussion of the results and implications of the research, limitations of the study, and a brief discussion of areas for future work.

6.2 BACKGROUND

6.2.1 PLANNING FOR RESILIENCE, SUSTAINABILITY AND CLIMATE CHANGE IN TRANSPORTATION

Transportation systems, including road infrastructure, are vulnerable to adverse and extreme weather conditions (EEA 2014; Nemry and Demirel 2012; NRC 2008). This vulnerability is reflected in maintenance planning and cost-benefit analysis to determine acceptable levels of cost and risk in designing and maintaining infrastructure (Neumann et al. 2011; UNFCCC 2011). As increased risks associated with a changing future climate become more apparent, there is a rising awareness of the need to address potential impacts at the policy level (Berkhout et al. 2006; Bruin et al. 2009; Burton et al. 2002).

Climate change poses high levels of uncertainty for decision makers, particularly in terms of medium and longer-term transportation planning, because transportation infrastructure is one of the most susceptible sectors in the civil infrastructure realm (Bollinger et al. 2014; Meyer et al. 2010). This is important because transportation systems are the foundation upon which economic growth, commerce, and social activities rely and therefore holds implications for other areas, including urban planning, health, and disaster preparedness (Erath et al. 2009; Schweikert et al. 2014a). Additionally, large climate-related extreme events can cause a set of adverse reactions along an entire transportation system, posing particularly severe impacts in densely populated areas (Koetse and Rietveld 2009).

Predictions for significant levels of climate changes pose challenges to engineering design, maintenance scheduling, and disaster preparedness plans, mainly because current standards, design practices and building codes are based on historical weather patterns that will be obsolete with the future changing climate (Lisø 2006). New transportation projects and old infrastructure must consider climate change, as it will lead to an increase in maintenance budgets (Schweikert et al. 2014b), to investments diverted for climate change repair, and to disruption of system functionality, all contributing to negative impacts on transit. (Hambly et al. 2013; Keener 2013).

While uncertainty is a part of routine decision-making, the potential changes in climate pose challenges on an order of magnitude that lack any historical precedent and are unaccounted for in existing policies (Baynham and Stevens 2013; Picketts et al. 2013). Other fields, including water management (Mailhot and Duchesne 2010; Murphy et al. 2011) recognize the potentially large risk created by climate change; practitioners in these areas are actively engaging in measures to incorporate climate risk into current policies. Learning from these policies, it is clear that there is a need for new approaches to planning, managing and designing road infrastructure to account for climate change uncertainty.

Building upon lessons learned in the water management approach to incorporating climate change uncertainty, and the needs expressed by transportation fields, it is clear that there is a desire from decision-makers to address climate change to reduce risk, life-cycle cost (including unplanned maintenance and repair), and the degradation rates of roads, which are increasing beyond historical precedent (Füssel and Klein 2006). Incorporating potential future climate conditions into current decision-making will support to a more holistic, forward-looking approach and ultimately more climate-resilient road infrastructure designs (EEA 2014; Meyer et al. 2010; Meyer and Weigel 2011).

Several existing studies demonstrate how proactive investment in transportation infrastructure to be equivalent to or lower than life-cycle cost estimates, while also improving the performance of the infrastructure to climate stress throughout its lifetime (Chinowsky et al. 2014b; Schweikert et al. 2014b). These cost savings are usually due to retrofit or repair needs for infrastructure that are unable to withstand future damages because they were built to historical climate standards. While uncertainty in climate modelling limits the ability of planners to invest with perfect foresight, the recognition of changing future weather variability and incorporation of flexible design and adaptation options today should be a consideration for transportation decision makers (NRC 2008).

There is agreement on moving from traditional cost-benefit approaches to setting priorities for adaptation projects, there is as well recognized need for advanced climate change adaptation costing methods that incorporate the full range of climate projections to properly reflect the uncertainty of the problem (Dessai et al. 2004; Fankhauser and Soare 2013; Hallegatte 2009; Watkiss et al. 2014; Weitzman 2009). The issue of uncertainty leads to the next section, describing advances in decision-making under uncertainty of climate change.

6.2.2 DECISION-MAKING UNDER UNCERTAINTY OF CLIMATE CHANGE

Decision theory and game theory was developed almost fifty years ago by mathematicians, statisticians, and economists (Luce and Raiffa 1957; Savage 1951; Wald 1971) through the concepts of utilities and, more specifically, pay-off tables. A pay-off table is a matrix composed of utilities; the matrix's columns are states of nature, while the rows are the possible actions to choose (Benjamin and Cornell 1963; Jordaan 2005).

The pay-off table provides information about the outcome of each of the actions, but after building this table there remains a need for criterion to determine which action is most desirable. The traditional criterions in decision theory are *maximax*, *maximin* and *minimax*, each based on the "risk attitude" of the decision-maker. The minimax criterion connects to the opportunist risk attitude, as the action that minimizes losses. In the early 20th century, Van Neumann identified minimax as the optimal criterion for selecting an action (Neumann and Morgenstern 1944). The minimax concept was refined by Savage in the mid-century using regret instead of losses; redefining it as the criterion that minimizes the worst regret from each state of nature (Savage 1951).

These criteria, together with decision theory and game theory, are widely used among practitioners and engineers and it is still taught as part of decision-making under uncertainty around the world (Hansson 1994; Resnik 1987). However, climate change poses a unique threat to this traditional theory, because uncertainty increases exponentially with the uncertainty in future climate modelling. The states of natures, or changes in climate, which may occur in the future are almost unpredictable and each of potential state carries a deep and severe uncertainty.

Deep uncertainty in climate change impact assessments has been a highly discussed topic for almost 20 years among economists, mathematicians and scientists (Fankhauser et al. 1999; Jones 2000; Lempert et al. 2004; Yohe and Neumann 1997). Deep uncertainty describes a scenario when decision-makers cannot agree on the prior probabilities and interdependencies of system model inputs (Lempert et al. 2004). *Severe uncertainty* has been defined similarly as a situation where a large amount of lacking information is expressed as a non-probabilistic information gap (Ben-Haim 2000). The term *deep uncertainty* seems to be more commonly used in the literature than *severe uncertainty* despite having almost the same definition, and therefore the term *deep uncertainty* will be used throughout the remainder of this chapter (Brown et al. 2011; Kasprzyk et al. 2013; Nassopoulos et al. 2012).

Deep uncertainty can be dealt with using "robust decision-making," described as the strategies with lower regret (Dessai and Hulme 2007; Gupta and Rosenhead 1968). Robust decision-making practices perform better than optimization techniques when probabilities of state of nature are not well understood (Lempert and Collins 2007; Rosenhead et al. 1972).

The notion of robust decision-making first appeared in the context of operations management and systems modelling (Ben-Haim 2001; Rosenhead et al. 1972), where the robust option is least sensitive to the uncertainty of outcomes. More recently, the idea of robustness has been applied to climate change impact assessment (Dessai and Hulme 2007; Hallegatte 2009) and to decision-making for adaptation strategies (Lopez et al. 2014; Moody and Brown 2013), especially in the context of water management (Brown et al. 2011; Lempert and Groves 2010).

Climate change poses a particular challenge for prioritization of adaptation investments due to the deep uncertainty of projected costs and benefits (Dessai et al. 2007; Dessai and Hulme 2007).There has yet to be an example in the literature applying the robust decision-making process for transportation planning climate change adaptation projects. Robustness has been used in other contexts in the realm of transportation engineering, but only while dealing with transportation networks and traffic engineering, mainly in route optimization problems (Huynh and Walton 2008; Yan et al. 2013).

6.3 METHODOLOGY

The methodology introduced in this research brings uncertainty and decision-making theory into the field of climate change infrastructure adaptation. Using established fields of study on uncertainty, this chapter presents a framework to address uncertainty in climate change impacts on the transportation sector.

The proposed framework follows a five stage approach (Figure 6.1). The first stage identifies infrastructure design adaptation strategies. The second stage quantifies the costs and benefits of possible adaptation strategies. The third stage calculates economic indicators for each of the strategies based on perfect future climate foresight. The fourth stage compares each strategy across all possible climate scenarios; it builds a three-dimensional matrix that is the foundation for choosing an adaptation strategy. The fifth and final stage of the framework uses robust decision making to determine the regret between strategies and between possible future scenarios. The end result of this framework is to select the most robust adaptation strategy from among the strategies identified in stage one. Although this framework is introduced in terms of road-specific design adaptation strategies to climate change, the proposed framework is flexible enough to be applied to adaptation strategies for any type of infrastructure system. The following sections detail each stage of the methodology.

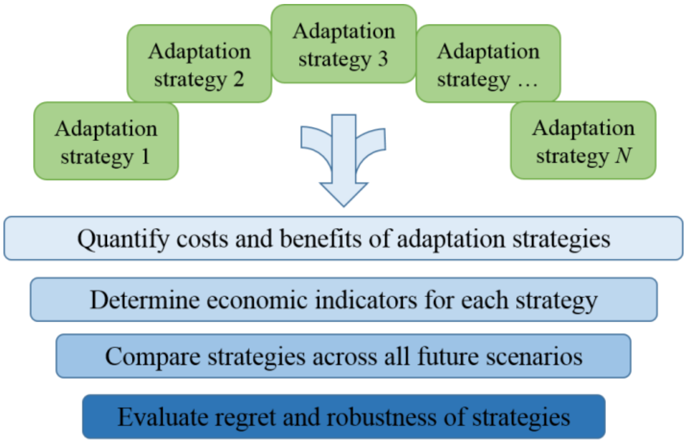


Figure 6.1: Diagram of Proposed Framework

6.3.1 COSTS AND BENEFITS OF ADAPTATION

The first stage of the methodology is to identify adaptation strategies that can be implemented to offset vulnerabilities due to future climate projections. Concurrently, the cost of these adaptation strategies needs to be specifically quantified to determine the potential benefits of each adaptation option. The methodology used to evaluate these options and obtain the costs of adaptation to climate change is conducted through a four-step process. First, the projected climate scenarios are identified for the geographical area of study. Second, the impact of each model on the road stock is evaluated. In the third step, the costs for each scenario are determined. Finally these costs are compiled and summarized to provide recommendation for road planning in response to the future environment and climate change.

The four steps of this stage of methodology exist in a single software tool created to address each of these steps. This software is called the *Infrastructure Planning Support System*, or IPSS, and was created by the Institute for Climate and Civil Systems (iCliCs) Research Group at the University of Colorado at Boulder (Schweikert et al. 2014c). IPSS is a computer-based tool that includes six areas of analysis including climate change, environmental and social impact to provide a holistic vision and a long-term planning capability. It has been used to quantify the impact of climate change on transport infrastructure in African countries, (Schweikert et al. 2014d), in Asia (Chinowsky et al. 2012a) and several comparative studies of different countries around the world (Schweikert et al. 2014b).

6.3.2 ECONOMIC ANALYSIS OF ADAPTATION STRATEGIES

The third stage of the framework is to identify economic indicators based on future climate projections. As each of the climate models predicts a different impact and vulnerability, a different economic value will be obtained for each of the climate scenarios.

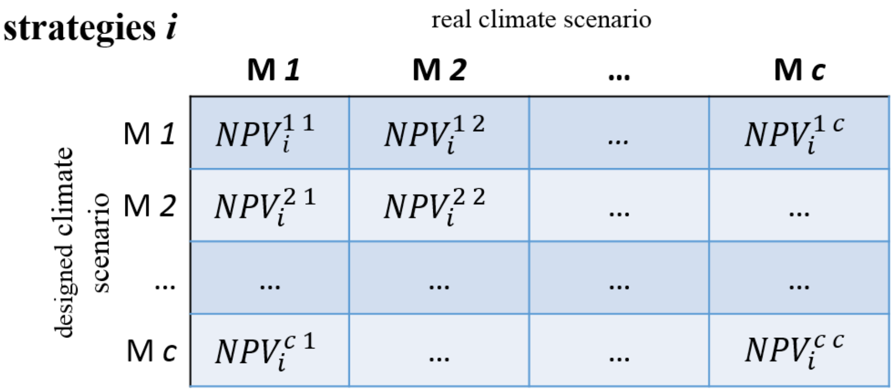
In the previous stage, the cost of each adaptation alternative and the remaining risk after adaptation was obtained, the remaining risk being the vulnerability cost to the roads that are not adapted to climate change risks. A *zero-level* of remaining risk occurs if the roads are fully adapted to all climate risks. A *full-level* of remaining risk exists if no adaptation is put into place. Each option in between results in some level of remaining risk or vulnerability. The cost of this remaining risk as well as the cost of adaptation are presented in terms of the total cost at Net Present Value. Following previous literature the Net Present Value (NPV) will be a sum of both the costs for adapting (initial capital investment) and the remaining risk (cost of repair during lifespan of the road). The strategy with lowest NPV will be the one with a lower life-cycle cost and so the most economically desirable.

6.3.3 COMPARISON ACROSS ALL FUTURE SCENARIOS

In the previous stage, the Net Present Value of each strategy applied to each climate scenario was obtained, producing as many outcomes for NPV as there are climate scenarios for each strategy. Even for the same strategy, values of NPV may differ highly as they are directly influenced by the projected climate change impact and the subsequent adaptation. To define these NPV's, we denote k as the scenario for which the adaptation strategy has been designed, and then NPV_i^k, as the NPV of strategy *i* designed for climate model *k*.

Once the NPV for each strategy in each climate scenario is known, the next step is to choose which climate scenario may be the most beneficial economically to use as a design basis. However, it is likely that the climate scenario that will actually happen will differ from the one that was selected as the basis. For this reason, the potential difference in costs between what was planned for and what might actually occur needs to be considered. In this case, we define l as the climate scenario that could happen. Then, $NPV_i^{k\,l}$ will refer to the NPV of strategy *i* designed for climate *k*, now assuming that scenario *l* occurs.

Once each of these NPVs are determined, the next step is to integrate the decision-making process along all possible climate scenarios. To accomplish this, a pay-off table is built to facilitate the integration and comparison of the different adaptation strategies. For each strategy i, a two dimensional matrix is constructed where the rows are each of the scenarios that the strategy is designed for, denoted as *k*, and the columns are the scenarios that actually happen, denoted as *l*. In the diagonal of the matrix, when $k = l$, the values of NPV are the ones obtained in the previous step of the framework and are equivalent to having perfect foresight about the strategy to choose and the climate scenario that will occur. Figure 6.2 shows the two dimensional matrix for strategy *i* assuming *c* total number of climate model.



strategies *i*

real climate scenario

designed climate scenario

	M *1*	**M *2***	**...**	**M *c***
M *1*	$NPV_i^{1\,1}$	$NPV_i^{1\,2}$	...	$NPV_i^{1\,c}$
M *2*	$NPV_i^{2\,1}$	$NPV_i^{2\,2}$	...	...
...	...	...	...	...
M *c*	$NPV_i^{c\,1}$	...	...	$NPV_i^{c\,c}$

Figure 6.2: Diagram of NPV matrix for strategy i

To calculate the values outside the diagonal we need to make a differentiation between two different possible outcomes. Decision makers can overestimate the projected impact of climate and then over-design the infrastructure, or they can underestimate the climate change, assuming a less severe climate projection, which could result in a design that does not address all possible impacts. In order to express this difference using the variables defined above, this analysis assumes that if climate change is overestimated, then the risk reduction predicted will be larger than the real risk reduction. Conversely, if climate change is underestimated, then the risk reduction assumed will be smaller than the real risk reduction. Table 6.1 summarizes these definitions, where CA is the cost of adapt, R the remaining risk and RR the avoided damaged due to adaptation.

The calculation of NPV for each of the three assumptions above differs slightly and is defined as follows. The values in the first quantity represent the total benefits. The components of the second quantity are the initial cost of adaptation plus the cost of the remaining impacts that have not been addressed.

Table 6.1: Notation for Net Present Value Comparison across Scenarios

Design Case	Formulation	
Over design	$NPV_i^{k\,l} = \left(\frac{CA_i^k}{(1+r)^n} + \sum_{j=1:m} \frac{R_{ij}^l}{(1+r)^j}\right)$	$RR_i^k > RR_i^l$
Under design	$NPV_i^{k\,l} = \left(\frac{CA_i^k}{(1+r)^n} + \sum_{j=1:m} \frac{R_{ij}^l}{(1+r)^j} + \sum_{j=1:m} \frac{\Delta RR_{ij}^{l-k}}{(1+r)^j}\right)$	$RR_i^k < RR_i^l$
perfect foresight	$NPV_i^{k\,l} = NPV_i^k$	$RR_i^k = RR_i^l$

Now the components of the pay-off matrix are $NPV_i^{k\,l}$ with k, l = 1, 2…, c with c equaling the total number of climate scenarios. This payoff matrix is based on traditional and elementary decision theory (Benjamin and Cornell 1963; Jordaan 2005). Using the traditional terms, the states of nature will be the climate scenarios that actually happen while the actions are both the possible strategies and designs. The suggested pay-off matrix is an expansion of the traditional pay-off matrix, but with the introduction of a third dimension: the climate change for which we are going to design the strategy. Now, the pay-off table contains dimensions *i* and *k* as actions, and *l* states of nature (Figure 6.3).

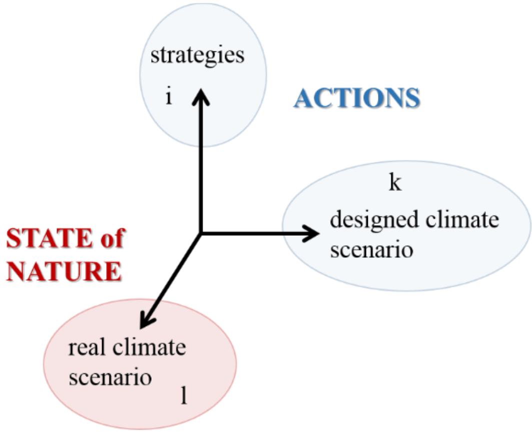


Figure 6.3: Diagram of three dimensional pay-off table

6.3.4 ROBUST DECISION-MAKING UNDER UNCERTAINTY

As presented in the previous section, there is a basis for using the expected value of future costs and benefits to rank and prioritize adaptation strategies and determine optimal value based on maximizing benefits. However, as mentioned earlier, assigning probabilities to climate models and future projection is challenging and can be misleading if not done appropriately. Given that there is disagreement about the possible probabilities of climate scenarios (Brown et al. 2011; Dessai and Hulme 2004; Groves and Lempert 2007), the resulting expected values should be treated carefully.

Robustness has recently gained academic popularity as the optimal criteria for investments with deep uncertainty. Robustness is the property of being less sensitive to uncertainty. In the climate change adaptation problem, the robust strategy will be the one with the least regret variance among all possible scenarios.

A regret matrix can be obtained using the NPV matrix built in the previous stage. The relative regret for each combination of strategy and design will be calculated as a percentage of the expected values. The denominator is the expected cost, so when the real climate is the same as expected $l=k$. The relative regret is denoted as follows, note that the most desirable option will be the one with lower cost and smaller value of NPV:

$$Regret_i^{kl}(\%) = \frac{NPV_i^{kl} - (\min_k(NPV_i^{kl}))}{NPV_i^{kk}}$$

To visualize robustness, boxplots of the regret are displayed across the strategies. Boxplots, together with the statistical values, allows for the selection of the most robust strategy. This research effort suggests the use of a deviation from zero that can be defined similarly to the notation of standard deviation, where c is the total number of climate models and RI_i is the robustness indicator for strategy i. This indicator shows the average distance of the regret from zero. Low values of the robustness indicator signify a regret distribution closer to zero, indicating a strategy that has low sensitivity to uncertainty. High values of the robustness indicator will result from a strategy with a wide regret distribution, that it is highly dependent on the future climate and uncertainty.

$$RI_i = \sqrt{\left(\sum_{k,l=1:c} \left(Regret_i^{kl}\right)^2\right)/c}$$

The adaptation strategy with the lowest value of the robustness indicator will be selected as the most robust strategy. The three dimensional matrix again can allow the decision-maker to incorporate flexibility. The matrix can find the most robust combination of strategy and design, or used separately to obtain the most robust design for a specific strategy or the most robust strategy based in a predetermined design. In this methodology, it is suggested to first find the most robust strategy based on all possible design and projected climate scenarios. Once the strategy has been selected, then once can find the corresponding most robust design standards.

6.4 RESULTS

This section demonstrates the proposed methodology through discussion of a pilot study with real project characteristics. Mexico has been chosen for this case study due to its geographic location with some of the world's most diverse climate systems. Most climate models suggest serious consequences of climate change in the Mexican environment, with a general shift toward warmer and drier conditions.

The section that follows introduces a pilot study of the robust-based prioritization framework. As an example, the north-eastern state of Mexico, Coahuila, has been chosen as the study location. The State Department of Transportation, *Secretaria de Comunicaciones y Transporte*, has declared a need for maintenance work on more than 1,400 kilometers of paved road during the year 2015 (SCT 2012). The next stage of the framework seeks to identify the adaptation needs for the paved roads, and specifically, what kind of adaptation strategy will lead to the most robust decision if climate change adaptation were incorporated into the maintenance and design strategies.

Based on three distinct adaptation measures that address changes in precipitation, temperature and flooding frequency, eight different possible adaptation strategies have been analyzed as combinations of the three main adaptation investments described above. The eight strategies are summarized in Table 6.2. In particular, *R_0* represents the no adaptation option, and *A_PTF* represents the total adaptation for all three stressors, precipitation, adaptation and flooding. For simplification during the rest of this pilot study the abbreviations for each of the strategies will be used.

Table 6.2: Adaptation strategy abbreviation for the pilot

Strategy Abbreviation	Definition
R_0	Initial Risk - No Adapt
A_P	Adapt to Precipitation only
A_T	Adapt to Temperature only
A_F	Adapt to Flooding only
A_PT	Adapt to Precipitation and Temperature
A_PF	Adapt to Precipitation and Flooding
A_TF	Adapt to Temperature and Flooding
A_PTF	Adapt to All Stressors

The second step of the framework is to quantify the costs and the benefits for each of the strategies. *IPSS* has been used to obtain these results. For simplification of this pilot study, only five climate scenarios have been used. These models are part of the CMIP 3 developed from general circulation models and approved by the IPCC in its fourth report. The IPCC Fourth Report describes models, scenarios and data quality (IPCC 2014c). The following table summarizes the characteristics of the five models used in this pilot:

Table 6.3: Summary of Climate models used in the pilot study

Abbrev.	Agency	Model	Scenario
M 1	BCCR - Bjerknes Centre for Climate Research, Norway	bcm2	a2
M 2	CNRM - Center National Research Metheorologiques, France	cm3	a2
M 3	GFDL - Geophysical Fluid Dynamics Laboratory, USA	cm2	a2
M 4	NCAR - National Center for Atmospheric Research, USA	ccsm3	a1b
M 5	NCAR - National Center for Atmospheric Research, USA	ccsm3	a2

The third stage of the framework, once the cost and benefits have been obtained, is developing the economic analysis based on climate scenario projections. This means assuming that the future climate is the same as it has been predicted, so in a perfect foresight case. The economic analysis has been built independently for each of the five climate models.

In order to build the economic analysis for each strategy, both the cost of adaptation and remaining risk have been obtained from IPSS. These two components summed together result in the total cost of each strategy. The NPV has been calculated using both the adaptation cost and the remaining risk Table 6.4 summarizes the economic analysis of the eight strategies based on perfect foresight of climate model M1.

Table 6.4: Economic analysis of eight strategies based on climate M1

Model M1	Adapt Cost	Remaining Risk	NPV
R_0	$ -	$ 104.27	$ 104.27
A_P	$ 1.86	$ 102.56	$ 104.42
A_T	$ 30.93	$ 3.38	$ 34.30
A_F	$ 13.24	$ 102.59	$ 115.83

A_PT	$ 32.78	$ 1.67	$ 34.46
A_PF	$ 15.10	$ 100.89	$ 115.98
A_TF	$ 44.16	$ 1.71	$ 45.87
A_PTF	$ 46.02	$ -	$ 46.02

The six strategies, from A_P to A_TF, are partial adaptation strategies, meaning that their adaptation cost is lower than that of the cost of total adaptation. For the partial adaptation strategies, some remaining risk is not addressed, recorded in the second column in the table. The strategies A_P, A_F, and A_PF have large values of present cost. This means that none of these strategies will be selected because they are not economically efficient. This is a common trend in all five economic analyses, because these three strategies do not address increased temperature, which accounts for the largest impact.

For this specific case study, it appears that the most desirable adaptation strategy is A_T, which considers adaptation only for temperature. A key challenge with the threat of climate change and the range of possible climate scenarios is that each model provides a different “best” strategy. As such, it is important to continue with the next step of the framework to compare strategies and designs across all climate scenarios.

As described in the methodology section, the fourth stage is building the pay-off matrix in order to compare the investments across all future climate scenarios. The matrix in this example has size 8x5x5 for the dimensions *i, k* and *l* respectively, representing the eight strategies, five design scenarios, and five possible climate scenarios that can occur. Each matrix component is a value of NPV calculated as described in the methodology section at the same time the regret matrix is obtained. Table 6.5 is an example of a layer of the matrix, describing strategy A_T, where *i*=3:

Table 6.5: NPV climate comparison for strategy A2

NPV A_T		Real Climate Scenario				
		M 1	**M 2**	**M 3**	**M 4**	**M 5**
Design Climate Scenario	M 1	$ 34	$ 44	$ 100	$ 245	$ 226
	M 2	$ 50	$ 33	$ 115	$ 260	$ 241
	M 3	$ 45	$ 54	$ 55	$ 200	$ 181
	M 4	$ 114	$ 123	$ 124	$ 152	$ 139
	M 5	$ 111	$ 121	$ 122	$ 155	$ 136

The fifth and last stage introduces robust decision-making principles in order to identify which of the strategies is least sensitive to different possible future climate scenarios. In particular, regret demonstrates the sensitivity of each strategy to the uncertainty of possible outcomes. It will be used therefore as the primary metric for determining the robustness of each of the strategies. The outcomes from this analysis will show that the strategy with a regret distribution with an average closer to zero and a small variance will indicate the least sensitive strategy to uncertainty. However, it is important to distinguish between regret that comes from over-expenditure and regret from under-expenditure. To complete this discussion, two new concepts are introduced. The first - that regret that comes from under-design - will be denoted as negative; while regret from over-design will be denoted as positive. The other concept introduced for comparing different strategies is that of *relative regret*. The notation for relative regret was introduced previously in the Methodology section. Relative regret describes the relative distance from the value of the expected expenditure for all the possible scenarios. Figure 6.4 shows the relative regret distribution for four of the adaptation strategies, A_T, A_PT, A_TF and A_PTF. Table 6.6 shows a summary of the statistics of the distribution for each of the three strategies.

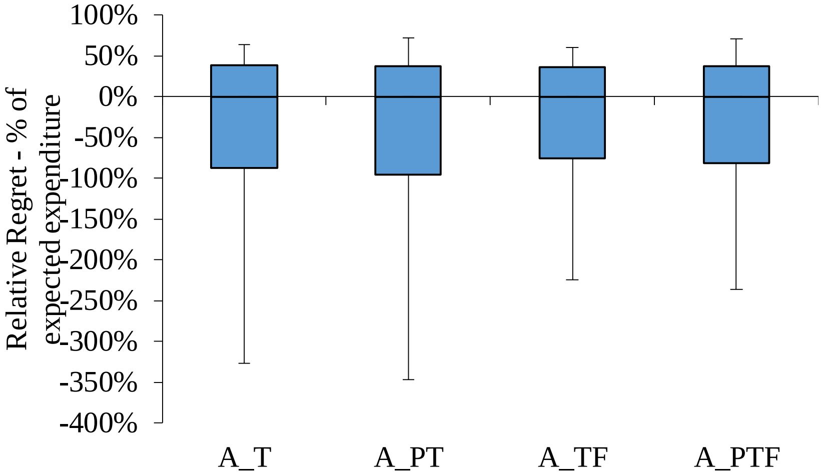


Figure 6.4: Relative Regret Distribution for Strategies A_T, A_PT, A_TF and A_PTF

The relative regret distribution shows a particular difference between the four adaptation strategies analyzed. While there is no significance to differentiate between distributions A_T and A_PT, and between A_TF and APTF, the four strategies consistently show a distribution with more skew towards negative numbers than the total distributions. The explanation for this trend may be that options with positive regret, where adaptation involves overdesigning, have larger values of expected net present value, while options with negative regret, with adaptation that is under-designed, have smaller values of expected worth. This trend shows that more desirable options (those with smaller net present values) may have a larger regret than options that are less economically efficient, with large values of present cost.

Table 6.6: Summary of Statistics for Relative Regret Distributions

Relative Regret	A_T	A_PT	A_TF	A_PTF
Mean	-52%	-53%	-32%	-32%
Standard Deviation	122%	129%	89%	95%
Robust Indicator	1.32	1.39	0.95	1.00

All the distributions shown in this section come from a sample of 25 values, as the study uses only five climate scenarios. Incorporating a larger range of future scenarios will increase the sample of regret and will likely display more significance when differentiating the distributions between different strategies.

From this section we can conclude that two of strategies under consideration (A_TF and A_PTF) are equally robust, displaying similar sensitivity to uncertainty. The two other strategies (A_T and A_PT), consistently show lower values of robustness. There is, however, no strong significance interval to determine whether A_TF or A_PTF is more robust. The following section expands the use of robust decision-making to explore which climate scenario should a strategy be designed for in order to minimize the regret and provide a robust strategy design.

6.4.1 ROBUST DESIGN CLIMATE SCENARIO

The last stage of the framework is to determine which is the most robust design standard. In general, this exercise will be conducted using only the most robust strategy determined in the previous section. As concluded above, it is not clear between A_TF and A_PTF which strategy is the most robust. However, this section will assume that adaptation A_TF has been chosen as the "best" strategy, because it shows the best results from the robust indicator.

Figure 6.5 and Table *6.7* display the regret distributions and statistics for relative regret produced by the expected climate scenario. The results are displayed only for adaptation A_TF. Each of the distributions is based on only five values, from the five possible climate scenarios. Including more climate scenarios in the analysis will allow for a well-informed decision with stronger conclusions.

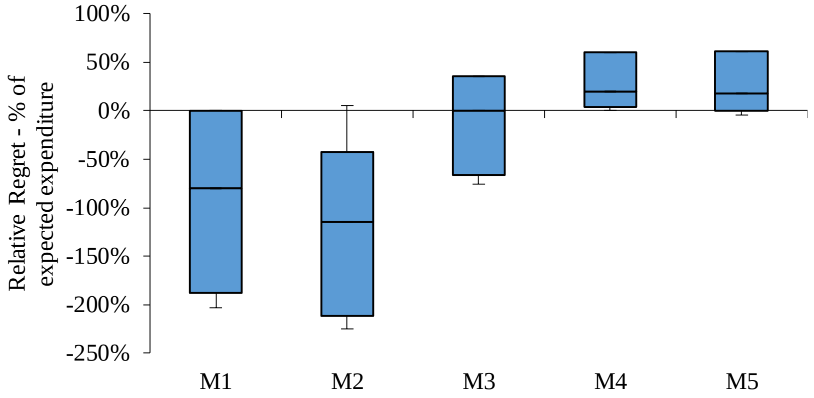


Figure 6.5: Regret distribution for design Climate Scenarios M1, M2, M3, M4 and M5

Designing strategy A_TF for either M1 or M2 can potentially lead to a large range of regret, from zero to more than twice the expected present value of each design. Both strategies show a negative regret, meaning regret that comes from underestimating the real impact of climate change and under-designing the adaptation strategy. Conversely, designing for scenarios M4 and M5 will result in a smaller regret in terms of absolute values, with a maximum regret below 75% of the expected present worth. The regret from both designs comes in this case from overestimating the climate impact and therefore overdesigning the road infrastructure. M3 shows results that fall between the two groups mentioned above. The M3 outcome for this strategy shows a negative mean of -14% underspending from the expected value. It has robust indicator similar to M4 and M5 and much smaller than M1 and M2. It is hard to decide between M3, M4 or M5 as they show very similar values or robustness. However while revising Table 6.5, M3 projects consistently lower impacts than M4 or M5, so designing for M3 is less costly but equally robust than M4 and M5.

Table 6.7: Summary of Statistics of Regret Distributions by Design Scenario

Relative Regret A_PT	M1	M2	M3	M4	M5
Mean	-94%	-118%	-14%	34%	32%
Standard Deviation	88%	91%	48%	27%	29%
Robust Indicator	1.29	1.48	0.50	0.43	0.43

Finally, for the pilot study presented here, using the proposed framework of robust-based prioritization of adaptation investment shows the best adaptation strategy appears to be A_TF designed for climate M5. It is therefore recommended that the roads in this northeast part of Mexico should be adapted to the projected increase of temperature and flooding, to reduce future projected damage and to reduce the vulnerability of the transportation system. In order to produce the most robust adaptation, this strategy design for climate scenario M5 that predicts a high to medium severity of impact. This investment will lead to the most robust decision, when comparing across the five different possible climate scenarios.

6.5 LIMITATIONS

The aim of this research is to provide a transparent new model and framework to incorporate robustness, resilience and sustainability in the decision making process of infrastructure adaptation strategies to climate change. In order to simplify the case study, a large number of assumptions and considerations have been taken. Different assumptions may lead to different results. This study does not deal with the potential of delays in adaptation investment, it solely considers the option of adaptation in the current year. At the same time, the result comes from investigating three specific climate-stressors: temperature, precipitation and flooding, and it does not consider other impacts such as sea-level rise, earthquakes, or hurricanes.

This model uses costing results from the tool IPSS. IPSS in this analysis was using baseline data, which means the analysis presented here considers only uncertainty coming from climate change models and does not include any other type of uncertainty such as price fluctuations, innovative construction methods, or uncertainty on previous damage states.

Finally, the decision of the most robust strategy and most robust design climate scenario is based on a smaller sample of only five climate projections. Future work will introduce a large range of climate scenarios bringing more accurateness to the decision-making process and the subsequent selection of the best strategy.

6.6 CONCLUSIONS

The deep uncertainty currently inherent in climate change modeling poses significant challenges for infrastructure planners dealing with long-term investment strategies. Selecting the appropriate economic and engineering strategies under the reality of this uncertainty requires a new method of thinking by transportation and policy decision-makers. This chapter introduces a robust cost prioritization framework which provides a comprehensive and viable tool for dealing with deep uncertainty in transportation adaptation investment strategies for climate change. Building from this concept, the framework developed for this research offers a novel method for robust and low-regret decision-making for infrastructure adaptation investments.

The proposed framework follows a five stage approach: the first identifies infrastructure design adaptation strategies. The second quantifies the costs and benefits of possible adaptation strategies. The third calculates economic indicators for each of the strategies based on perfect future climate foresight. The fourth compares each strategy across all possible climate scenarios. The fifth and final stage of the framework uses robust decision making to determine the regret between strategies and between possible future scenarios.

This methodology presented in this chapter promotes a more efficient and accurate long-term, environmental and holistic planning of road infrastructure, leading to resilient, robust and sustainable transportation systems. While deep uncertainty of future climate changes is currently a challenge facing decision-makers, tools such as this framework make it possible to incorporate and understand climate change impacts into planning strategy.

Chapter 7 DISCUSSION

7.1 DECISIONS UNDER CONSTRAINED BUDGET

The main focus of this chapter is to discuss how to incorporate economic considerations into the robust prioritization methodology presented in Chapter 6. This is intended to solve one of the limitations of this methodology, as the most robust option is often the most expensive of all strategies as well as the most conservative. This chapter reintroduces the problem as a multi-objective optimization; both the economics and the robustness of results will be studied. Two economic constraints will be utilized in this discussion: the upfront cost, the "*adaptation cost"* which is the cost to upgrade the infrastructure to withstand climate change stress; and the cost of maintenance and repair during the rest of its lifespan, the "*additional maintenance"*, caused by the impact of climate change.

This chapter builds upon the three previous chapters and summarizes and compiles the research discussed in this dissertation. It utilizes two case studies to illustrate the methodology and to provide arguments for the discussion of decisions made under a constrained budget. At the same time, this chapter expands the methodology developed in Chapter 6 by adding all possible climate scenarios - more than 40 in each case - and presenting and discussing possible visualization options to support and assist decision-makers.

This discussion chapter uses two distinct case studies, the first one in Coahuila, a northern state of Mexico, and a second case study in Kenya. These two cases have been chosen because climate change is projected to be substantially different in each location. While Coahuila will suffer from severe increases in temperature and possible droughts, Kenya is projected to have higher intensities of precipitation and risk of flooding, with only a modest increase in temperature. The data used in *Case study #1: Coahuila, Mexico* is first introduced in Chapter 6, however only a small piece of inventory (approximately 30 kilometers) is used in this analysis. The data, costs and road inventory used in the *Case study #2: Kenya* in this chapter are the same as introduced in Chapter 5. While the Kenya study takes a high level approach by considering an entire corridor that crosses the country, the first case study will focus on a portion of a highway. This difference will be utilized to showcase the flexibility of the framework and methodology. Each of the case studies is divided into three sections: *Vulnerability, Regret* and *Robust Decision-Making*. Each of these sections relates directly with Chapters 3- 6 in this dissertation.

Table 7.1 summarizes the distinct features of Case Studies 1 and 2. It includes the location, type of infrastructure asset, the length of inventory in kilometers, climate units used, number of climate projections per climate unit, and the climate variables. Case Study #1 is a more simplistic case study: it has a smaller inventory and uses only one climate unit and two climate variables (temperature and precipitation). This simplicity is intended to provide a more understandable and transparent set of results when compared with Case Study #2.

Table 7.1: Summary of features for each case study

Case Study	Location	Years	Infrastructure Asset	Length of Inventory	Climate units	Climate projections/unit	Climate variables
#1	Coahuila, Mexico	2015-2050	Highway	30 km	1	52 CMIP3	Temperature Precipitation
#2	Kenya	2015-2050	Primary Paved Road Corridor	1,450 km	75	39 CMIP5	Temperature Precipitation Flooding

7.1.1 CASE STUDY #1: COAHUILA, MEXICO

The first case study uses the north-eastern state of Mexico, Coahuila, as the study location. The State Department of Transportation, *Secretaria de Comunicaciones y Transporte*, has declared a need for maintenance work on more than 1,400 kilometers of paved road during the year 2015 (SCT 2012). This case study uses 30 kilometers out of the entire inventory to test the framework and identify the possible need for adaptation. The research undertaken in this study uses 52 climate scenarios from the ensemble of CMIP3 approved by the IPCC 4th Assessment Report. This is a different ensemble of models from the second case study to point out the flexibility of this methodology. These models are used to estimate the potential impact of climate change on the infrastructure and the total financial regret in the time period 2015-2050. For these case studies, the net present values and costs are calculated for each scenario using a discount rate of 3%. This case study uses the cost and maintenance procedures as introduced in Chapter 6. However, this case study extends the range of climate projections from 5 to 52. This larger ensemble of climate projections is the same as used in Chapter 4. A detailed list of CMIP3 scenarios used in this study can be found in *Appendix 1*.

7.1.1.1 VULNERABILITY AND ADAPTATION

The vulnerability and adaptation costs for this first case study are summarized and displayed in the next two figures. These two concepts are first introduced and defined in Chapter 5. Figure 7.1 shows the range of costs from the 52 climate projections, in USD for both vulnerability and adaptation. The box ranges from 25th to 75th percentile, whiskers indicate the 5th and 95th percentiles, the thick black line in the middle of the box is the median and the black circles are minimum and maximum values. Boxplots consistently follow this same description throughout over this chapter. The costs are divided into three stressors; precipitation, temperature and flooding. In this figure the adaptation cost is calculated considering only that specific stressor; the cost is not combined across stressors.

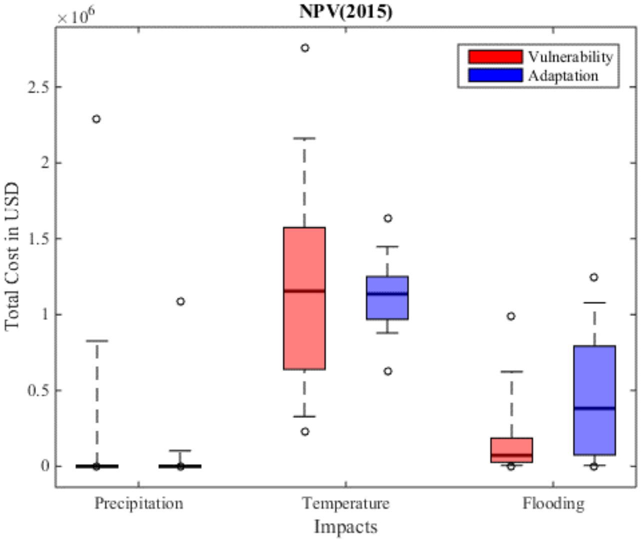


Figure 7.1: Case study #1; Net Present Value of Vulnerability and Adaptation by stressor, Precipitation, Temperature and Flooding

In this particular case study, the road inventory is projected to be more vulnerable to temperature impacts, followed by a similar level of impact from both precipitation and flooding. This reinforces the conclusion of Chapter 4: in the northern part of Mexico a severe impact on the transportation system due to temperature is projected by the mid-21st century. The cost of adaptation for both temperature and precipitation is projected to be significantly lower than the cost from repairing vulnerabilities. Adapting to both stressors may be economically efficient. However, adaptation to flooding is projected to be more expensive than the costs resulting from repairing vulnerabilities. The next section will evaluate the robustness of these findings.

To simplify this first case study only adaptation to temperature and precipitation impacts are evaluated. That leads to a total of four possible combinations: adapting to precipitation only; adapting to temperature only; adapting to both precipitation and temperature; or choosing to not adapt (a reactive approach). All the road inventory in this case study is located in the same geographic climate unit, so we are using a single climate change modelling data unit over time to evaluate the impact. The simplicity of this first case study is intended to be transparent and straightforward. Once multiple locations and a larger inventory is added, as in case study #2, the complexity increases greatly.

Figure 7.2 introduces the net present value of the four possible adaptation strategies: adapting to precipitation only; adapting to temperature only; adapting to both precipitation and temperature, or choosing to no adaptation (a reactive approach). In this figure the impact of the stressors are combined. For example for the first strategy, adapting precipitation only, the cost of adapting to precipitation is combined with the additional repair and maintenance from impact of temperature, as defined first in Chapter 3 and Chapter 6. The graph on the left is calculated as perfect foresight, assuming that the climate model being adapted is actually the one happening, while the graph on the right displays imperfect adaptation, assuming all possible outcomes. Thus, each of the distributions on the left contain 52 values, while the distributions on the right contain 2704 values. The methodology to calculate imperfect adaptation is detailed in both Chapter 3 and Chapter 6 of this dissertation.

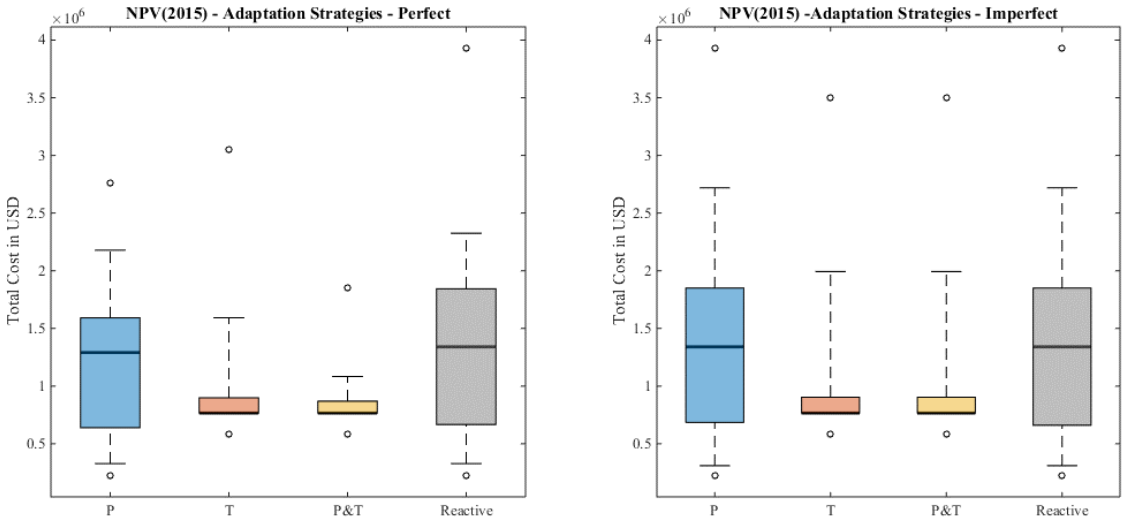


Figure 7.2: Case study #1; NPV of All Adaptation Strategies combined. Perfect Foresight (left) and Imperfect Foresight (right)

For this first example in Coahuila, looking at perfect foresight shows that the strategy projected to have a lower net present value is adapting to both precipitation and temperature. However, by including imperfect foresight, the conclusion seems to be more ambiguous, requiring a more in depth analysis on the regret and robustness.

7.1.1.2 REGRET

This section builds on the concept of imperfect foresight and the development of the metric of regret designed to assist decision-makers. This section closely follows the methodology presented in Chapter 5. Figure 7.3 shows the regret distribution for each of the 4 strategies including no adapt-reactive approach. Each distribution includes 2704 regret values coming from comparing each of the 52 possible adaptation designs to the 52 possible climate projections.

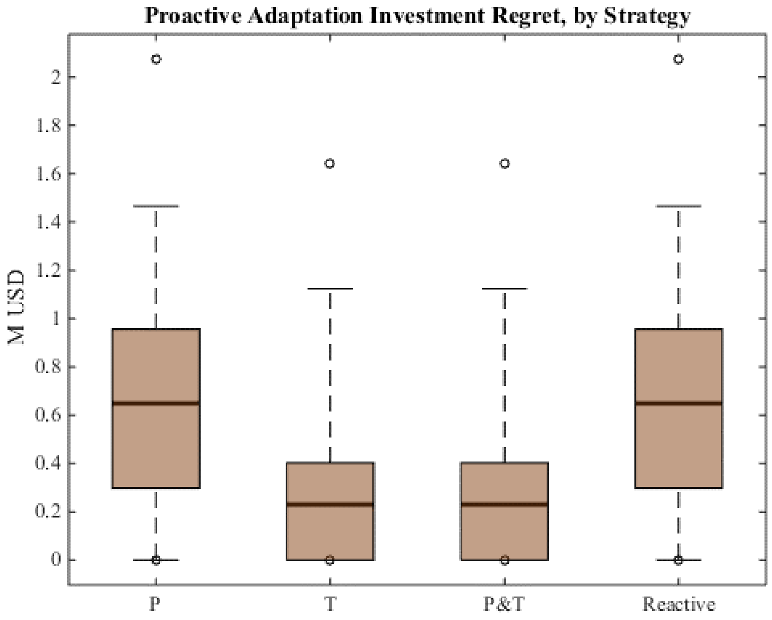


Figure 7.3: Case study #1; Regret Distribution for each adaptation strategy

From Figure 7.3 shows that adapting only to temperature as well as adapting to both precipitation and temperature seem to have the lower median value across all distributions (thick dark line). These two strategies also have the smallest range of regret (size of the brown box). This indicates a low variability and low sensitivity to uncertainty. Conversely, the strategies of adapting to precipitation as well as being reactive show the largest distribution both in terms of median value and in terms of interquartile range. This indicates a very poor robust behavior as they seem to be very sensitive to uncertainty. Each of the distributions include all the possible adaptation designs for each strategy, including conservative design and minimal adaptation design. Next we will explore and discuss regret distributions for each of the 4 specific design strategies.

In the following figures (Figure 7.4), the regret distributions are plotted by the climate model they are design for. The total upfront adaptation cost is added to the graph (green line). In this case, each distribution contains 52 values equal to compare each design with the 52 possible climate projections.

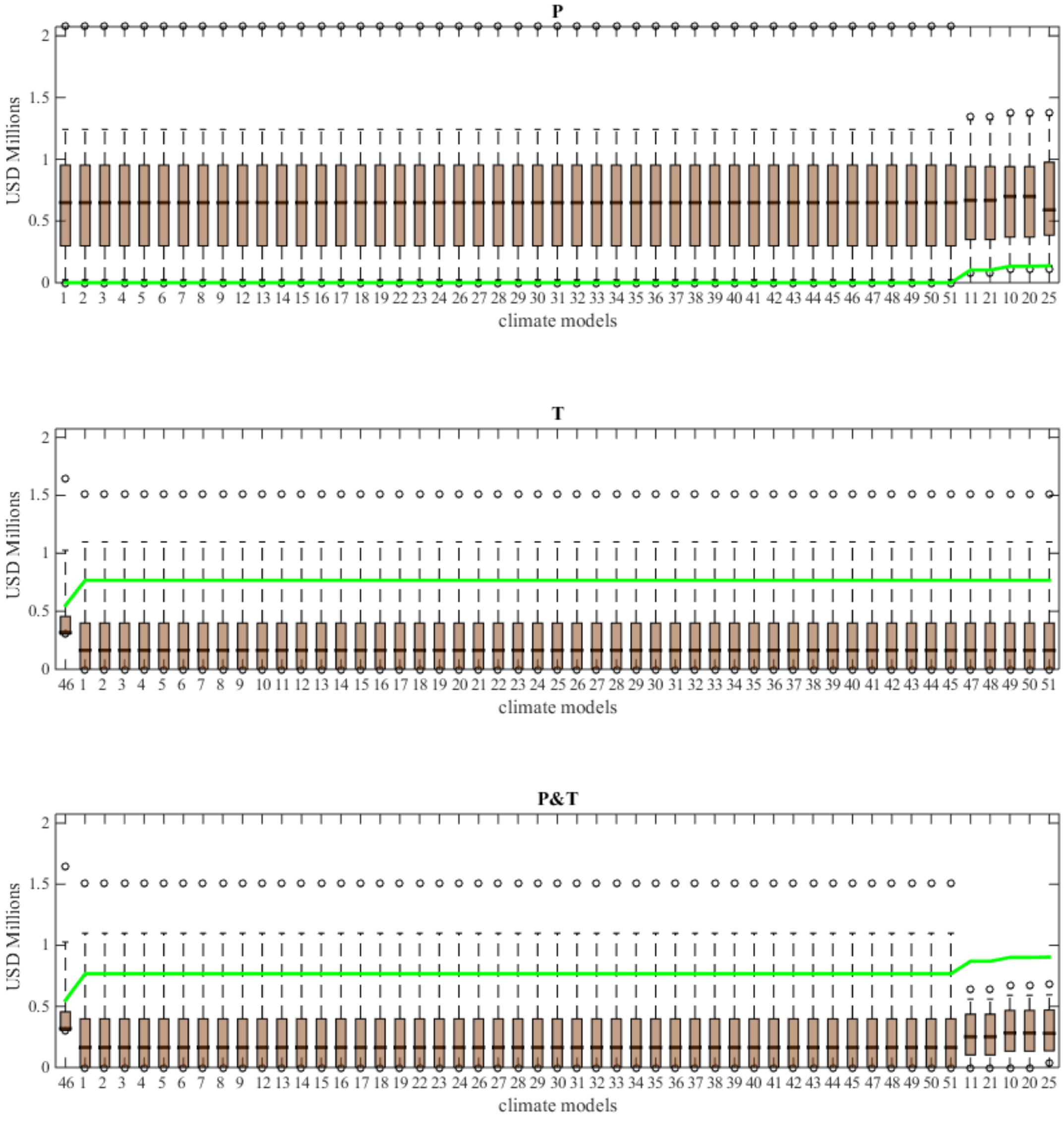


Figure 7.4: Case study #1; Regret Distributions and Adaptation Cost (green line) for Adapt to Precipitation only (A), Adapt to Precipitation and Temperature (B) and Adapt to all (C).

In this case study, it seems that in both adapting only to temperature and adapting to both temperature and precipitation, there is a correlation: the higher the cost of adaptation, the smaller the distribution is. This means that investing more money upfront for adaptation can lead to more robust strategies (Figure 7.4 B and C). The strategy for adapting only to precipitation has five possible levels of adaptation (five total possible designs). Most of the climate models project no need of adapting; while the most conservative adaptation design would cost $0.2 MUSD approx. (green line in Figure 7.4 A). Additionally, when considering adaptation for changes in temperature, there are only two possible designs projected by the climate models: one model demands for $0.5M USD adaptation cost; the remaining climate models project $0.75M USD (Figure 7.4 B). Adaptation which considers the two stressors together produces a total of five combinations of possible adaptation designs (Figure 7.4 C). These figures visually display the range of potential adaptation strategies that could be used to reduce regret and increase robustness.

7.1.1.3 ROBUST DECISION MAKING

The previous section indicates that each decision needs to be treated independently as there are substantial differences between the regret distributions when looking at different potential adaptation strategies based on different climate models. This section focuses on the distribution of regret, which is simplified to a single metric, the “regret indicator”, introduced and defined in Chapter 6.

For this section, a “higher regret” indicator describes a wider distribution of regret, and thus a higher sensitivity to uncertainty. “Lower values” of regret describe adaptation options with smaller regret distributions, indicating an option with a more robust behavior. This section incorporates the regret indicator analysis with the budget constraints presented earlier in this chapter; the upfront adaptation costs and the remaining additional maintenance required for the lifespan of the infrastructure.

In Figure 7.5 below, the 52 possible adaptation designs are plotted for each of the four strategies; three adaptation options and the reactive approach. It is important to note that the reactive strategy have only one point in the plot as this strategy is reactive to climate change and does not consider climate projections on the planning process. In total, there are 12 options are plotted in Figure 7.5; four which consider adaptation only to precipitation, two which consider adaptation only to temperature, five options which consider adapting to both precipitation and temperature and one reactive strategy which does not consider proactive adaptation to the climate change impacts. The horizontal axis is the expected additional maintenance costs from all the possible climate projections. The vertical axis is the upfront adaptation cost required to upgrade the infrastructure to withstand future climate impacts. Both axes are expressed in millions of USD and are discounted at a 3% rate for the total length of study 2015-2050.

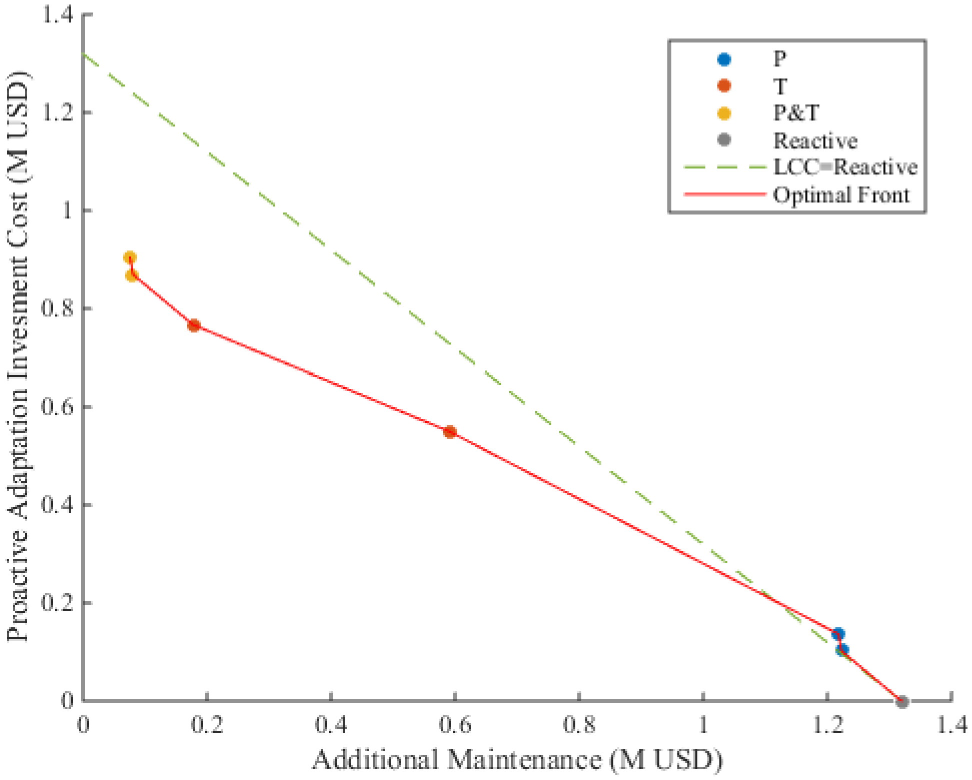


Figure 7.5: Case study #1; Adapt cost vs Additional Maintenance scatter plots

The red line in Figure 7.5 is the “optimal line”, or “Pareto front”, and the green dashed line shows the total life-cycle cost (sum of horizontal and vertical axis) equal to the reactive strategy. These results indicate that there are a number of options for decision investments. A conservative strategy would pick a strategy that minimized additional maintenance, as well as any of the other strategies that involve lower adaptation costs. The impact of projected temperature change is so severe that any option that doesn’t include adapting to temperature has no economic feasibility, as the life-cycle cost is higher than the reactive strategy (above the green dashed line). The negative slope of most of the design strategies reveals that strategies with higher proactive adaption investment leads to a lower projected additional maintenance over time. In particular, adapting to both temperature and precipitation impacts would result in a total proactive adaptation investment cost of \$0.8M USD, while reducing the expected additional maintenance to almost zero cost. If proactive adaptation investments are constrained by budget considerations, Figure 7.5 reveals a lower cost option: adapting only to temperature impacts, which will cost approximately \$0.5 MUSD and will reduce the projected additional maintenance costs to \$0.4 MUSD, saving almost \$1MUSD compared with the reactive approach. The next section will introduce the metric of regret, designed to aid in the evaluation of which of the 12 design strategies will most robust.

The following figures incorporate the metric of regret and are combined with either of the two budget constraints; upfront cost or expected additional maintenance. Similar to the previous figure, each of the possible levels of adaptation designs are plotted for all adaptation strategies in Figure 7.6. The horizontal axis is the upfront adaptation cost, while the regret indicator is on the vertical axis. Unit of regret indicator are millions of USD.

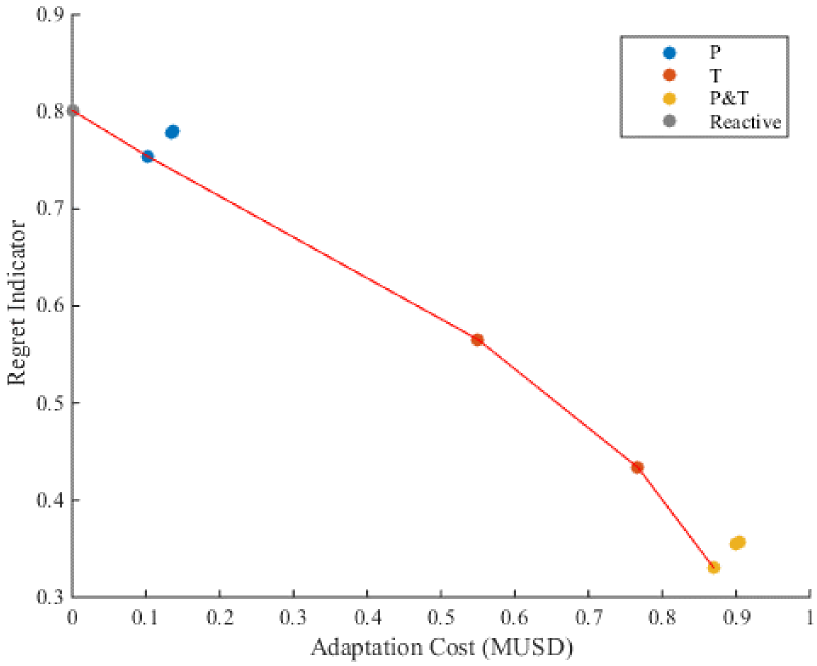


Figure 7.6: Case Study #1; Regret Indicator vs Adaptation Cost scatter plots

The red line in Figure 7.6 indicates the optimal front when the regret indicator is compared to the adaptation cost. In this case, each of the four strategies lie along the optimal line. However, adaptation only to precipitation only is located in the upper range of the regret indicator, showing a large distribution of potential regret. Adapting both to precipitation and temperature seems to have the lowest value of regret indicator - around $0.4 MUSD - which indicates the high robustness of this option. It is interesting to note that two of the designs for adapting to both precipitation and temperature have a higher regret than adapting only to temperature, even more money towards proactive investment is allocated. One explanation could be that the regret comes from extra proactive adaptation expenditure, so possibly adapting to both precipitation and temperature could result in large values of overspending, as described in Chapter 5.

In a similar way, the regret indicator is plotted against additional maintenance in Figure 7.7. The horizontal axis is the expected value of additional maintenance, while the regret indicator is on the vertical axis. Unit of regret indicator are millions of USD.

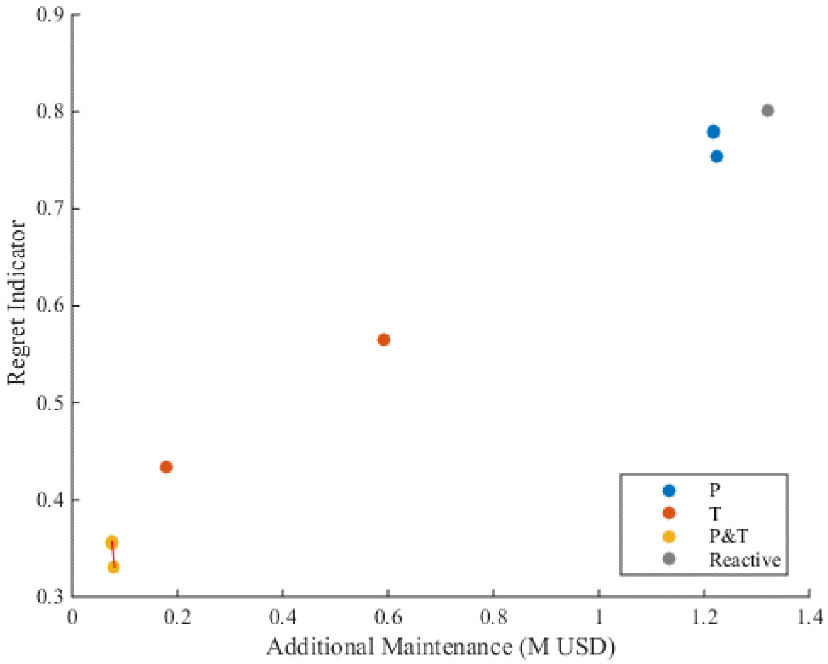


Figure 7.7: Case study #1; Regret Indicator vs Additional Maintenance scatter plot

The general trend in Figure 7.7 indicates that the higher the expected value of additional maintenance, the higher the potential regret. Therefore, decisions that lead to large value of projected additional maintenance will imply a large value of regret. In particular, adapting to both precipitation and temperature impacts are the optimal decision, as this strategy have the lowest value of regret and a relatively small value of additional maintenance.

Finally, in an effort to combine the information displayed in the last three figures in a single visual graph, Figure 7.8 was created. It follows the same characteristics as Figure 7.5, where the strategies are plotted against the upfront adaptation cost and additional maintenance. Each of the points in the plot is given a radius; the size of the radius is a function of the regret indicator (large regret indicator values are represented by a larger circle). Finally, each of the four strategies is given a different color. To add another piece of information, the points are accompanied by a number that indicates the climate model used to define the adaptation threshold. To simplify the scatter plots, only strategies that are in the Pareto or optimal front, have been plotted. Figure 7.8 summarizes all the information provided in this chapter in a single figure and is intended to clearly support and assist managers in choosing the optimal decision for their specific inventory and location.

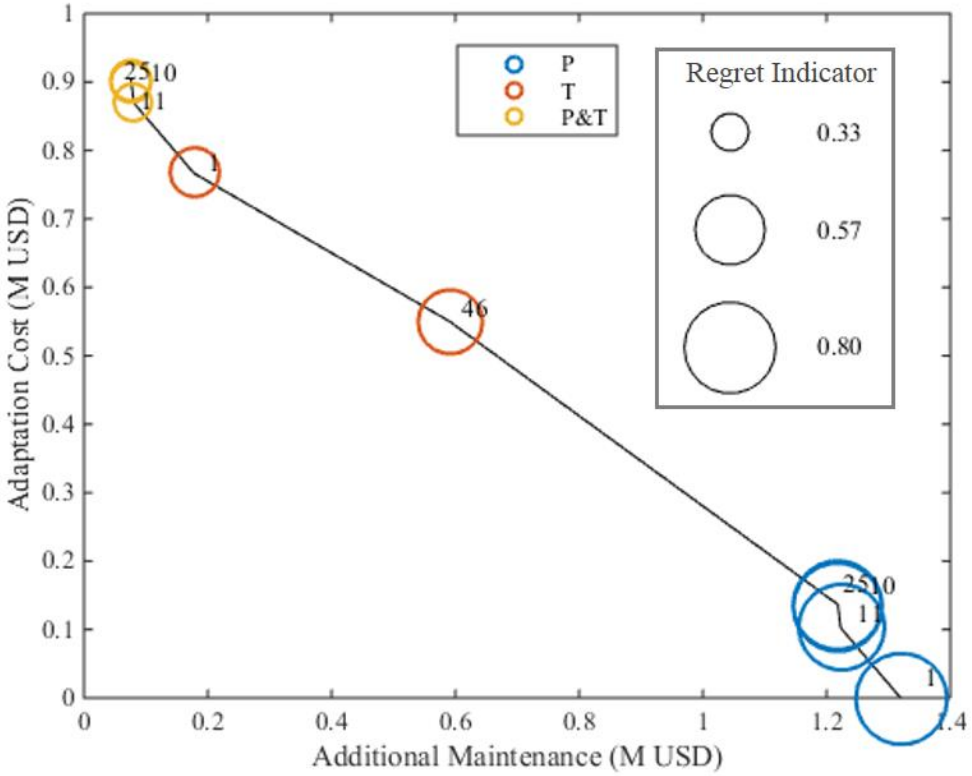


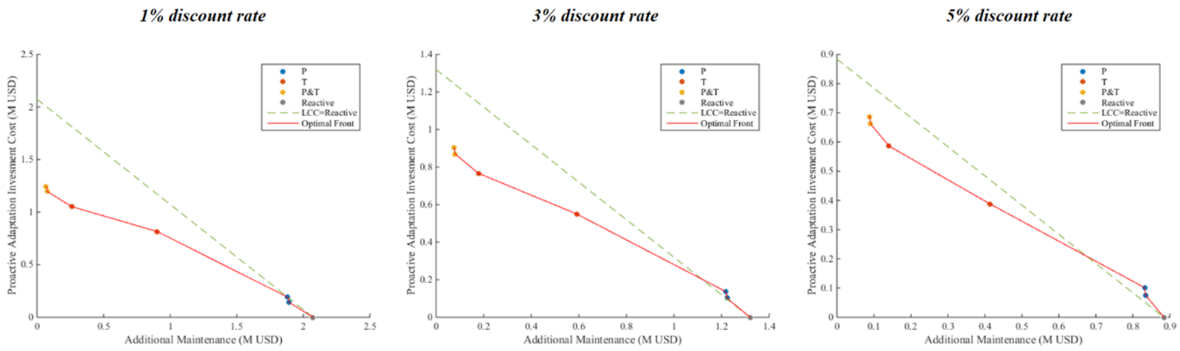
Figure 7.8: Case study #1; Regret Indicator with budget constrains

From Figure 7.8 several conclusions can be drawn. First, by looking at the size of the bubbles, the general trend shows again that the lower the adaptation cost, the higher the regret indicator. The results show that adapting to both precipitation and temperature have the lowest regret, especially when adapting using climate model design numbers 10, 11 or 25. These three designs will cost around $0.9 M USD for adaptation while expecting additional $0.1 M USD for additional maintenance during the lifespan of the inventory. The regret of these designs is similar to the regret for adapting to temperature only, approximately $0.30 MUSD, less than half the regret of adapting only to precipitation or choosing the reactive strategy, which has a cost of $1.05 MUSD. However, if there is a constraint on upfront costs and adaptation costs cannot be the suggested $0.85 M USD, the figure could be used to choose the most appropriate investment based on a particular constraint.

7.1.1.4 SENSITIVITY ANALYSIS

The final section of this case study discusses the sensitivity of choosing a discount rate to the results presented above. As introduced at the beginning of this section all the results presented above use a discount rate of 3%. In this section, these results are compared to the results using a 1% and a 5% discount rate. Discount rates of 3% and 5% have been accepted by the World Bank (Lopez 2008). A discount rate of 1% is it not commonly used in any economics exercises but it will be used to represent a baseline where the discounting is minimized.

Figure 7.9 shows the sensitivity of the economic analysis (presented first in Figure 7.5 for a 3% rate) using 1%, 3% and 5% discount rate. The sensitivity of the regret analysis that was presented first in Figure 7.6 is displayed in Figure 7.10.


1% discount rate

3% discount rate

5% discount rate

Figure 7.9: Sensitivity of discount rate – economics analysis

The total additional maintenance required from a reactive strategy has a large sensitivity to the chosen discount rate, with a net present value of $2 or $0.9 M USD, for 1% and 5% respectively (Figure 7.9). This cost is calculated as the cost of projected additional maintenance and repair to address future projected climate impacts. The analysis is done over the period 2015-2050. Therefore, projected costs from additional maintenance from the end of the analysis (when the climate change gets more severe) has a huge sensitivity to discounting, as the discounting factor for 2050 ranges from 0.7, 0.35 and 0.18 for 1%, 3% and 5%, respectively. Conversely, the present value of options with a higher initial adaptation cost have a lower sensitivity ranging from $0.7 to $1.1 M USD. The adaptation options have a discounting sensitivity because the net present value includes the cost of rebuilding the infrastructure at the end of the lifespan. The lifespan of the roads analyzed in this case study is 30 years, so rebuilding happens in 2045 and is included in the period of analysis. However the lower sensitivity of this cost come from the fact that most of the investment is required early in the study period at 2015.

It is interesting to discuss the sensitivity of the economic viability of each strategy. Using a 1% discount rate makes any adaptation strategy much more beneficial than the reactive approach (indicated in Figure 7.9 where the points are far from the dashed line). For a higher discount rate, 5%, the adaptation options are closer to the dashed line, meaning that they do not offer higher benefits compared to the reactive approach. Therefore, it is expected that if the discount rate is increased above 5%, the adaptation options will become not economically feasible when compared with the reactive approach.

While looking at the sensitivity of the regret analysis, the conclusions are similar to the ones in the above lines. The regret of the adaptation options seems to not be sensitive to discounting. However, the regret from the reactive approach drops by almost half when using a 5% discount rate (Figure 7.10). Also similar to the previous discussion, using higher discount rates will lead to higher values of regret from adaptation strategies and may result in selection of a reactive approach as the most robust investment. However in the selected range of discount rates between 1-5%, the result of the methodology are the same: suggesting that adaptation to both precipitation and temperature is the most robust option and the most economically feasible. Therefore, these results demonstrate that use of the methodology and the selection of a robust investment has almost no sensitivity when using discount rates under 5%.

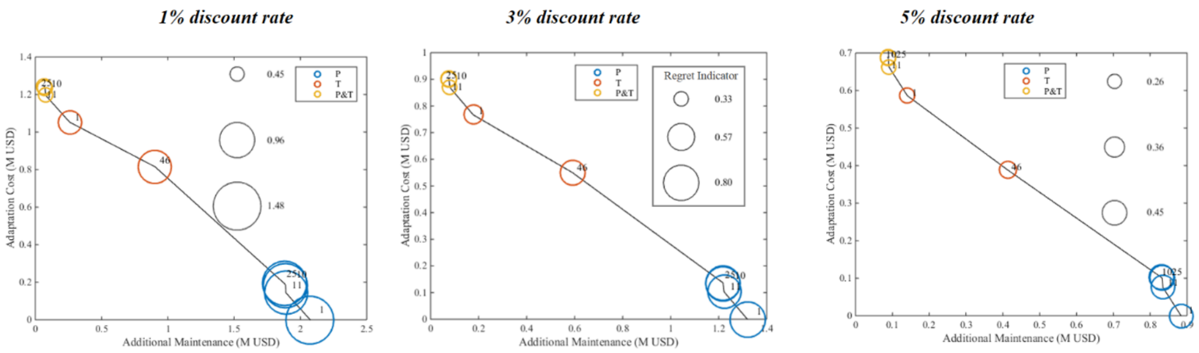


Figure 7.10: Sensitivity of discount rate – regret analysis

7.1.2 CASE STUDY #2: KENYA

This second case study uses the Kenyan context with the Northern Multimodal Corridor as a specific example. The area covered in this partial corridor analysis is 1,450 kilometers of paved primary road. The research undertaken in this study uses 39 separate climate scenarios from the ensemble of CMIP5 approved by the IPCC 5th Assessment Report (IPCC 2013). A detailed list of CMIP5 used in this study can be found in *Appendix 1*. This larger project uses more 75 climate data points for each of the 39 climate model to capture geographical variability. These models are used to estimate the potential impacts on the infrastructure as well as financial regret in the time period 2015-2050. For this case study, the analysis costs are calculated for each scenario using a discount rate of 3% to calculate present value costs.

7.1.2.1 VULNERABILITY AND ADAPTATION

The vulnerability and adaptation costs of this second case study are summarized and displayed in the next two figures. Figure 7.11 shows the range of costs projected by the 39 climate projections. The box ranges from 25th to 75th percentile, whiskers reach 5th and 95th, the black think line in the middle of the box is the median and the black circles are the minimum and maximum values. The costs are divided into three stressors: precipitation, temperature and flooding. In this figure, the adaptation cost is calculated considering only that specific stressors, so the cost is not combined across stressors.

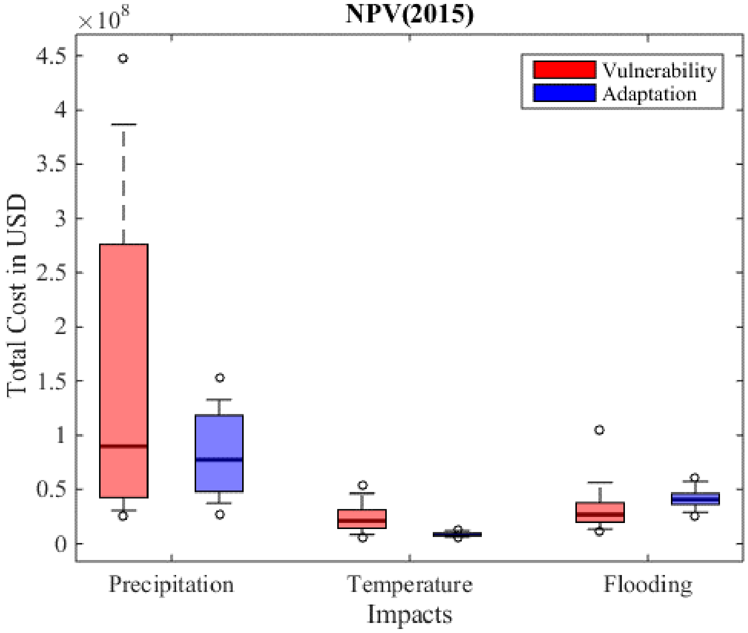


Figure 7.11: Case study #2; Net Present Value of Vulnerability and Adaptation by stressor, Precipitation, Temperature and Flooding

In this case study, the road inventory is projected to be more vulnerable to precipitation impacts, followed by a similar impact from both flooding and temperature. The cost of adapting to precipitation seems significantly lower than the cost from vulnerability. The cost of adapting to temperature is much lower that the vulnerability cost. However, adapting to flooding is projected to be more expensive than the vulnerability cost. From this initial figure, it is clear that adapting to precipitation and temperature will be economically feasible. The next sections will evaluate whether these strategies are also robust.

Figure 7.12 introduces the net present value of the eight possible adaptation strategies: adapting only to precipitation; adapting only to temperature; adapting only to flooding; adapting to both precipitation and temperature; adapting to both precipitation and flooding; adapting to both temperature and flooding; adapting to all of them; or not adapting at all (a reactive approach). In Figure 7.12 the impact of the three stressors are combined; for example, the first strategy the cost of adapting to precipitation is combined with the additional repair and maintenance costs from the impacts of temperature and flooding. The graph on the left is calculated as perfect foresight, which assumes that the climate model being adapted to is actually the one happening. The graph on the right displays imperfect adaptation, assuming all possible climate outcomes. Each of the distributions on the left contains 39 values, while the distributions on the right contain 1521 values. The methodology to calculate imperfect adaptation is detailed in both Chapter 3 and Chapter 6 of this dissertation.

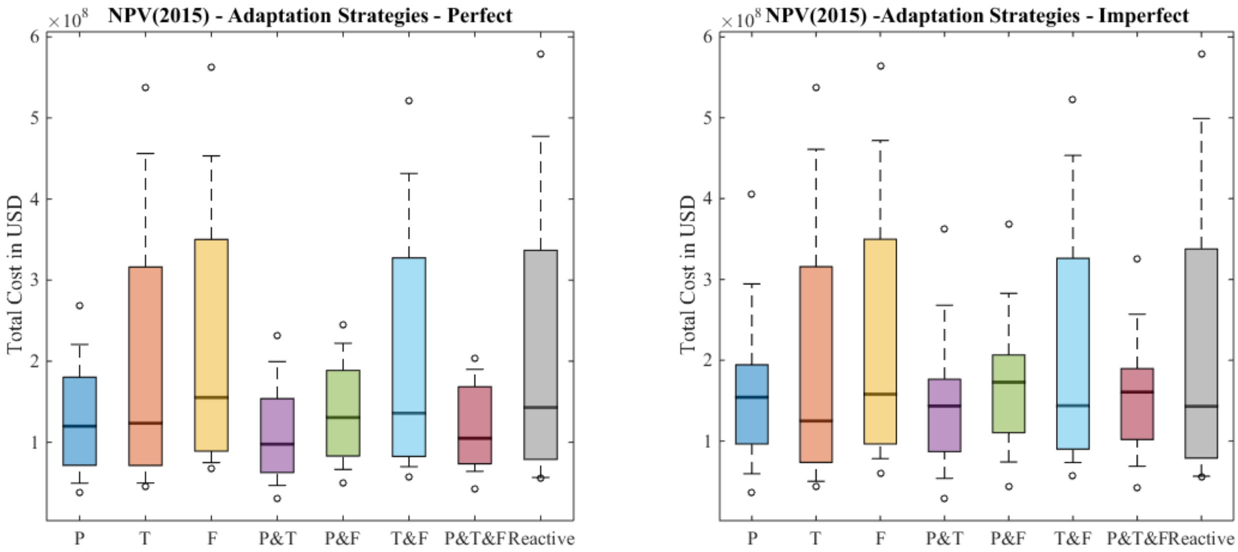


Figure 7.12: Case study #2; NPV of All Adaptation Strategies combined. Perfect Foresight (left) and Imperfect Foresight (right)

For this second example in Kenya, looking at the perfect foresight shows that the strategies projected to have a lower net present value are those which adapt using four strategies: adapting to only precipitation; adapting to both precipitation and temperature; adapting to both precipitation and flooding; and adapting to all of the stressors. However, when considering imperfect foresight, the conclusion requires a more in depth analysis of regret and robustness.

7.1.2.2 REGRET

This section builds on the concept of imperfect foresight and the development of the metric of regret. This section closely follows the methodology presented in Chapter 5. Figure 7.13 shows the regret distribution for each of the eight strategies including the reactive strategy. Each distribution includes 1521 regret values coming from comparing each of the 39 possible adaptation design to 39 possible climate projections.

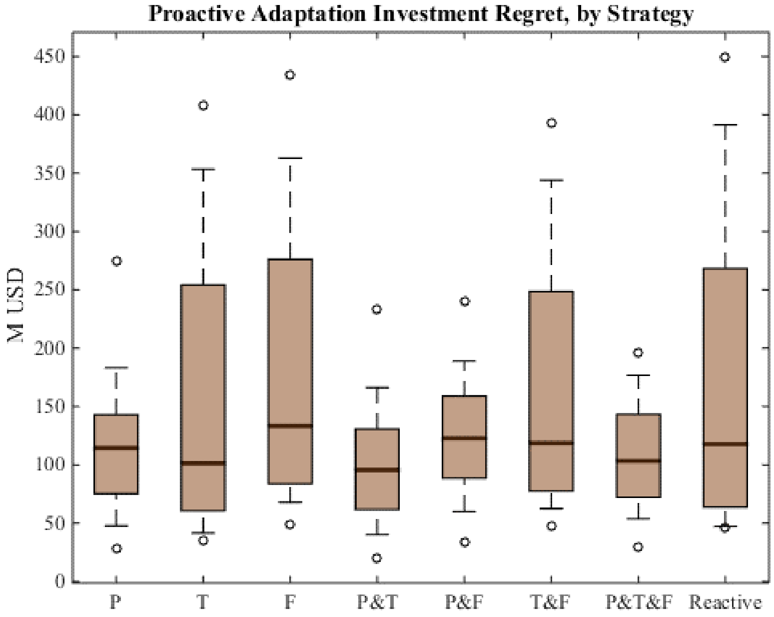


Figure 7.13: Case study #2; Regret Distribution for each adaptation strategy

From Figure 7.13, adapting only to temperature as well as to precipitation and temperature have the lower medians across all distributions (thick back line inside box). However, adapting only to temperature have the widest range of regret (size of the brown box), indicating a large variability and sensitivity to uncertainty. Adapting only to precipitation as well as adapting to all three stressors has a slightly higher median but a much narrower range; half the interquartile range of adapting only to temperature. Each of the distributions includes all the possible adaptation design for each strategy, including conservative design and minimal adaptation design. Next, this case study will explore and will discuss regret distributions for all designs.

In Figure 7.14, the regret distributions from adapting a specific stressor to a certain climate model are plotted with the adaptation cost (the green line). In this case, each distribution contains 39 values equal to compare each design to the 39 possible climate projections.

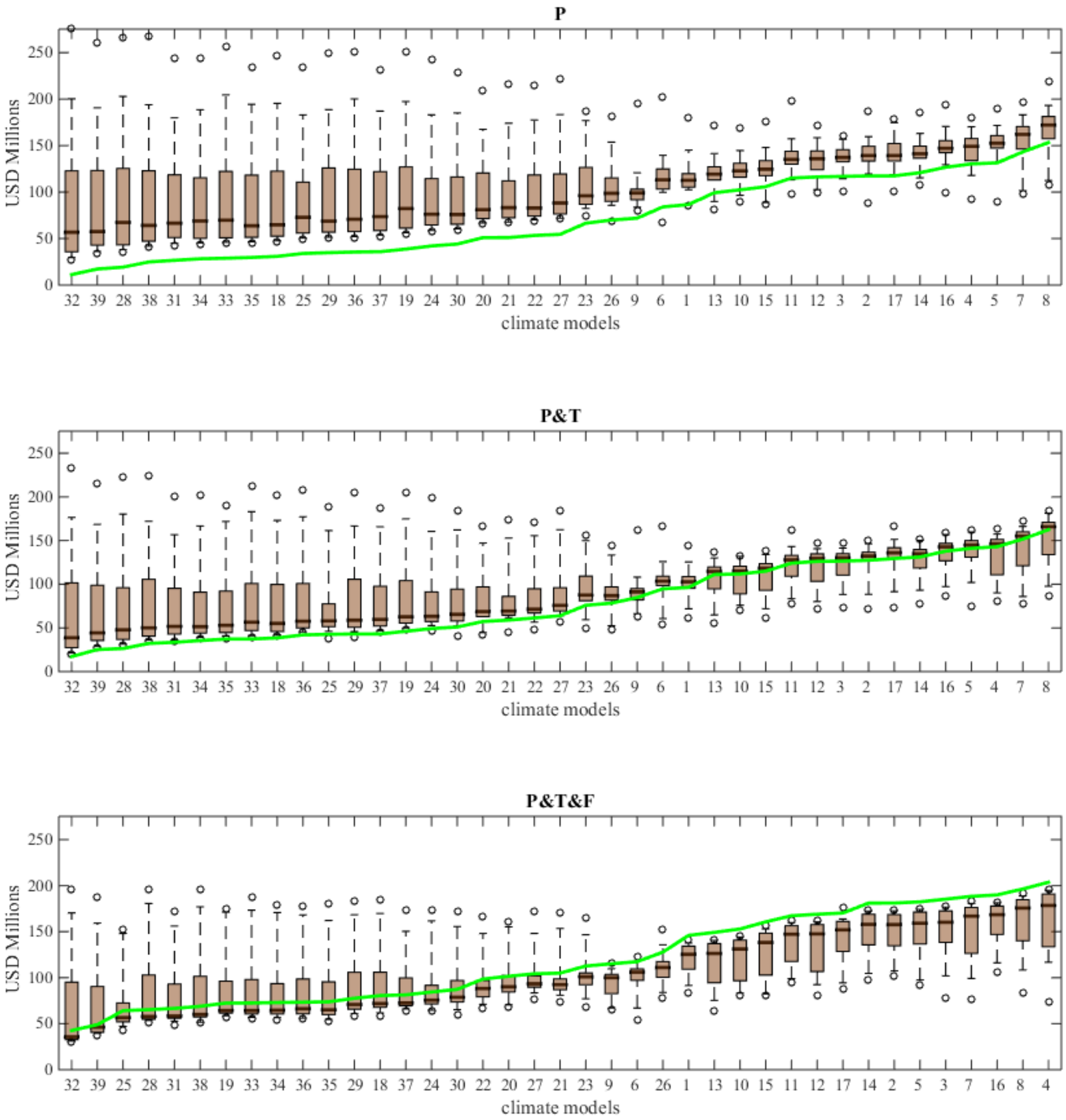


Figure 7.14: Case study #2; Regret Distributions and Adaptation Cost (green line) for Adapt to Precipitation only (A), Adapt to Precipitation and Temperature (B) and Adapt to all (C).

From Figure 7.14, it is clear that putting more money towards adaptation using any of the strategies will result in a more robust decision as the regret distribution gets smaller while the adaptation costs increase. This is clear for adaptation only to precipitation and adaptation to both for precipitation and temperature, Figure 7.14 B and C. However adapting to all three stressors does not make this clear. This may be explained by the concept of regret from over-expenditure and the high variability of flooding impacts.

7.1.2.3 ROBUST DECISION MAKING

The previous section indicates that each decision needs to be treated independently as there are substantial differences between the regret distributions when looking at different adaptation design based on the severity of climate projections. This section focuses on the distribution of regret which is simplified to a single metric, “regret indicator” introduced and defined in Chapter 6.

As a reminder, a “higher regret” indicator describes a wider distribution of regret, and thus a higher sensitivity to uncertainty. “Lower values” of regret describe adaptation designs with smaller regret distributions, indicating a design with a more robust behavior. This section incorporates the regret indicator analysis with the budget constraints presented earlier in this chapter; the upfront adaptation cost and the remaining additional maintenance required for the lifespan of the infrastructure.

In Figure 7.15 below, the 39 possible adaptation designs are plotted for each of the eight strategies. It is important to note that the no adaptation strategy (reactive) only have one point in the plot as this strategy is a reactive approach that does not consider climate projections. In total, there are 274 options plotted in Figure 7.15. The horizontal axis is the expected additional maintenance cost from all the possible climate projections. The vertical axis is the upfront adaptation cost in order to upgrade the infrastructure to withstand future climate impacts. Both axes are expressed in millions of USD, and are discounted cost at a 3% rate, for the total length of study 2015-2050.

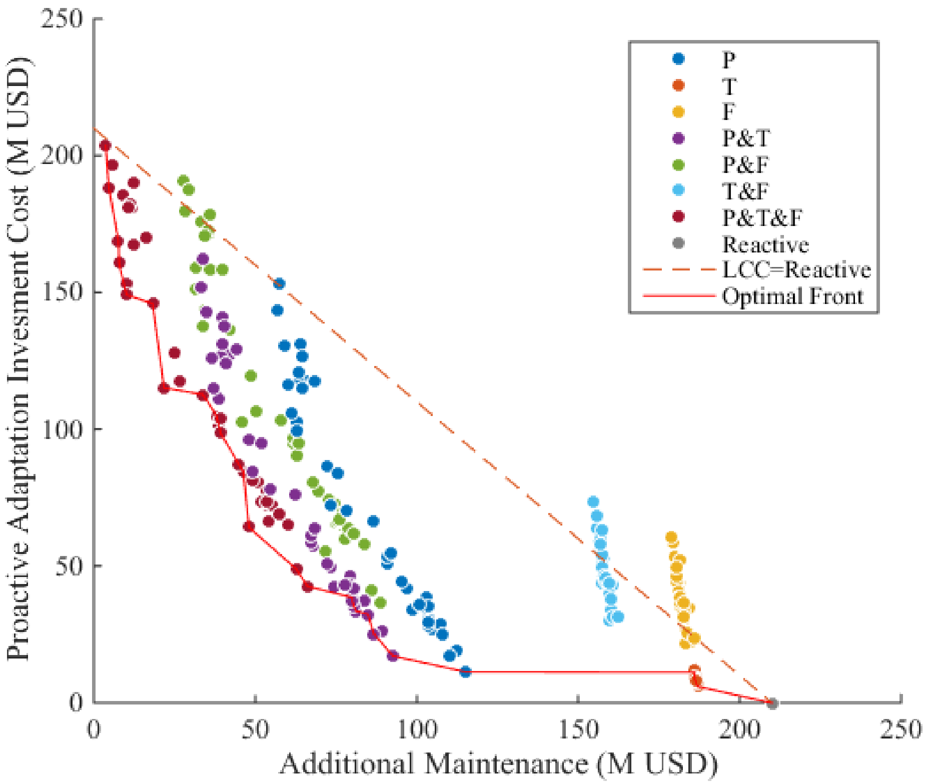


Figure 7.15: Case study #2; Adapt cost vs Additional Maintenance scatter plots

The dashed line in Figure 7.15 shows total life-cycle cost (sum of horizontal and vertical axis) equal to the reactive strategy, so again any option above the dash line will not be economically preferable than reactive approach. On the other side the further below from that line will show lower overall net present value. The negative slope of most of the strategies suggests that increasing upfront adaptation cost will reduce the expected additional maintenance cost. The red line is the “optimal line”, or “Pareto front”. From this figure some discussion and conclusion can be drawn from this second case study. Adapting only to precipitation, adapting only to temperature, adapting to both precipitation and temperature and adapting to all three stressor are in the optimal frontier. However each of them have substantial difference. Adapting to all stressor is on the most conservative strategy with the highest adaptation cost and the lowest additional maintenance. Adapting only to temperature has, on the other side, a very lower adaptation cost but a large values for expected additional maintenance. Adapting only to precipitation impacts or adapting to both precipitation and temperature represent a middle ground on the optimal frontier. Interestingly, adapting only to flood or adapting to both flood and temperature are cluster in the higher additional maintenance zone even with high adaptation cost. These two strategies don't have an optimal behavior and are projected to have a higher life-cycle cost than the reactive approach. This can be explained looking back at Figure 7.11; precipitation is the stressor with larger impact. Failing to adapt to precipitation will result with larger projected maintenance. At the same time, the projected impact from flooding is highly uncertain, so increasing adaptation protection for flooding does not exactly correlate with lower additional maintenance. This may be explained by the higher geographical variability of flooding event. The area of analysis covers more than 200,000 sq. km. Therefore, certain models could project sever floods in a certain area while others project more intense events in the other side of the state. These statements are clear while looking at adapting only to flooding or adapting to both temperature and flooding (yellow and light blue respectively). All points in these two strategies fall around \$160 MUSD or \$180 MUSD of additional maintenance, the expected impact cost for precipitation plus temperature (Figure 7.11). Additionally, adaptation only to temperature (orange) are more clustered than any other option. This may be explain because there is much agreement and less variability between the models while projecting increase of temperature. On the other side projections of precipitation have a wider range of values, with high variability across the country, leading to a less clustered distribution of adapting only to precipitation (dark blue dots).

The following figures incorporate the metric of regret and are combined with either of the budget constrain variables. Similar to the previous figure, each of the 39 possible adaptation designs are plotted for all adaptation strategies in Figure 7.16. The horizontal axis is the upfront adaptation cost, while the regret indicator is on the vertical axis. Units of regret indicator are millions of USD.

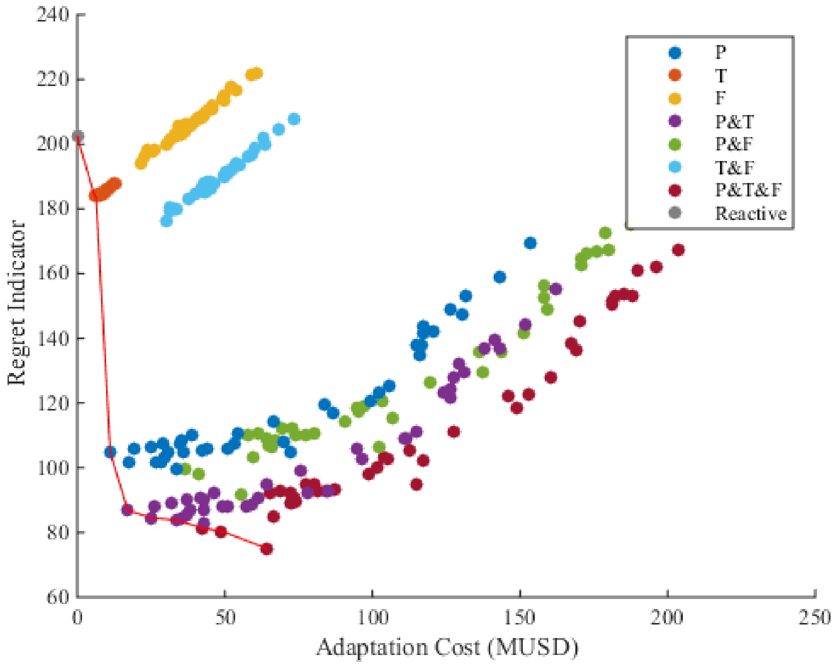


Figure 7.16: Case Study #2; Regret Indicator vs Adaptation Cost scatter plots

The red line in Figure 7.16 indicates the optimal front when the regret indicator is compared to the upfront adaptation cost. In this second analysis, adapting only to precipitation, adapting only to temperature, adapting to both precipitation and temperature and adapting to all the three stressor are on the optimal front. However adapting only to temperature has a large value of regret indicator showing a wide distribution of regret when compared to the other strategies. Adapting to all three stressors has the lower value of regret indicator indicating a high robustness. The trend of any adaptation that includes addressing precipitation impacts reveals a bi-slope behavior. These strategies seems to have a slightly negative slope until reaching an adaption cost around $60 MUSD. Then the slope becomes positive revealing that more upfront investment in adaptation will result in higher regrets. One explanation could be that the regret comes from extra proactive adaptation expenditure as described in Chapter 5. This bi-slope behavior indicates optimality around $60 MUSD of proactive investment.

Finally in a similar way, the regret indicator is plotted against additional maintenance in Figure 7.17. The horizontal axis is this time the expected value of additional maintenance, while the regret indicator is on the vertical axis. Unit of regret indicator are millions of USD.

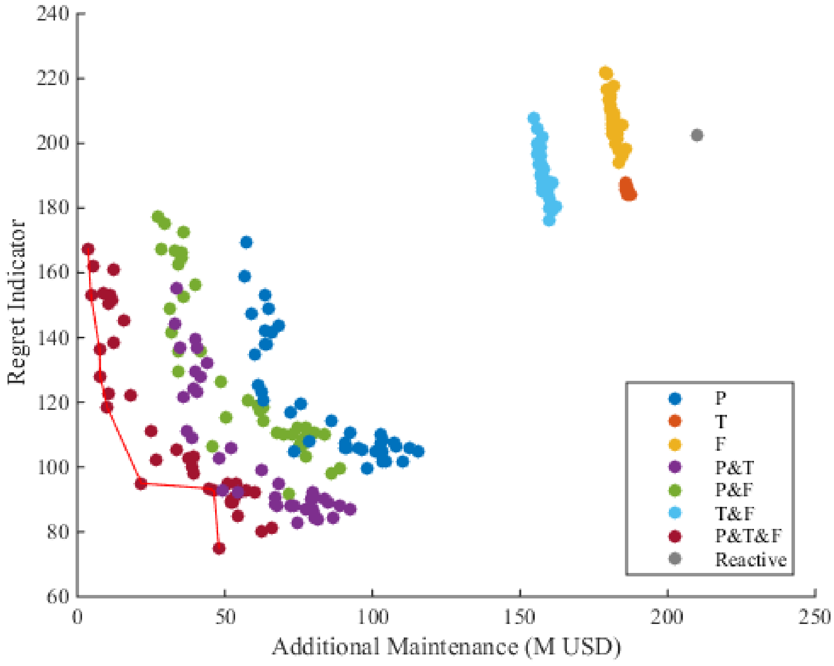


Figure 7.17: Case study #2; Regret Indicator vs Additional Maintenance scatter plot

The general trend in Figure 7.17 combines the two previous figures presented above. Surprisingly if a single strategy is analyzed the higher the additional maintenance the lower the regret. This is connected to the conclusions from the previous figure, where higher proactive adaptation investments lead to higher regret. However while looking across strategies adapting to the three stressors will reach the lower regret while projecting the lower expected additional maintenance.

Finally in an effort to combine the information displayed in the last three figures in a single visual graph, Figure 7.18 was created. It follows the same characteristics as Figure 7.15, where the strategies are plotted against the upfront adaptation cost and the cost additional maintenance. Each of the points in the plot is given a radius; the size of the radius is a function of the regret indicator. To add another piece of information, the points are accompanied by a number that indicates the climate model used to define the adaptation level. To simplify the scatter plots only strategies that are in the Pareto or optimal front have been plotted.

Figure 7.18 summarizes all the information provided in this chapter in a single figure and is intended to clearly support and assist managers in choosing the optimal decision for their specific inventory and location.

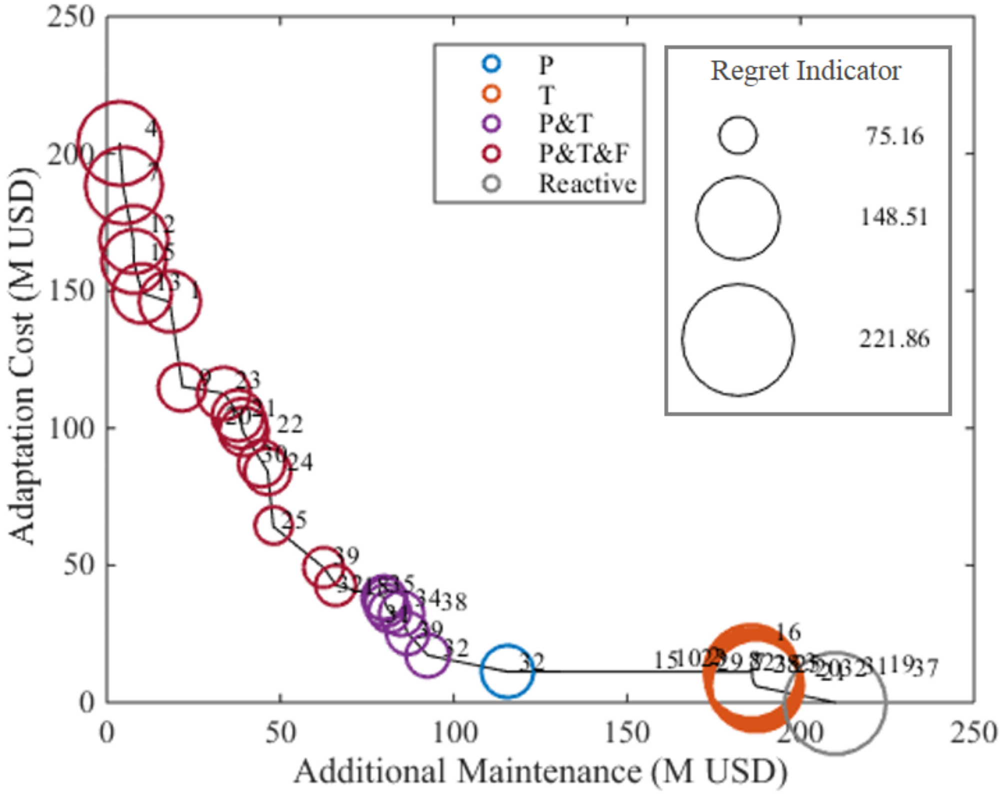


Figure 7.18: Case study #2; Regret Indicator with budget constrains

This second case study has revealed that the most robust designs are not achieved by higher proactive up front adaptation investment. In particular, the designs with lower regret are middle range adaptation, around $50 MUSD of proactive investment. At the same time these options are projected to have the lower total life-cycle cost, when upfront cost and projected additional maintenance are summed. Adapting to all three stressors using model 25 or 39, is economically optimal and have the least of all regrets. These two designs have a proactive upfront investment of $50 MUSD, leading to $50 MUSD of projected additional maintenance. The regret of both designs is around $75 MUSD, being model 25 slight inferior to that value. If upfront investment is constrained by budget allocation, adapting to both precipitation and temperature is the next best option. Most of the design for this strategy will result in a similar regret, above $80 MUSD with an upfront proactive investment under $40 MUSD. If the upfront cost is limited to $20 MUSD, adapting only to precipitation using design 32 will be the optimal option with a projected regret above $100 MUSD. Finally, adapting only to temperature will result in very small value of upfront adaptation investment with a slightly reduction of regret and a smaller total life-cycle cost when compared to the reactive approach.

7.2 LIMITATIONS

The purpose of this chapter is to discuss the flexibility of the framework and explore different methodologies to deal with situations where the budget is constrained, either upfront adaptation cost or projected additional maintenance or both. Prioritization problems are highly complex and for this discussion chapter a lot of simplification and assumptions have been made. Each of the chapters is built on the previous one; therefore limitations and scoping discussed in one chapter are carried to the following one. Each of the previous chapters includes a final section which discusses the limitations specific to that particular chapter. In this section, the following paragraphs highlight additional limitations of the framework and methodology presented in this dissertation which have not yet been addressed. Firstly, It is considered through this dissertation that each climate projection is equally likely to occur. This limitation come from the fact of lower consensus among researcher and scientist about the probability distribution of climate projections.

This chapter does not deal with different choices made across geographical locations. The impacts and values of regret through this chapter are quantified at a climate unit scale with a resolution of 0.5x0.5 degrees. In studies that include multiple climate units, the values are then added together. The regret distributions and regret indicator are calculated for the entire area of analysis and the decision on robustness are made at a national scale. Case study #1 did not have this limitation as it only uses one specific location.

However this limitation is present in the second study where the analysis is made at a system perspective including more than 1,400 kilometers of inventory.

Similar to the limitation presented above, the design options considered in this chapter do not contemplate the option of combining the design of one stressor for one climate and a different climate for another stressor. This limitation could be easily addressed in the methodology but it will require a large amount of computational power as the options will increase exponentially. The second case study deals with 274 options while allowing combinations of climate design will result in 64,000 options.

The first limitation simplifies the geographical variability and the second limitation simplifies the number of options, both made in order to reduce computational effort. Another limitation deals with time scale of the analysis. The impacts are calculated over time from 2015 – 2050. However, the adaptation is only considered as a possibility at the beginning of the analysis. Lower values of regret and more robust decisions could point towards options that delay the adaptation several years; this option is not included in this analysis. Additionally, once the decision to adapt is made, the adaptation is considered to remain constant for the rest of the analysis. If the life of a piece of infrastructure ends before the period of analysis finishes it is considered that the infrastructure will be rebuilt to serve in the remaining years of analysis with the same adaptation design decided at the beginning of the analysis.

Most of the above limitations could lead potentially to future work as each of the points could be developed with more time and resources. The next section is devoted specifically to discussing the future steps of this research.

7.3 FUTURE WORK

One of the first future steps to continuing this research will be to incorporate the option of combining strategies with different climate designs. More robust design could mean to upgrade the temperature for one climate projection while looking at another climate model to design the proactive adaptation for increase of precipitation. This dissertation does not intend to find the one climate model that will lead to the most robust decision, its aim is to suggest engineering design that are more robust under the uncertainty of climate change. So from this perspective it would seem reasonable to uses different climate projections to define the adaptation levels of different stressors. It is expected that combining strategies with different climate design could result in options with lower values of regret indicator, which would therefore provide more robust investment. Following this task, a further step is to develop the option of different proactive strategies and designs based on geographic locations. If an infrastructure system is analyzed in the proposed framework it will only consider one single adaptation investment for the entire system. Implementing this task will allow to go one step farther into finding robust designs, and it will be expected to find options that substantially lower the regret respect the current approach when entire systems are analyzed, as in the second case study on this chapter.

Another future task could explore the option of including time and delay in the period when the proactive investment occurs. It will be interesting to test if delaying the proactive investment could result in higher robustness and therefore lowering the regret of the adaptation designs. Another task following the previous one would be to explore the idea of adaptive or flexible designs (Gersonius et al. 2012; Haasnoot et al. 2013), indicating proactive investment in projects and designs that can be modified and upgrade over time once less uncertain climate is projected.

This dissertation focuses on fiscal costs for repair and maintenance of the infrastructure or costs to upgrade and adapt to future climate impacts. It excludes other types of costs associated with the impact of climate change in the infrastructure, such as the costs to users of infrastructure or to businesses and markets due to delays and disruptions of transport. A reasonable next step in this arena of study will be to incorporate these other types of cost into the analysis.

Several times in this dissertation it has been stated that the framework and methodology are flexible enough to work in proactive investment of any type of infrastructure system. A reasonable next step would be to actually test the framework using a case study with a different infrastructure system, such as buildings, bridges, or pipelines. In the same line, this methodology has been built to work with cost inputs coming from the IPSS tool developed by Dr. Chinowsky's research group. A next step would be to implement the methodology in a software tool that could allow any types of cost input and not only information directly from IPSS.

A final broader future line of work will be to incorporate the results from this framework in a more holistic multi-criteria decision analysis to discuss the viability of combining these results with other aspects as social impacts, community vulnerability environmental impact and others.

7.4 FINAL THOUGHTS

This section is designed to present the final thoughts and discussion points of this limitations chapter specifically, and from the dissertation overall. It represents a wrapping-up of this section before progressing into the general conclusion chapter.

First, it is important to consider the size of the area of analysis in order to get accurate results from the framework. In general, smaller areas will be preferable. Where this framework is used in a large infrastructure system covering an extensive area of analysis – especially if it has substantial climatological variations - it can lead to prioritizing investment that are not the most robust options if considered at a more local scale. Large infrastructure systems should be located in a small region or a region with similar climatology and have homogenous characteristic in order to get accurate results from this methodology. The framework provides in any case the most robust asset of investment for the same decision all over the infrastructure system, however when the area of analysis is large there could be other region-specific combination of investments that are would lead to a more robust investment.

Given the research and studies done in this dissertation, it is not valid to provide general conclusions as to what type of investments are generally "most" robust. From the different examples provided in this dissertation, it is clear that robust investments are specific to a geographic location. While more conservative designs tend to be more robust in some cases (as shown in case study number 1), the middle-range adaptation level is the most robust option across all possible investments for the second one. In this second example, more conservative designs imply large potential regret from over-spending.

This dissertation and the novel proposed methodology is rooted in classic decision making and serves as an expansion of the existing approaches. Current decision making on civil infrastructure systems looks at historical climate values to design and build. Chapter 4 of this thesis identifies the need of advancing this current approach of decision making, with the consequence that huge amounts of effort and investment could be wasted if climate change is not incorporated into the current practices. Chapter 5 incorporates a new metric to consider during cost-benefit analysis to better capture the impacts of climate change and the uncertainty associated with the impact analysis. Chapter 6 develops a methodology to support and assist decision makers to choose climate change adaptation options including the regret metric identified in the previous chapter and a new method to calculate robustness. Finally in Chapter 7 the concept of limited budget is discussed and several solutions are presented for decision makers to evaluate their adaptation options while different investment options are constrained.

This dissertation directly improves and benefits the current approach as it adds another piece of information to allow decision makers to make a more accurate choice on how to allocate their investments. It reinforces the idea that proactive climate change adaptation designs in infrastructure systems is an imperative.

Lastly, social prioritization and criticality studies are indispensable to accompany this methodology. This framework solely looks at the robustness of investments by determining strategies and designs that have the least amount of potential economic regret. Civil infrastructure systems are put in place to serve people and communities with very distinct needs and vulnerabilities, therefore, it is indispensable that prioritization of proactive adaptation investments looks at a geography around the infrastructure and to a broader perspective, making sure to include other considerations such as environmental or social.

Chapter 8 CONCLUSION

The deep uncertainty of climate change adaptation measures and the challenges that arise when selecting appropriate economic and engineering strategies for this uncertainty require a new method of thinking by transportation and policy decision-makers. The project has shown thus far that robust cost prioritization provides a comprehensive and viable tool for dealing with deep uncertainty in transportation adaptation investment strategies for climate change. Building from this concept, the framework developed for this research offers a novel method for regret-based decision-making of transportation adaptation.

At the beginning of this dissertation two research questions where formulated:

- How can uncertainty on climate change impact assessments be incorporated into transport planning? Can a framework for incorporating uncertainty be developed to assist in addressing this area of concern?
- Would considering uncertainty allow transport governance agencies to make more holistic and efficient decisions?

These questions have not yet been explicitly answered but they have been addressed through the chapters and sections of this dissertation. This dissertation concludes that it is possible and necessary to include climate change into transportation planning. The issue of uncertainty can be address with new method of prioritizing transportation investments that will support the planning process. This dissertation presents a framework that will assist infrastructure planners on dealing with uncertainty in proactive adaptation projects through providing robust options that are less sensitive to uncertainty. As it has been demonstrated through the case studies incorporating and considering uncertainty and utilizing the novel approach presented in this dissertation could lead to make more efficient decision minimizing potential regret and increasing savings.

In Chapter 4 a tool to model potential vulnerability and potential impacts of climate change on road infrastructure is presented using a case study in Mexico primary transportation network. The goal of this chapter was to identify the critical effects of climate change into the engineering design of roads, focused specific on long-term and chronic stressors as increase of average temperature or cumulative precipitation. It is demonstrated through the case study that climate change will substantially increase the cost associated with maintenance and repair and will represent a financial burden for the already under budgeted transportation department and agencies. These findings show that impacts and vulnerabilities are geographically heterogonous as they depend on the local climate projection and the regional road inventory. Particularly the North East region of Mexico is highly vulnerable to climate change in terms of both financial costs and relative impacts, with a projected increase in total fiscal cost between 2015 and 2050. The state of Coahuila, located in the North East, is particularly vulnerable compared to its neighbors, with an opportunity cost that ranges from 54% - 145%. These results highlight the importance of considering climate change projection in present engineering and design decision and into present day maintenance budgets. This chapter builds the need for the research undertaken in Chapter 5, Chapter 6 and Chapter 7 and serves as point of departure for the other chapters of this dissertation.

Based on the need, presented on Chapter 5, to update and expand classic costing methods for adaptation to climate change projects, Chapter 5 introduces the concept of regret as a viable and ready to use alternative to conduct cost-benefit analysis of proactive adaptation design. This concept is illustrated using a transport infrastructure project in the countries of Kenya and South Sudan, which is part of the African Continental infrastructure plan PIDA. This study reveals that the road investments in this region are threatened by future climate impacts. The climate change impacts could incur extra repair and maintenance costs that range from $73-348 MUSD in Kenya and $127-492 MUSD in South Sudan, due to increase of heat, precipitation, and frequency of flooding events. The metric of regret is presented valuable to determine the most suitable adaptation design from a suite of options. In particular, the findings demonstrate that the decision of what climate projections to adapt for could result in an extra impact of more than 10 times the planned budget, while the maximum regret from overspending is less than 80% of the predicted cost for the case of the Kenya PIDA project. These results are an illustration of the critical importance for planners to begin broadening the perspective with which future investment and planning decisions are made. By utilizing the tools and techniques put forward in this chapter, planners can significantly reduce not only the financial cost of climate change, but increase the robustness, resiliency, and integrity of the road infrastructure network in the coming decades.

Chapter 6 goes a step forward and proposed a framework to assist transportation planners in selecting the most appropriate proactive adaptation projects for their specific asset and location. The framework follows a five stage approach: the first identifies infrastructure design adaptation strategies. The second quantifies the costs and benefits of possible adaptation strategies. The third calculates economic indicators for each of the strategies based on perfect future climate foresight. The fourth compares each strategy across all possible climate scenarios. The fifth and final stage of the framework uses robust decision making to determine the regret between strategies and between possible future scenarios. This methodology promotes a more efficient and accurate long-term, environmental and holistic planning of road infrastructure, leading to resilient, robust and sustainable transportation systems. Chapter 6 uses a road maintenance project as a showcase for the framework. It uses the state of Coahuila, the most vulnerable region in Mexico identified in Chapter 4, as the location for the case study. Proactively adapting to increase of precipitation and temperature is found to be the most robust investments option for the state of Coahuila department of transportation. While the case study is specific for transportation infrastructure, the framework is intended to support any adaptation project in any civil infrastructure system. Finally Chapter 7 takes the output of the framework presents in Chapter 6 and discusses the possible visualization options to support decision makers when facing situation of budget constrain in both the upfront proactive investment cost and projected additional maintenance due to climate change impacts.

While deep uncertainty of future climate changes is currently a challenge facing decision-makers, tools such as the framework proposed in this dissertation make it possible to incorporate and understand climate change impacts into planning strategy.

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APPENDIX 1: LIST OF CMIP 3 AND CMIP 5

The results in Chapter 4 and Chapter 6 are obtained using CMIP3 climate models. Table 0.1 lists the climate models names and the institution they belong too. For each model three scenarios where used A2, A1B, and B1 when available. In Chapter 5 an ensemble of CMIP5 where used. Table 0.2 lists the climate models. For each of CMIP5 models two scenarios were used rcp 4.5 and rcp 8.5. The two variables used from these models are maximum temperature and precipitation rate.

Table 0.1: List of CMIP3 used in this dissertation

CMIP3 Models Downloaded for A2, A1B, B1 scenarios:		
Model Name	**Institute Name**	**Institute ID**
bccr-bcm2.0	Bjerknes Centre for Climate Research	BCCR
cccma-cgcm3.1	National Center for Atmospheric Research	NCAR
cccma-cgcm3.1-t63**	Canadian Centre for Climate Modelling and Analysis	CCCMA
cnrm-cm3	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS
csiro-mk3.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
csiro-mk3.5	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
gfdl-cm2.0**	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
gfdl-cm2.1	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
giss-aom**	NASA Goddard Institute for Space Studies	NASA GISS
giss-eh*	NASA Goddard Institute for Space Studies	NASA GISS
giss-er	NASA Goddard Institute for Space Studies	NASA GISS
fgoals-g1.0**	LASG/Insitute of Atmospheric Physics	LASG-CESS
inm-cm3.0	Institute for Numerical Mathematics	INM
ipsl-cm4	Institut Pierre-Simon Laplace	IPSL
miroc3.2-hires**	Center for Climate System Research (The University of Tokyo)	MIROC
miroc3.2-medres	Center for Climate System Research (The University of Tokyo)	MIROC
mpi-echam5	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M

mri-cgcm2.3.2	Meteorological Research Institute	MRI
ncar-ccsm3-0	National Center for Atmospheric Research	NCAR
ncar-pcm1**	National Center for Atmospheric Research	NCAR
ukmo-hadcm3**	Met Office Hadley Centre for Climate Prediction and Research	MOHC
ukmo-hadgem1**	Met Office Hadley Centre for Climate Prediction and Research	MOHC

* only one scenarios used / ** two scenarios used

Table 0.2: List of CMIP5 used in this dissertation

CMIP5 Models Downloaded for RCP 4.5 and RCP 8:		
Model Name	**Institute Name**	**Institute ID**
access1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	BCC
canesm2	Canadian Centre for Climate Modelling and Analysis	CCCMA
ccsm4	National Center for Atmospheric Research	NCAR
cesm1-bgc	Community Earth System Model Contributors	NSF-DOE-NCAR
cnrm-cm5	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS
csiro-mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
gfdl-cm3	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
gfdl-esm2g	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
gfdl-esm2m	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
inmcm4	Institute for Numerical Mathematics	INM
ipsl-cm5a-lr	Institut Pierre-Simon Laplace	IPSL
ipsl-cm5a-mr	Institut Pierre-Simon Laplace	IPSL
miroc-esm	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
miroc-esm-chem	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
miroc5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
mpi-esm-lr	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M
mpi-esm-mr	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M
mri-cgcm3	Meteorological Research Institute	MRI
noresm1-m	Norwegian Climate Centre	NCC