Infrastructure life cycle management under climate change uncertainty

A new dynamic method applied to road tunnels in the Netherlands

Ioannis Savvidis

October 2020

TU Delft

SWECO

-Page intentionally left blank-

Author

Name: Ioannis Savvidis

Student number: 4794982

Email address: I.Savvidis@student.tudelft.nl

Graduation Thesis

University: Delft University of Technology

Faculty: Civil engineering and Geosciences

Track: Construction Management & Engineering

Course: CME2001 Master Thesis Preparation and CME20000 Graduation Thesis

Committee

Chairman
Prof.dr. G.P. (Bert) van Wee
Faculty of Technology, Policy and Management

Supervisor
Dr.ir. Martine van den Boomen MBA
Department Materials, Mechanics, Management & Design (3Md)
Integral Design & Management Engineering Project Management

Supervisor
Dr. J.A. (Jan Anne) Annema
Faculty of Technology, Policy and Management

External Supervisor
Ir. Jielis van Schnijdel
Sweco Netherlands

Acknowledgement

This graduation thesis is conducted as a research requirement for the acquisition of the MSc diploma in Construction Management & Engineering at the Delft University of Technology and is carried out in collaboration with Sweco Netherlands. The research work concentrates on the asset management of big road infrastructure, particularly in the road tunnels of the Dutch highway network. The ongoing climate change triggered my focus to study how to correlate and define a long-term decision-making process that considers the effects of climate change. Although the venture was quite complex and scientifically demanding but also due to the strange conditions of 2020, I am still very excited about this choice of my research subject. The graduation committee acknowledged and praised me for completing the research with desired results.

My thesis committee in TU Delft was always willing to respond to my questions and the supervisors were motivating me throughout the research progress. I would like to thank them for their support and positiveness. Dr. Martine van den Boomen was involved since the beginning and inspired me to this scientific direction. She was my 1st supervisor, and her guidance was enough to motivate me to the right scientific way of research. I would also like to thank Dr. Jan Anne Annema, my 2nd supervisor. During the meetings, he was always concerned about the thoroughness of my report and advised me to make continuous progress. Finally, I would like to express my gratitude to Prof. dr. Bert van Wee, the chairman of my committee, who always asked me critical and direct questions so as to ensure that my research would add value to science and society.

Moreover, I felt very honored for being a part of the asset management team of Sweco, Netherlands (in De Bilt) for a period of seven months. I express my gratitude to Sweco, Netherlands and all the team members for the knowledge, guidance, and support they gave during my graduation internship. We shared common research concerns and ambitions for the future outcomes of the research. Everyone was enthusiastic about my research attempt and was willing to spend time in discussing and advising me on the research progress. I would like to pay my regards to Mr. Peter Vermey, the first person from the company who embraced my research interests and supported me in drafting the final research proposal. Additionally, Mr. Jielis van Schijndel, my company supervisor, who helped me throughout with my general concerns and introduced me to any personnel in the company that I needed to consult for my research.

Last but not the least, special thanks to my family for supporting me to realize my goals all these years and my friends for their unreserved attitude towards me. Their encouragement in decisive moments for me made me enjoy these two academic years to the maximum.

Ioannis (Yagos) Savvidis
Delft, October 2020

Executive Summary

Climate change is widely known about the uncertainties that come up for the future of road tunnel infrastructure. The effects can be considerable and effective life cycle management of those assets is getting integral for their prosperity. The limitations of current decision-making processes to deal with deep uncertainty, like the climate change, inspired the exploration of an alternative methodology that it is promising to face the dynamic nature of such uncertainties in long-term horizon in a flexible rather than static way proposing adaptation measures that are implemented when the future climate indicates and not the current climate forecasts. This report attempts to answer the following research question: ***To what extent can Dynamic Adaptive Policy Pathways be deployed for the life cycle management of road tunnel infrastructure mitigating the long-term effects of climate change to result in useful decision-making information?***

The model of Dynamic Adaptive Policy Pathways consists of ten theoretical steps, and the execution of the first six of them takes place in this research work. The steps are facing in three phases, two steps in each phase. To give the answer to this main research questions, three sub-questions were defined and are addressing in each phase correspondingly. Indicated colors explain these connections. The rest of steps (7-10) are not in the scope of this research work, mainly because the execution of them is an act of personal decision-making process without the use of a method or tool to support this process.

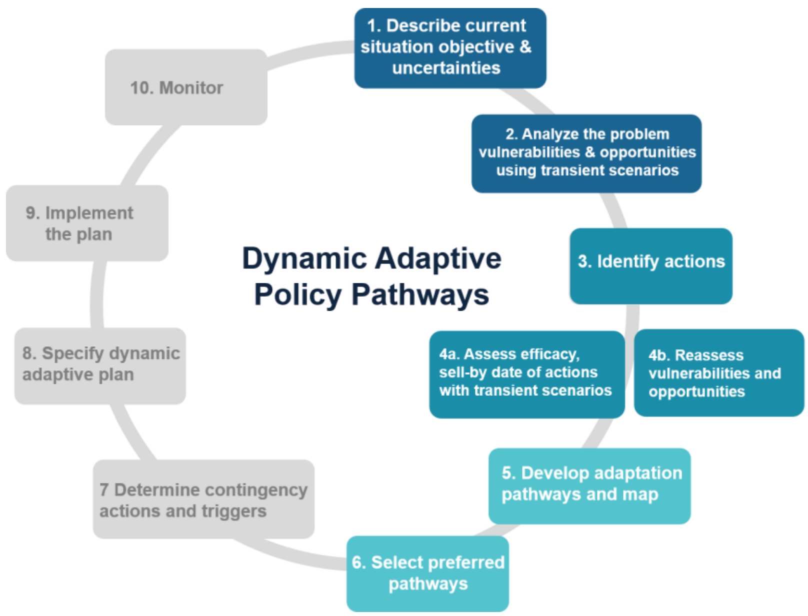


Figure I: The Dynamic Adaptive Policy Pathways model and the executed step in this research work

Phase I. What are the functions of a road tunnel and to what extent can future climate change impact the system's functional failure?

The analysis of the Functional Breakdown Structure (FBS) of a road tunnel and the identification of the associated climate variables respond to the first part of this sub-question and realize the first DAPP step. The definition of functional requirements, the conduction of functional decomposition through the Hamburger model to define the systems and performances which fulfill these functions, and the execution of a Fault Tree Analysis to define the modes of function failure take place in this DAPP step 1. The quantitative and qualitative assessment of the road tunnel's functional failure caused by the identified relevant climate variables gives an answer to the second part of this sub-question and realizes the second DAPP step. The estimation of caused unavailability and qualitative assessment of the resulting impact on six organization values is the content of this DAPP step 2 which summarizes which potential dangers must be faced by proposing adaptation actions.

Phase II. What actions could be taken to prevent functional failures and mitigate consequences?

The indications of the needs for functional failure prevention and impact mitigation are used as input in this phase to achieve the definition of appropriate actions. The BowTie diagrams seem to be suitable to visualize the connection of the events that cause road tunnel unavailability with the associated impact and at the same time to include the associated proposing measures which either they could prevent the event of functional failure or mitigate the impact on the organization's values if a failure occurs. Moreover, the efficacy and a sell-by date of the implementation of the proposals are assessed when the latter are defined, and the actual contribution to their purpose is assessed too. Therefore, the DAPP steps 3 and 4 take places at this phase II.

Phase III. What are the potential dynamic pathways that model the life cycle adaptation strategies? Which ones are preferred to be followed and to what extent do these pathways result in decision-making information that policymakers might use?

The selection of the proposed measures that finally will be included in the strategy is the first task of this phase. The selection of the actions that prevent failure is done based on the seeking action robustness by the methodology executors and the selection of the ones that mitigate the impact if a failure occurs is done based on a scoring process of them on how positive their contribution will be on preserving these six organization values. The formulation of sets of sequential actions and the grouping of them later into sets of actions that follow the same period of implementation for every measure allows the creation of the adaptation pathways. Subsequently, the visualization of them into a map for failure prevention actions and a map for impact mitigation actions is the last task of executing the DAPP steps 5 and 6. Finally, the validation of research work is conducting when assessing the opinion of two interviewee experts for this purpose who answer the question of whether these action pathways result in decision-making information that methodology executors might use in real projects.

By implementing DAPP, I was able to define and conclude to simpler and more compact decision-making plans dealing with deep uncertainty over longer timeframes. These adaptation plans for cause prevention and impact mitigation can be applied regardless the actual climate conditions. In the DAPP methodology, the actual climate conditions indicate the moment the proposed adaptation actions are taken and consequently time flexibility is achieved. The research results seem more effective than the ones of the currently applied decision-making practices. The added value of the DAPP approach lies in its flexible character compared to the to date practices, which mainly define robust adaptation actions that deal with any extreme future and propose strict implementation times. By paying extra attention to the sensitivity of the assumptions and the feasibility of the proposed measures/actions, the decision-making methodology can be improved. Therefore, a useful decision-making methodology for long-term road tunnel assets adaptation, led by environmental changes, was established and further research for improvements are proposed.

List of Contents

List of Figures

List of Tables

1. Research Introduction

The *Research Introduction* consists of the *Problem description* in *subchapter 1.1*. which presents the *Climate change uncertainty (1.1.1.)* in the Netherlands, the *Decision-making limitations (1.1.2.)* to integrate the risks of climate change in long-term horizon and the *Dynamic Adaptive Policy Pathways* characteristics *(1.1.3.)* recognizing the knowledge gap and pointing out the intentions of this research. In *subchapter 1.2*., the *Research objective* is any road tunnel asset that DAPP method is implemented on and the consideration of this asset selection is given. The *Research design*, in *subchapter 1.3.*, aims to define the *main research question (1.3.1.),* the *sub-questions (1.3.2.)* and the *research outcome (1.3.3.)*. Finally, *in subchapter 1.4.* the *Research methodology* is elaborated providing information regarding the *research phases (1.4.1.),* the *data collection and analysis (1.4.2.)* and the process of *verification and validation (1.4.3).*

1.1. Problem description

The problem consists of two correlated parameters. The undoubted global issue of climate change and the decision-making limitations that methods show when dealing with uncertainty in life-cycle road asset management. Climate change is a phenomenon which attracts the attention of more and more infrastructure owners and asset managers nowadays. Its dynamic character brings a lot of uncertainties for the future of many infrastructure assets. These uncertainties are translated into effects in costs, performances and therefore into need for infrastructure adaptability (Auld, Maclver, & Klaassen, 2006). A recent study, which figures out the climate change adverse consequences, concludes that infrastructural assets will mainly experience damages and extended deterioration and, in less extent, temporal loss of their functionality or even permanent failure (Kenny, Dupré, & McEvoy, 2018). Such statements make asset owners and managers to reconsider the future of their asset portfolios and call for adjustments on the new demands. Although the main planning issues are associated with future deep uncertainties, like climate change, which prove to be non-statistical in nature and cannot be reduced by collecting more information (Walker W.E., Lempert R.J., & Kwakkel, 2013), however, experts choose approaches for asset life cycle decision-making for adaptation based on forecasts for the future concluding in static-robust actions.

Dynamic Adaptive Policy Pathways emerges as a promising decision-making model. It is observed that this has not yet been applied in life cycle road asset management. As such the Dynamic Pathways for long-term decision-making lacks experience of being implemented in the road infrastructure both in scientific literature as in professional practice (Ranger, Reeder, & Lowe, 2013). This research gap is going to be explored in the due thesis.

1.2. Research objective

The DAPP model will be deployed at the attempt for life cycle management of road infrastructure dealing with deep uncertainties for the future. The research considers a component of the general road infrastructure system to develop the methodology, a road tunnel asset.

The selection of a tunnel as a case study is mainly reasoning from the system's characteristics. A tunnel is a complex system which performance and therefore well function is depended on its subsystems behavior and other correlated parameters. These components are differently affected from future uncertainties, in this case the future climate conditions. Moreover, a bridge asset would be an interesting choice as well because of the same level of system's complexity. However, data and information availability at that research time led to a tunnel asset selection. It worthy of mentioning the fact that highways are systems whose well function can be managed by taking adaptation actions which demand a shorter time of implementation compared with the ones of the systems. Therefore, the interventions may be of less extent and the investment funds available immediately. When the predictions for the short-term future is well defined, decision-making for the same period seems to perform adequately in highways and not so good for other road systems. DAPP is implemented in exact opposite conditions which is long-term decision-making under deep uncertain environment. Consequently, the advantages of this methodology could not be deployed in a case of highway study.

Future uncertainties regarding climate change effects on a road tunnel raise the concerns of when and how adaptation needs will emerge. This case of study requires processes like the ones which have been dealt with DAPP model. Quite important is the fact that this method is mainly used in water infrastructure decision-making, so by implementing the model's steps (*Figure I*) in road infrastructure management will fill in a knowledge gap and point out strengths and weaknesses of implementing an alternative decision-making approach.

The scientific interest might be expanded further whether the outcome of the current research provides another implementation perspective to DAPP. The specific implementation of DAPP for road tunnel asset management will result in valuable knowledge on the applicability of this methodology in another domain of infrastructure asset management. This applicability would open new directions of achieving optimum decision-making with innovative tools for life cycle infrastructure asset management.

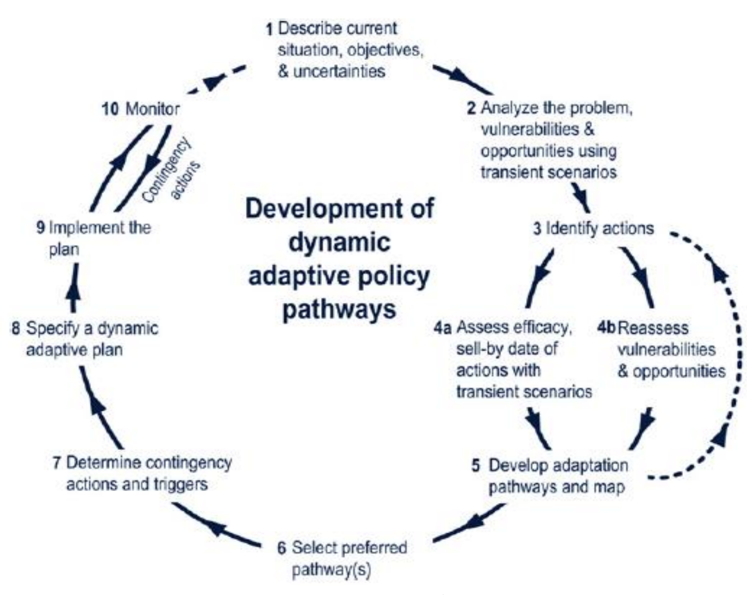


Figure II: The Dynamic Adaptive Policy Pathways approach (Haasnoot M., Kwakkel J.H., Walker W.E., ter Maat J.,2013)

1.3. Research design

The design of the research is presented in this chapter. A main research question is defined in *subchapter 1.3.1.* that reflects the intention of the whole research venture. In order that an answer to be given, three sub-questions have been defined showing at the same time the methodological phases that should be followed to result to sub-answers and consequently to the main one. *Subchapter* 1.3.2. contains the due questions indicating the phases they referred to. Finally, the research outcome, as it is intended in front-end phase, is elaborated in *subchapter 1.3.3.*

1.3.1. Main research question

To what extent can Dynamic Adaptive Policy Pathways be deployed for the life cycle management of road tunnel infrastructure mitigating the long-term effects of climate change to result in useful decision-making information?

There is a variety of methodologies for infrastructure life cycle decision-making under deep uncertainty. However, DAPP is a methodology which presents favorable perspectives regarding the benefits could emerge. It is an approach that could potentially fill in the gap other methods are limited to do so and facilitate adaptive management capable to face the dynamics of deep uncertain future. The so-far successful implementation in water management could be promising for other types as well. The answer to the main question will be a synthesis of answers to the following sub-questions in *subchapter 1.3.2.*

1.3.2. Sub research questions

The definition of three sub-question in this *subchapter* clarifies the focus that is given in each sub-question and indicates the way that will be followed by making a distribution of the research process into three phases. In each Phase, the research will try to give an answer to a given question.

1.3.2.1. Phase I - Sub-Question 1

What are the functions of a road tunnel and to what extent can future climate change impact the system's functional failure?

This question addresses steps 1 and 2 in *Figure I.* The starting point is the outcome analysis of the identification of the main uncertainty drivers of climate change and understand the potential impact on a road tunnel system based on the KNMI'14 scenarios of W_H until 2100. Identification of the road tunnel system function requirements, the definition of function specification (performance) and function solutions (systems), and development of the modes of system's function failure are the tasks in order that the first part of the sub-research question 1 be answered. Based on the findings, the second part of the sub-question 1 is faced. The road tunnel system's functions are analyzed based on their fault tree structures and basic events to express the road tunnel system's functional failure into caused unavailability. It is worth mentioning that the basic events, which are defined considering the products of climate change, are the ones that can make a road tunnel unavailable for operation. In this phase, basic events are indicated that preventive and/or mitigative measures should be defined to face them in order that the adaptation of a road tunnel to the new demands to be done and the tipping points for these potential adaptations are given too (time periods).

1.3.2.2. Phase II – Sub-Question 2

What actions could be taken to prevent functional failures and mitigate consequences?

This sub question addresses steps 3 ad 4 in *Figure I*. Analysis for unavailability response is required at this point by defining the needed adaptation acts (preventive measures, mitigative measures). These are the measures that are proposed to be taken for every basic event, if needed, in its corresponding period and are visualized. These measures will address vulnerabilities and seize potential opportunities. Definition of the moment an action should be taken and when the goal cannot sufficiently be met by this action is also part of this phase.

1.3.2.3. Phase III – Sub-Question 3

What are the potential dynamic pathways that model the life cycle adaptation strategies? Which ones are preferred to be followed and to what extent do these pathways result in decision-making information that policymakers might use?

This sub-question addresses step 5 and 6 in *Figure I.* The pathways are sets of potential sequences of measures that model the adaptation strategies. In the third phase, classifying the measures into order will support the process of shaping the strategies by connecting potential predecessors and successors of every particular action. For the preventive measures, this is executed on robustness term and for the mitigative measures, based on the efficacy of mitigating the potential impact meaningfully.

1.3.3. Intended research outcome

The deployment of Dynamic Adaptive Policy Pathways methodology will give an insight into decision-making under deep uncertain future conditions for road tunnel infrastructure life cycle management. The current research proposes a structured method for designing adaptive paths as part of steps 1 to 6 in *Figure I*. The identification of actions that face risks will be a result of a thorough analysis of climate change effects and reflection of them on the performance of road tunnel system's objects to conclude potential function unavailability. The reassessment of action efficacy to mitigate those risks will conclude to the actions the decision-makers could take. Finally, formulating the strategies will be the last step facing the problem of deep uncertainty and risk dynamics.

2. Research methodology

The first six steps of *Figure I* were followed to give an answer to the main research question and the division into three phases eased the research process. The *subchapter 2.1.* describes the content of them correlating these steps and the tools that support answering the sub-questions. The data acquisition and methodology of analysis is presented in *subchapter 2.2.* Finally, the *subchapter 2.3.* elaborates the process of verification and validation and participating parties.

2.1. Research phases

Phase I

The first two steps of the DAPP method were followed, *1) Describe the current situation, objectives & uncertainties and 2) Analyze the problem, vulnerabilities & opportunities using transient scenarios*, to describe the current situation, objectives, and uncertainties. Review of road tunnel standards and self-assessment defined the road tunnel system's functional breakdown structure (FBS). The FBS was formulated by three parts. Firstly, the establishment of five function requirements was executed based on documentation regarding road tunnel specifications in the Dutch territory, and particularly of RWS. Secondly, the functional decomposition of those five established function requirements was executed to identify the required performance and needed systems of those functions. The methodological tool of Hamburger model was the most appropriate option because its structure supports, in a clear way, the decomposition of an function into subfunctions and then the recognition of latter specifications (required performance) and solutions (required systems to fulfil the performance) which consequently are the ''specifications'' and ''solutions'' of the main function. Thirdly, the construction of the functional failure of each function was taken place by considering the previously gained information and using the methodological tool of Fault Tree analysis model. The top-down analysis that this FT model allows the definition of the initial incidents that lead to functional failure and are named ''basic events'. In this case, the model was deployed to define these basic events that lead to functional failure and the definition was made in such a way to indicate the implicit or explicit connection with climate variables.

After completing the theoretical analysis of the FBS, the quantitative analysis of the road tunnel system's function based on their Fault Tree structures was begun. Starting from the establishment of the timeline of analysis and its division in four segments as tipping points for adaptation, the assessment and calculation of the potential unavailability rates caused by each basic event in every time period allowed the calculation of the total unavailability rate of the associated function based on its Fault Tree structure. This rate reflects its effect on making the road tunnel unavailable for operation. The mathematical expression that was used for the estimation of the unavailability rate is NA= MTTR / (MTBF + MTTR), where NA=unavailability rate, MTTR=Mean Time To Repair and MTBF=Mean Time Between Failure. The MTTR was assessed in days that may are needed to make a road tunnel system operational again but the MTTR was calculated as a ratio of one divided by the assumed failure rate. Subsequently, the percentage contribution of every basic event on the associated function's unavailability was reckoned necessary to be found out because this directed the attention to the basic events that act to a considerable extent. Excel spreadsheets were developed to allow the execution of the calculations. At the same time, qualitative assessment of the caused unavailability impact on organization values that were linked with the road tunnel system for every basic event was executed to complete the tasks of this phase. The outcomes of the quantitative estimation of unavailability percentage contribution rates and qualitative relevant impact produced valuable information for further analysis in *Phase II* by presenting Unavailability percentage contribution – Organization Values impact matrices for each time period of every function. In this way, the conclusion of which basic events require both preventive and mitigative measures, or only preventive, or only mitigative or nothing was able to be done.

Phase II

The answer was given by following the third and fourth steps of *Figure I., 3) Identify actions, 4a) Assess efficacy, sell-by-date actions with transient scenarios, 4b) Reassessment vulnerabilities & opportunities*. Having concluded which basic events required both preventive and mitigative measures, or only preventive, or only mitigative and which basic events did not require any measure to be proposed and taken, the definition of the actual measures was the next act and done in this phase. The methodological tool of BowTie analysis was used for the definition of the adaptation measures which was implemented up to four times (as the number of time periods) for every of the five established road tunnel functions. The BowTie analysis diagram in the due research consisted of the top event, which is the underperformance of the function ''X'', the events that cause the function's underperformance, which were located on the left side of the diagram, the categories of associated impact on organization values that were resulted by these events, which were located on the right side of the diagram and finally, the preventive measures which could help to prevent the top event and mitigative measures which could help the mitigation of the caused impact on organization values. The whole process was visualized in such a way that reminds a bowtie. The purpose of using the BowTie analysis was to provide a structured approach for identifying cause and impact mitigation measures to shape later the strategic map of adaptation to the new demands.

The consideration behind the definition of preventive and mitigative measures was based on the view of what action can prevent underperformance of the function not to happen. With brainstorming, actions that prevent a failure or mitigate the consequences were defined. It was also necessary to evaluate the circumstances under which the actions could substantially be used and the ones the actions could not achieve the object goals, set the sale-by-date of those actions and reassess the efficacy of the mitigative measures by taken them.

Phase III

In this phase the fifth and sixth step were followed*, 5) Develop adaptation pathways and map and 6) Select preferred pathway(s)*, where the decision-making model was finalized. The modeling of strategies was a result of the mutual connection of the concluded actions in *Phase II*. The author recognized the potential predecessor and successor for every adaptation action by assessing actions interdependencies and robustness. Every preventive measure was stated in such a way to deal with the dynamic of the relevant basic event for a particular time period, so when four preventive measures were proposed for a basic event, the way in which the unavailability percentage contribution of that event in the total unavailability rate is evolved over time, indicated how robust decision-making for adaptation should be done. On the other hand, every mitigative measure was stated in such a way to deal with the identified potential impact, of the relevant basic event, for a particular time period, which at the same time indicated the lifespan of these measures. Therefore, by scoring the grade of mitigating the impact on every organization value and then estimating the total score of each mitigative measure, it indicated the preferred order in which the measures should be implemented. In this way, the creation of sets of serial actions was followed and were named, pathways. Visualization of them into a map made clear and specific the outcome of this graduation research. Two maps, one for preventive measures and one for mitigative measures, were depicted similarly as the one on the following map (*Figure III*).

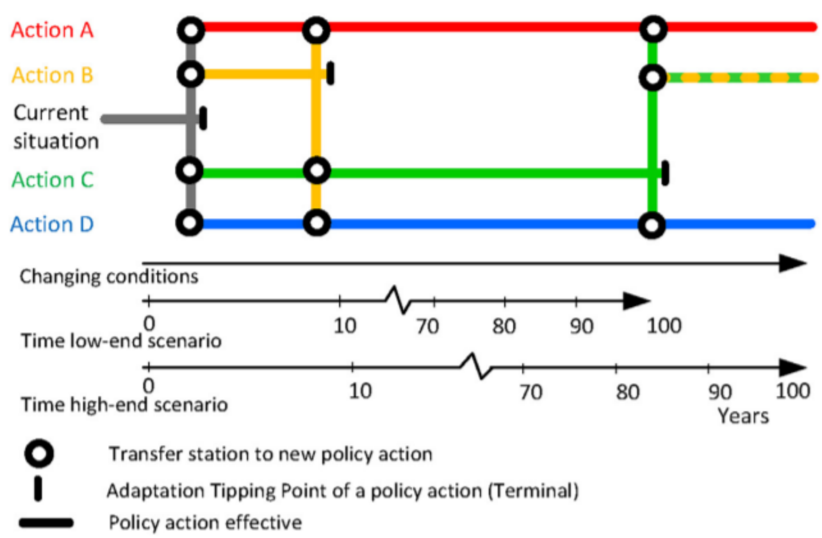


Figure III: An example of an Adaptation Pathways Map (Kwakkel, Haasnoot, & Walker, 2016)

2.2. Data collection

Koninklijk Nederlands Meteorologisch Instituut (KNMI) is a reliable organization that provides information about climate change through a thorough and consistent study of climate change scenarios anticipated with well-recorded data and analysis. The climate change scenarios of 2085 (G_H, W_H, G_L, W_L) were elaborated extensively on the potential evolvement overtime of the climate change impacts (temperature, precipitation, wind, etc.) (KNMI, KNMI'14: Climate Change scenarios for the 21st Century - A Netherlands perspective, 2014). The most extreme scenario of W_H was chosen to be analyzed for this research and elaborated further in following sections. The size of this impact was assessed on the tunnel's components regarding the performance and therefore, functional influence of them.

In *Phase I*, the functional breakdown structure of a road tunnel system was developed based on a review of the National Tunnel Standards (LTS) of RWS by the author and selection of the content that could be used in this case. It includes the definition of functional requirements with the prior study of this reliable literature and the execution of function decomposition and fault tree analysis for each function to result in useful information. The collection of the outcomes supported the correlation process of climate change with the road tunnel system function failure. Quantitatively, the frequency, the Mean Time Between Failure (MTBF), the Mean Time To Repair (MTTR) and then the unavailability rate and percentage contribution on function's unavailability were estimated for every basic event, taking into account the aforementioned correlation. Finally, the impact was assessed qualitatively based on subjective opinion.

In *Phase II*, the actions emerged by assessing the received information from the previous phase. Sets of preventive and mitigative actions was formed for the indicated basic events of road tunnels system unavailability. Under the form of Bow-Tie analysis, for each of the 5 functions and repeatedly for 4 time periods adaptation actions were proposed. Finally, these actions were proceeded in the final third phase for the modelling of strategies.

To support the long-term decision-making for the road tunnel infrastructure asset, strategy modeling was required. The adaptive actions were assessed on the logical connection of each other. In this way, the author tried to find out when an action was to be activated and when to be terminated, formulating the sets of potential actions by connecting them. These were defined as the strategies of actions to react to the changes that would be happening over time. The last part was to visualize the strategies into a map for prevention and a map for mitigation where the pathways of action sets were depicted. By following the steps of analysis, the decision model for a road asset was formulated. The final part, the questionnaire, was organized in advance to host experts to assess the usefulness of DAPP in road infrastructure domain.

2.3. Verification & Validation

Verification is the process of testing in any stage of the research that the specified requirements were met. In this case, each of these three phases defined its requirements into a form of things that had to be done. The author under the guidance of the internal and external supervisors testified whether the required outcome of the phase was available and the content was solid for the continuation on the next research phase and executed at the end of the due phase and not during its execution.

On the other hand, the process of research validation was on the final part. It was a high-level activity that requires experts to be involved in. Ms. Nikeh Booister is applying DAPP for climate change adaptation in water management and Mr. Peter Vermey in infrastructure asset management contributed by responding in a questionnaire about the outcome of the research based on the general results. They assessed whether the research accomplished to fill in the knowledge gap, a primary intention of this venture. Moreover, they evaluated how useful the DAPP method could be found to provide valuable information to the interested parties. The main question of consideration in this case was whether long-term decision-making for road tunnel infrastructure assets facing the climate change could be achieved when DAPP method is implemented for this purpose. Could experts expect general implementation of DAPP for life cycle decision-making of road infrastructure assets? How useful would the emerging information be to policymakers, road asset owners or road asset managers?

3. Literature study

In this chapter, the presentation of the theoretical background of the research takes place. The aim is to connect the due research with the literature and confirm the need for long-term decision-making for road tunnel systems by associating it with the conceptual AM model of IAM and the WBG processes for long-term adaptation in climate change where multi-objective solutions are proposed (*subchapter 3.1.).* Later in *subchapter 3.2*., the decision-making limitations are presented just as they have been emerged by other models that have been deployed in the past. The theory of DAPP model is followed and its correlation with the research (*subchapter 3.3.).* Finally, an introduction to the climate change uncertainty of the Dutch territory is the content of *subchapter 3.4*. to communicate the concern for action.

3.1. Road tunnel Asset Management under uncertainty

The meaning of Asset Management is quite broad and is generally defined as ''the coordinated activity of an organization to realize value from assets'' (ISO55000, clause 3.3.1.). An activity could be the selection of an approach or methodology for the design and implementation of a life cycle management plan for an infrastructure asset. On the other hand, realizing value is more complex. The identification and face of risks and seizing opportunities, management of costs and performance benefits are the ones that would eventually reflect the asset's value.

Road infrastructure assets require huge investments for their development and therefore, their owners and investors expect proportionately high returns. The longer the service life of the asset, the greater the returns should be if high level of uncertainty exist. Life cycle management of those assets is important to ensure that asset's value is created over time. However, precision on the predictions for the future evolvement of some risks and reflection of them into decision-making is hard to be done. For instance, our planet faces changes in the climate that although are known, the greatness of them in the future is, however, almost unknown. The dynamic nature of these risks, which are constantly progressing, makes hardly precise the time and quantity of their impact. Adaptation actions should be, consequently, included in the life cycle decision-making process for a road asset to keep in line the organization's requirements for that object.

Road tunnel

Adaptation actions can be considered as a set of short-term and long-term measures. The service life of an asset could indicate the adaptation strategy someone should follow. At the same time, consideration of the climate change evolution over time could support the decision of whether that particular asset requires short-term or long-term adaptation measures to be identified and taken during its life cycle. The diagram of *Figure IV*. depicts the correlation between the components. The longer the service life, the greater the focus should be given on long-term adaptation actions provided that the uncertainties of climate change evolution are greater. The scientific interest of the due thesis is focusing on the road tunnels because they trigger many parameters of consideration. The development of road tunnels requires many years of service reliability which reflects into a high amount of life cycle investments especially under the prism of an unforeseeable future environment. Road tunnels seem to need mostly the running of long-term decision-making processes to prevent and therefore, prepare any adaptation actions for implementation whenever it is necessary.

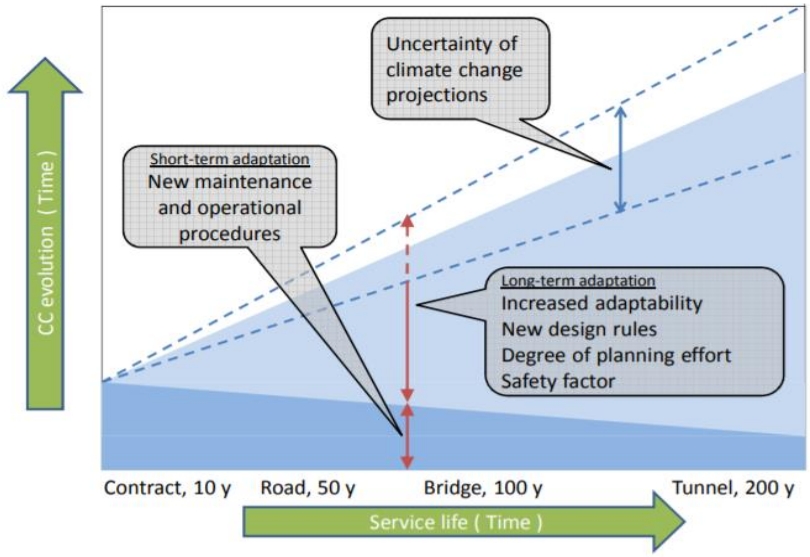


Figure IV: Service life, climate change and short-term and long-term adaptation measures for maintaining the acceptable risk level (Grendstad, 2013))

A long-term adaptation strategy allows tunnels to adjust to the new demands and develop increased adaptability as it is required in an uncertain future condition like the climate change projection. The authors also propose that adaptation must also consider new design and planning rules and safety factors that may be established based on this prediction (Grendstad, 2013). For an organization which manages an existent asset, it is important to deploy a methodology which provides the necessary flexibility to analyze risks and adjust the proposed adaptation measures given the due environment.

Asset Management

The scientific research of (Meyer, Amekudzi, & O'Har, 2010) suggests that in early phase the project development process should incorporate proper and flexible design, maintenance strategies and risk-oriented analyses. It will allow the identification of vulnerabilities that in the future the long-lived infrastructure asset will be called to face to. The authors point out that given the long useful lifespan of road tunnels, this should be the main consideration for new assets development. However, renovated assets should also be counted as new ones. Their service life is expanded which could be even considered like the beginning of a new cycle of service life for that object. The project development process constitutes from an amount of activities referring to different asset management subjects. The Institute of Asset Management is committed for the standardization of asset management practices and draw the guidelines to provide the required knowledge for high level asset management services provision.

An overview of six subjects was presented from the Institute of Asset Management in 2015 to define the activities that may be required in a conceptual model for asset management. IAM suggests that it is up to the organization to identify which activities are important to be in place; based on the needs of its asset management system. The subject groups are depicted in *Figure V*. including the sets of proposed activities. Group 6 is the one that suggests the activities referring to the identification and management of risks and

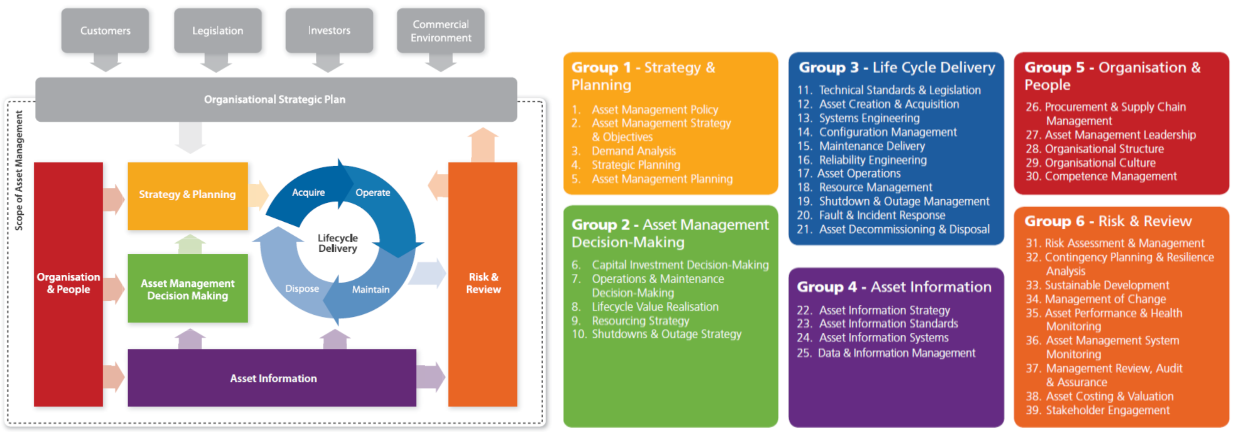


Figure V: IAM conceptual Asset Management model and its subject groups with their contented activities (IAM, 2015)

it is of high importance because it feeds with information other subjects of asset management. The information refers also to the monitoring mechanisms which assure that the project objectives are being delivered at the desired level during the asset's lifecycle. Moreover, information is sharing to support the ongoing improvement of asset management activities for all the other groups. Additionally, useful input in the asset management groups for the strategy & planning and asset management decision-making is provided through the organization's strategic plan, the primary plan of the organization for the achievement of its goals for all its assets.

The activity number 31: ''Risk Assessment & Management'' of the subject group 6 is defined as ''the policies and processes for identifying, quantifying and mitigating risk and exploiting opportunities'' (IAM, 2015) and is the main focus of the due research. Making an explorative research on a process to execute the tasks is a challenge. An effective implementation would mean valuable input for the life cycle decision-making process and value realization of the examined asset.

The uncertainty of climate change

The integration of climate change in the asset management processes seems to be detrimental because more and more experts and practitioners understand its importance. In 2017, the World Bank Group published a report regarding the road asset management associated with the phenomenon of climate change (World Bank Group, 2017). The authors recommend many actions that ought to be taken so that someone integrates the climate uncertainty in asset management practices. Based on the International Infrastructure Management Manual (NAMS, 2011), the traditional road infrastructure asset management consist of three different processes; Understand and Define Requirements, Developing Asset Life Cycle Strategies, and Asset Management Enablers. For each process, there are some steps that should be followed by the organization to achieve the optimum organization and management of a particular road asset. The following *Table I*. presents the asset management processes and their steps indicating the timing for response in a risk event resulted from climate change. Only three steps are proposed for reactive response during the event and one step for retroactive response. Most steps refers to proactive response demonstrating a preventive way for integration of climate change risks into the asset management processes. The report of WBG concludes that the focus should be given in prevention rather than in reaction.

By reviewing the recommended actions, the focus of the thesis is found on the process of ''Understand and Define Requirements'' and particularly in the step of ''Identifying Asset and Business Risks''. The authors propose how this step should be approached by the following actions (World Bank Group, 2017):

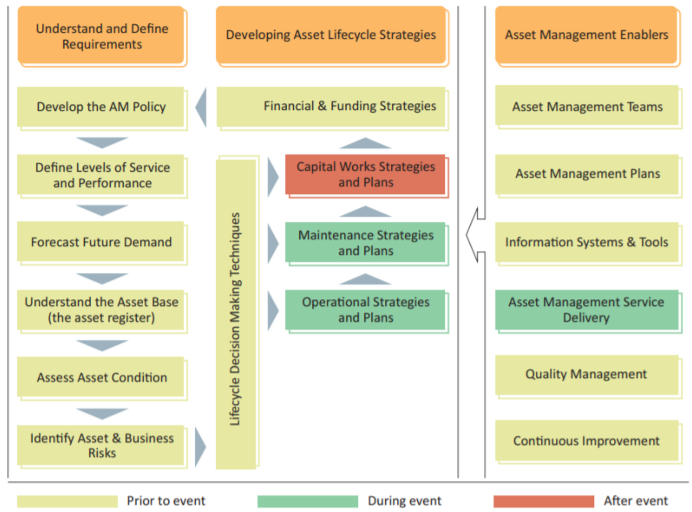


Table I: Road Asset Management processes, steps, and response timing. Source: (World Bank Group, 2017)

- *Ensure climate change is recognized as a risk to the asset and delivery of services*
- *Risk and vulnerability assessments are already commonly used for climate adaptation. These processes should be integrated with risk management from an organizational risk perspective*
- *The integration with asset management risk in particular promises significant efficiency gains*

The significance of the phenomenon of climate change and its evolution over time indicates the recognition of it as a risk for the road infrastructure assets. The literature shows that the climate change influence in road infrastructures may create opportunities but also vulnerabilities in achieving road asset's service goals. Associated risk identification and management is undoubtedly an important aspect to be considered. The organization that is assigned for the management of an asset will receive lots of benefits whether long-term planning for asset's adaptation to the new demands is getting prepared in early phase.

The life cycle decision-making is also supported from the outcome of the risk management and mitigation of climate change effects. The road asset management process of ''Developing Asset Lifecycle Strategies'' and particularly the step of ''Lifecycle Decision Making Technique'' attracts the interest for further discussion. Selection of an appropriate decision-making technique is a thorough process for an asset manager which depends on the characteristics of the due asset or system of assets. The report of WBG suggests the following action (World Bank Group, 2017):

- *Current analyses processes need to incorporate multi objective capabilities*

The selected decision-making technique/methodology should possess some flexibility in its decision proposals regarding the timing of implementation. Moreover, a proposal should combine more than one problem into one solution. Providing multi objective capability, unforeseeable or uncertain future conditions can be faced better when the technique does not impose static-robust adaptation actions/measures and strict boundaries regarding their implementation.

3.2. Decision-making limitations

Robust decision-making (RDM) is an analytic framework to identify robust strategies, assess their vulnerabilities and evaluate trade-offs among them (RAND.org, 2020). It is used to identify adaptation measures to allow infrastructure assets to handle the vulnerable impacts of future uncertainties. However, the measures refer to current time implementation without considering potential use of them later in the future (Espinet, Schweikert, & Chinowsky, 2015; Groves, Molina-Perez, Bloom, & Fischbach, 2019). On a bridge case study, Mondoro, Frangopol, & Liu (2017) elaborate that under great extent of uncertainties (i.e. modelling techniques of future, climate change scenarios, natural variability), RDM can bring about decent solutions when relative regret determination of the emerging strategies across the possible futures is happening. Espinet, Schweikert, & Chinowsky (2015) envisioned the low-regret assessment to optimize the RDM method for optimal results when investigating some climate change uncertainties in the Mexico transportation system. They support that *''Regret demonstrates the sensitivity of each strategy to the uncertainty of possible outcomes''.* Although RCM could lead to adaptation strategies under thorough study, the dynamic nature of the future is underestimated which could eventually be proved disastrous. The adaptation measures could be inadequate in case of future climate conditions beyond the predictions. ''Forward-looking'' adaptive strategies are integral as it is stated by Groves, Molina-Perez, Bloom, & Fischbach (2019) who refer to water infrastructure management. This could also be the case in any infrastructure asset management.

Strategies for infrastructure life cycle management can also be developed through a Decision Tree Analysis (DTA). ''*A decision tree is a diagram wherein the tree "branches" represent different chance outcomes. It is used to assess which risk response among alternatives yields the best-expected consequence''* (Nicholas & Steyn, 2017). A sequence of actions is identified in the process of long-term change and through whole-life performance evaluation the well-performed options on a variety of potential future conditions are selected to face the uncertainties of future change. The Thames Estuary flood defense system, for instance, deals with sea level rise through decision tree analysis (Sayers, Galloway, & Hall, 2012). However, in complex systems, decision tree analysis cannot be deployed in the presence of plethora of potential strategies which aim to respond to future uncertainty risks. The tree is getting complex (Buurman & Babovic, 2016). In such a case, adaptation pathways mapping seems to work better and decision tree analysis is used as a supplementary tool to convert the map into a tree to eventually allow the quantification of pathways costs and benefits with Real Options Analysis (ROA) (Buurman & Babovic, 2016). Therefore, decision tree analysis facilitates decision-making under well-characterized uncertainty risks mainly for operation short-term planning (Yaning, Medina, Myers McCarthy, Mallick, & Daniel, 2017; van den Boomen, 2020).

Real Options Analysis (ROA) is a methodology which communicates, through financial perspectives, the options for better life cycle management of an infrastructure system within its uncertain environment. It suggests which and when the most appropriate options should be taken to retain the expected performance of the system over the assessment period. Based on stochastic analysis, focus is made on the system's configuration and technical details and the interdependency among these options are defined. Gersonius, Ashley, Pathirana, & Zevenbergen (2012) implement ROA to assess economic benefits in the modification of an existent urban drainage system to provide climate change resilience. The strategy focuses on the establishment of a moderate configuration planning with the flexibility for further expansion later in the future. Safer conditions for return on investment can be achieved then. Although this adaptive strategy could work against maladaptation (increased risks coming from adaptation) (Barnett & O'Neill, 2010), the probabilistic assumptions used as input in the stochastic analysis of climate change can be difficult to estimate (Gersonius, Ashley, Pathirana, & Zevenbergen, 2012) and rely on subjective judgements (Gersonius, Ashley, Pathirana, & Zevenbergen, 2012; Kind, Baayen, & Wouter Botzen, 2018). The stakeholders would be the ones to define when the actions timely to be taken by leaving little space for the future to decide the time (Kind, Baayen, & Wouter Botzen, 2018). Therefore, inconsistency of results and potential opinion conflicts constitute limitations of ROA method's applicability.

The application of ROA or DTA makes long-term decision making difficult as these models quickly fall prey to state explosion when combining multiple uncertainties over longer time frames (van den Boomen, 2020). The difference between ROA and DTA stems from their origins. Many applications of DTA are found in the engineering domain. In contrast ROA originally emerges from the financial domain and includes market price uncertainty. ROA is an economically corrected version of a decision tree. Combining deep uncertainties related to climate change, asset integrity and market prices will lead to very large trees which will limit their application in practice for decision making. The trees will produce so many possible paths that a decision maker cannot obtain meaningful information from these trees.

The limitations of current practices are indicators for change into new practices for decisions on life cycle infrastructure asset management under deep uncertainty. Kenny, Dupré, & McEvoy (2018) support that *''There is a need to further promote tools and practices for the effective integration of climate change considerations within the asset management framework''*. The same conclusion for climate change uncertainty inclusion reaches by van den Boomen (2020) who proposes several methods for infrastructure replacement decision-making and points out the need for further investigation for climate change incorporation on the methods. This could happen only if the dynamic nature of deep uncertainty is recognized and considered. The development of static 'optimal' plans using the best possible future or static 'robust' plans which can respond in multiple possible futures (Walker, Haasnoot, & Kwakkel, 2013) seems to underperform and even fail in any different hypothesized climate conditions.

3.3. The model of Dynamic Adaptive Policy Pathways

The Dynamic Adaptive Policy Pathways (DAPP) is an approach for developing adaptive plans when the uncertainty is not well characterized, and large changes can frequently happen. DAPP could be positioned between RDM (robust) and DTA/ROA (adaptive). DAPP combines robustness and adaptiveness and as such can provide meaningful decision information when dealing with deep uncertainty over longer timeframes. It can support the identification of alternative adaptive options under different potential future conditions, the recognition of their applicability limits (tipping point) and finally the design of a pathway map indicating all possible sequence of actions the dominated future conditions would activate (Walker, Haasnoot, & Kwakkel, 2013; Haasnoot, Kwakkel, Walker, & ter Maat, 2013). These steps can be possibly followed in a repeated way as they are depicted in *Figure I* formulate a circle.

The method has been applied in the Delta Program, which is referred to the Rhine Delta in the Netherlands, an area prone to flooding events because of climate change. It is thought that by implementing this methodology Haasnoot, Kwakkel, Walker and Maat (2013) aimed to satisfy the requirement for a new way of planning which maximizes flexibility when dealing with the big challenge of uncertainty of the future climate. The authors achieved to produce adaptation actions for the next 100 years complying with the Delta Program's strict requirement for flood protection and adequate freshwater supply in the area. However, scientific works implement the DAPP model mainly into water management and long-term decision-making for water infrastructure assets. Different kind of assets like road infrastructure assets would be scientifically interesting cases where adaptation actions under deep uncertain future climate conditions are needed and produced through the DAPP methodology. The goal of this research is to fill in this knowledge gap by following the first six steps of *Figure I* in a road tunnel asset.

This kind of analysis could facilitate better outcomes when dealing with natural variability (impacts of climate change on infrastructures) and even optimal communication among the interested parties, especially in complex systems, through the visualization of the measures. DAPP is tested for its usability in life cycle road tunnel infrastructure asset management based on climate-related concerns in long-term horizon. The current research aims to provide a structured and reproducible approach for the implementation of steps 1 to 6 in *Figure I* to arrive at adaptive paths.

3.4. Climate change uncertainty in the Netherlands

The KNMI which is engaged in assessing the future climate conditions in the Netherlands presented in 2014 the impacts of climate change in the country. Variable changes in temperatures, precipitation volume, wind, solar radiation, drought and extreme weather (thunderstorms) are recognized (KNMI, 2014) and have potential impact on infrastructures.

Precipitation plays an important role. It has shown an upward trend during the last 60 years by 20% and a further advance is expected, however, little changes in wind storms are expected (Pereboom, van Muiswinkel, & Bles, 2016). Forecasts for the future precipitation deal with either increase by 5% or decrease by 6% depending on the climate conditions emerging in the future. Heavy rainfalls have already been more frequent which reflect higher river and water drainage flooding risks (Ligtvoet, van Minnen, & Franken, 2013). Moderate or strong temperature increase is the case in the future climate scenarios (KNMI, 2014). Drought phenomenon relates to precipitation and temperature variations. It has already shown an upward trend in the Netherlands, therefore more frequent drought periods are expected (Marijke , Bouwman, van Dorland, & Eerens, 2015). Also, more frequent and intense summertime thunderstorms and hailstorms are anticipated by the KNMI '14 climate models outputs. Finally, KNMI forecasts a potential downward or upward of 1,6% in solar radiation in the temporal scenarios of 2050 and 2085 (KNMI, 2014).

In 2012, Deltares (Bles, et al., 2012) assessed the physical effects and the impact on availability on the Dutch road network and territory based on three main flooding types presented in the Netherlands: failure of flood defenses, incapability for drainage of water system around the network and incapability for water drainage of road surface. The outcome was several maps (*Appendix-subchapter 3.4.*) where locations vulnerable to flood in association with the Dutch highways were identified. A risk assessment of these events was executed (Pereboom, van Muiswinkel, & Bles, 2016) and points out that the road assets (especially tunnels) which are located in sensitive locations where positive changes of groundwater levels is anticipated till 2050 are the due vulnerable ones. Although individual parts of road trajectories could be affected, eventually the whole road trajectory could even be unavailable. The road infrastructural assets may experience even harsher effects after 2050 where climate conditions are deeply uncertain.

Climate change effects trigger the need of ensuring the optimum life cycle management of infrastructure assets. Retaining transportations' well function is integral, especially in susceptible societies with high probabilities of flooding events and high impacts. The road networks availability can be achieved only if every individual component performs well. In case of emergency and evacuation situations, the road system must be able to respond successfully with the minor losses. This is the main purpose of this research, to propose a suitable method for the life cycle management of road infrastructures against the long-term climate change–related risks which can eventually secure asset's good performance and adaptability to the new demands.

3.5. Conclusion

It became apparent that the need for long-term decision-making processes for road tunnel systems adaptation, led by environmental changes, is necessary. The scientific interest of this graduation thesis is focusing on the road tunnels mainly due to the fact that they are infrastructure that require many years of service reliability and risks of high uncertainty that are associated with the infrastructure, like the ones of climate crisis, indicate the importance of establishing appropriate methodological processes to accomplish asset's long-term adaptation. The conceptual AM model of IAM and the WBG framework for long-term adaptation in climate change confirm that the focus should be given in prevention rather than in reaction. Therefore, by confirming this need, I am motivated to research and develop a structured methodology.

Current practices seem to either underestimate the dynamic nature of the future when long-term decision-making for adaptation is executed or be suitable mainly for short-term planning as in any other case, they result in complex decision plans. RCM promotes the definition of robust responses which could, however, be inadequate in case of different future climate conditions. Despite DTA and ROA perform well in long-term adaptation decision-making, they lack in actual methodological application. DTA underperforms in the presence of plethora of potential strategies in complex systems which confuses the decision-makers and, in general, DTA performs well mainly under well-characterized uncertainty risks for operational short-term planning. ROA is a methodology which communicates, through financial terms, the life cycle adaptation of an infrastructure system within its uncertain environment, the difficulty of estimating probabilistic assumptions which are used as input in the stochastic analysis of climate change raises the concerns about the efficiency of the results. Consequently, the current limitations call for development of long-term dynamic planning without focusing on the best possible future or proposing static 'robust' adaptations.

DAPP combines robustness and adaptiveness and as such can provide meaningful decision information when dealing with deep uncertainty over longer timeframes. It can support the identification of alternative adaptive options under different potential future conditions, the recognition of their applicability limits (tipping point) and finally the design of a pathway map indicating all possible sequence of actions the dominated future conditions would activate. This kind of analysis could facilitate better outcomes when dealing with natural variability (impacts of climate change on infrastructures) and even optimal communication among the interested parties, especially in complex systems, through the visualization of the measures.

The climate change in the Netherlands brings about considerable effects on the infrastructure based on KNMI. The anticipating increasing precipitation volumes, intense temperatures, frequent thunderstorms, and hailstorm events, and increasing CO_2 atmospheric concentrations are some climate variables that trigger the need of ensuring the ongoing transportation's well function and optimum life cycle management of road infrastructure assets. The road tunnels availability must be preserved and the viability of their structure as well mainly due to their long-term service life exposure to climate variations.

Phase I

<u>Sub Question 1 response</u>

In *Phase I*, the sub research question 1 is attempting to be answered

'' What are the functions of a road tunnel and **to what extent can future climate change impact the system's functional failure?''**

responding to the 3rd and 4th step of DAPP model (*Figure I.).*

''What are the functions of a road tunnel?''

Chapter 4. Climate change uncertainty

- Selection of the most intense climate scenario (*4.1.*)
- Selection of climate variables that are related to road tunnel infrastructures (*4.2.*)

Chapter 5. Functional Breakdown Structure

- Definition of road tunnel Functional Requirements (*5.1.).*
- Hamburger model for Functional Decomposition into systems and performance requirements (*5.2.*).
- Fault Tree Analysis for the definition of the functional failure modes related to the selected climate variables and presentation into diagrams (*5.3.*).

''To what extent can future climate change impact the system's functional failure?''

Chapter 6. Analysis of the road tunnel system's functional failure

- Analysis timeline of 4 periods (2020-2100) (*6.1.*).
- Analysis methodology *(6.2.)* for the assessment of the road tunnel system's unavailability rate through its functions *(6.2.1.)*, for the assessment of the impact on organization values when unavailability occurs *(6.2.2.)* and for the development of a *''Unavailability percentage contribution-Organization Values impact''* matrix *(6.2.3.).*
- Implementation of the analysis methodology (*6.3*)
  - ➢road tunnel system's unavailability rate for the functions A-E within analysis period
  - ➢assessment of the impact on organization values when unavailability occurs
- Development of *''Unavailability percentage contribution-Organization Values impact''* matrices (*6.4*)

4. Climate change uncertainty

In this chapter, the climate change uncertainty in the Netherlands is discussed and specifically:

- In *subchapter 4.1.,* The climate scenarios of KNMI are presented and concludes to the most intense one which is chosen for further analysis latter in this phase.
- In *subchapter 4.2.,* the climate variables that are recognized as associated ones to the road tunnel infrastructure are presented as well as the reasoning of their selection and of the exclusion of other climate variables.

The outcomes of this chapter contributes to both question parts of the Sub Question 1: *''What are the functions of a road tunnel'',* and *''To what extent can future climate change impact the system's functional failure''.*

4.1. Climate scenarios

The last version of KNMI climate scenarios and projections was published in 2014 based on the IPCC assessment report of 5th edition (KNMI, 2014). KNMI presents changes in climate variables including temperature, precipitation, wind, and sea level, for four different future climates in two periods of 2050 and 2085. The time horizons are distinguished for 2050 between 2036 and 2065 and for 2085 between 2071 and 2100. Moreover, as reference time for the comparison is used the period of 1981-2010 and observations of the climate variables since the beginning of 20th century are illustrated in this report.

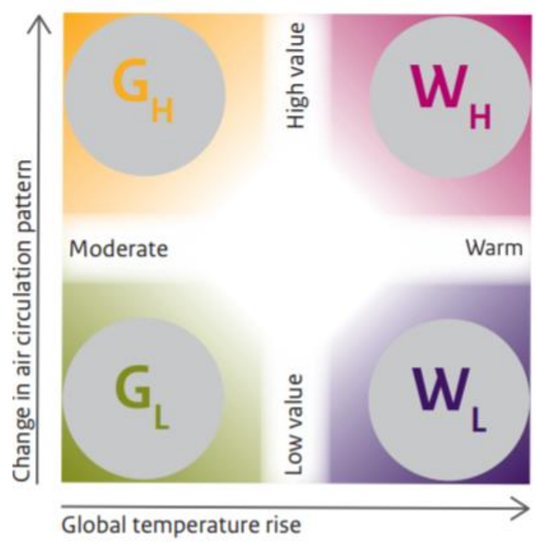


Figure VI: KNMI'14 future climate scenarios in the Netherlands (KNMI, 2014)

The KNMI'14 scenarios are a combination of two potential values for the global temperature rise and two values for the air circulation pattern. The temperature values are 'Moderate' and 'Warm' and the air circulation pattern values are 'Low change' and 'High change'. These combinations are the likely climate changes in the Netherlands according to the last updated knowledge. Consequently, G_H means low global mean temperature increase with wetter winters and drier summers, W_H means stronger mean temperature increase with wetter winter and drier summers, G_L means low global mean temperature increase with low influence of circulation change and W_L means stronger mean temperature increase with low influence of circulation change.

Finally, temperature estimates beyond 2100 are hard to be done mainly because of the uncertainties that bring such long-term assumptions. Consequently, the time horizon for the due research is defined as the period 2020-2100 and the projections of relevant climate variables are discussing based on the least favorable future climate of W_H.

4.2. Climate variables and road tunnels correlation

This subchapter contains some important information that refers to the impact of climate change on climate variables. Observations and forecasts of each variable are presented accompanied by figures to illustrate these observed changes and possible developments in the future (*Appendix – subchapter 4.2.)*. The overall changes are summarized as followed:

- Temperature: continuation of increase with more mild winters and hot summers
- Precipitation: overall increase with more extremes during winter, more intense rainfalls during summer and hail increase of intensity and frequency
- Wind: small or even no changes
- Mist: visibility improvement because of fog decline
- Solar radiation: slight increase on ground's surface because of clearer sight
- Evaporation: more intense drought periods
- Sea level: continuation of rise because of temperature changes regardless the actual future climate
- CO_2 concentration: continuation of CO_2 concentration upward trend even if CO_2 emissions are stabilized.

The climate variables that are finally selected to include in the research are elaborated in *Table II*. These variables are the important ones as they are relevant to and affect to some extent the viability of a road tunnel infrastructure. The projections of those climate variables, based on the least favorable future climate of W_H, are elaborated in the table too to incline the reader towards a deep understanding and give an insight in the further research study. The correlation of these figures with the Functional Breakdown Structure of a road tunnel system, later in *Chapter 5 and 6,* is required for the completion of *Phase I.* The reasoning of the relevance and selection of those climate variables in the research is given as followed:

Table II: Assumptions on the W_H scenario of KNMI'14 and (Stewart, Wang, & Nguyen, 2011) on climate variables until 2100, Source: own table

KNMI '14 scenario: **W_H**	**Reference period**	**2050**	**2085**
	1981-2010	2036-2065	2071-2100
Temperature			
mean	10.1°C	12.4°C	13.8°C
heat days (> 25°C)	21	36	48
ice days (< 1°C)	38	15	8
High water level (yearly mean precipitation)			
mean	851mm	894mm	911mm
summer wet days (> 20mm)	1.7	1.5-1.9	1.4-1.9
winter wet days (> 10mm)	5.3	7.2	8.5
wet days (> 0.1mm)	98	95	93
North Sea level			
water level above NAP	3cm	23-43cm	48-83cm
rate of rise	2mm/year	3.5-7.0mm/year	4.0-10.0mm/year
Solar radiation			
mean	354kJ/cm²	358kJ/cm²	359kJ/cm²
Evaporation			
potential evaporation (Makkink)	559mm	598mm	615mm
Drought (highest precipitation deficit more than once in 10 years)			
mean	230mm	288mm	322mm
Hailstorm			
	No data	twice as much and bigger hailstones	twice as much and bigger hailstones
Thunderstorm			
	No data	significantly increasing	significantly increasing
CO_2 concentration			
mean	1981: 340ppm	2040: 490ppm	2080: 640ppm
	2010: 390ppm	2060: 560ppm	2100: 720ppm

Relevant climate variables

- ***Temperature:***
  The fact that temperature is related to other climate variables (precipitation, evaporation, water level) and triggers their development made me to understand that temperature is the top variable to be considered. I reckon that the ongoing increase in mean temperature values is going to affect

the road infrastructure in an implicit way. The increase and decrease of extreme heat days and ice days make the road tunnel structures and their installations to be continuously exposed in hotter than it was expected environments. Structure deterioration, installations malfunction, or tunnel flooding events are some of the events that can be implicitly caused by higher temperature values and justify the selection of this climate variable in the research.

- ***Precipitation:***
  Since the early 20th century, precipitation shows an upward trend. The anticipated increase of mean precipitation in the following years is considerably rapid and therefore, it should not be neglected. It is not only that mean precipitation increases but also that the intensity of rain events. The groundwater level changes too which affect in turn the road tunnel structures. Therefore, it seems that the road tunnels are getting prone to flooding events and other precipitation-related events and indicates the inclusion of this climate variable in the table.

- ***North Sea level:***
  The sea level is changing enormously nowadays, and further increase is projected in the following century. Global warming melts the ice sheets and glaciers and seem to affect the North Sea region in the Dutch coast. The inland water level will either increase or decrease which in turn raising the concerns for the associated risks on the road tunnel infrastructure. The structural integrity and operationality of a tunnel, which may even intervene the water horizon, could be impacted by groundwater level fluctuations. Therefore, the North Sea level is correlated to the road tunnel infrastructures and its projected values are included in the table.

- ***Solar radiation:***
  The ongoing reduction of air pollution (non-CO_2 related) in the Netherlands facilitates the increase of solar radiation because the clouds become more transparent. The clearer the atmosphere is, the higher the solar radiation becomes. It is only known that solar radiation is getting bigger on ground's surface. The road tunnels could, for instance, be affected by fading marking on the road pavement that leads to the tunnel. Even though solar radiation is logically increasing, the actual development is going to be very little until 2100, the mean value is estimated to increase by only 5kJ/cm^2. Moreover, it is included in the selected climate variables because it not clear yet scientifically whether is a result of natural variability or it is human caused. Therefore, little attention should be given on this variable as any issues that might emerge in the future can possibly be addressed in a short-term decision-making plan. But it is early to say that at this moment.

- ***Evaporation – Drought:***
  Evaporation is a variable that is measured by the solar radiation and temperature and that it the justification of including evaporation in the table. The projections of future evaporation may differ quite a lot comparing the ones of temperature and solar radiation which inclines too towards this decision. The values of potential evaporation and mean precipitation deficit (drought) indicate potential impact of road tunnels. Landslide event due to extreme rainfall after a long period of drought could severely affect the operability of a road tunnel and its functions performance which therefore justifies the selection of this climate variable as relevant to road tunnel infrastructure.

- ***Hailstorm***
  Hailstorm events are expected to be double than they were used to being. The lack of a database for this variable increases the uncertainty of the size of its development. Hailstorms are not ordinary but when they occur, they can create big or even severe damages on road tunnel installations. The size of hailstones is expected bigger than it was usually, and the same expectations are there for the intensity of a hailstorm.

- ***Thunderstorm***
  Thunderstorms can also be a cause of malfunctions or implicitly affect the tunnel's functionality the moment of an event of extreme rainfall with thunders. These events are expected to be double than they were used to being like hailstorms. Limited tunnel entrance visibility, insufficient telephone communication or audio guidance are some examples of how the road tunnels can be connected to this specific climate variable.

- ***CO_2 concentration***
  The atmospheric carbon dioxide concentration is another variable that can develop extreme values within the 21st century. The climate scenario W_H expect the CO_2 concentration to be almost 1,5 times more than it is measured nowadays. Such a development can clearly change the needs of the civil structure of a road tunnel asset and could even bring about severe consequences if it is neglected. Therefore, it is integral to include this variable in the table of the climate variables that show the potential impact in road tunnel infrastructure.

The variables that are considered as less important or irrelevant ones to affect the viability of a road tunnel infrastructure and therefore, they are excluded in the research are presented as followed:

Irrelevant climate variables

- ***Wind***
  Wind changes over time are identified as not human-caused based on KNMI and additionally, assumptions for the future wind are even impossible to be made. Consequently, knowing that there is a lack of correlation of wind to climate change, any correlation of wind to the road tunnel infrastructures in Dutch territory is intentionally avoided because it would be out the scope of this research.

- ***Mist***
  The air pollution is gradually decreasing in the Dutch territory which in turn improves the sight, minimize the phenomena of mist and consequently, it is having limited influence on the road infrastructure assets. Moreover, the referring air pollution is not related to the carbon dioxide concentration which means it is not climate-change related. Therefore, mist developments are not human related which justifies mist's exclusion in the table.

- ***Cloudiness***

  Cloudiness is also a parameter that relates to the air pollution level as by decreasing the concentration of air pollutants (non-CO_2 emissions-related), the clouds become more transparent and the sky brighter. Clouds are not affected from the CO_2 emissions but from other parameters which justifies the reason that the specific climate variable is not considered. Especially in the W_H, where drier summers are expected, the cloudiness is decreasing to the minimal level based on KNMI'14.

4.3. Conclusion

The climate change uncertainty in the Netherlands of this chapter gave an overview about the most expected future climates based on KNMI and the connection of climate variables and road tunnel infrastructure was important in this early phase of the research. The content of *Chapter 4* responded to the first DAPP model step, *1) Describe current situation, objectives & uncertainties* by describing the uncertainty of climate change which synthesizes the current difficulties in planning the infrastructures adaptation on the future demands effectively. The climate projections *(4.1.)* and the selection of those variables that create impact on road tunnel infrastructure executed this DAPP step 1.

Moreover, it contributed to both question parts of the Sub Question 1: ''What are the functions of a road tunnel'', and ''To what extent can future climate change impact the system's functional failure'' which is proceeded in *Phase I*. The continuation to *Chapter 5* will give an explicit answer to the first question part of the Sub Question 1.

5. The Functional Breakdown Structure of a road tunnel

In this chapter, the Functional Breakdown Structure of a road tunnel is analyzed as followed:

- In *subchapter 5.1.,* the functional requirements are discussed and summarized into five functions, which are *Assimilating traffic flow, Providing route flexibility, Connecting with the road network traffic management facilities, Facilitating communication and Future-proofing system's prosperity.*
- In *subchapter 5.2.,* the functional decomposition of those five elements is taken place where the function specifications and function solutions/systems are defined for each of the function's components (subfunctions). Finally,
- In *subchapter 5.3.,* the modes of functional failure for each of the five functions are identified by correlating the failures with the climate variables of *Chapter 4* and elaborated.

The outcomes of this chapter reply to the first part of the Sub Question 1: ''*What are the functions of a road tunnel'',* and the analysis of them in *Chapter 6* will answer the second part of the research question of *Phase I, ''To what extent can future climate change impact the system's functional failure''.*

5.1. Functional requirements

The National Tunnel Standards (Landenlijke Tunnelstandaard, LTS) fulfil the vision for safe and reliable road network system in the Dutch territory. On this way, the complex tunnel systems can be successfully integrated into the rest highway network achieving the goal of unity. RWS has developed the LTS in cooperation with governmental and market parties, transport organizations and emergency service providers to ensure in early phase the optimal function of a new road tunnel by defining standard processes and functional requirements (RWS, 2020). LTS are applied also in the planning of renovation and restoration works in existing road tunnel assets. The establishment and implementation of standards seem to result in total cost minimization or even keeping the costs in the same level but handing over eventually better quality (Gram, 2012).

The last update of the LTS was made in 2016 and up until now the specifications of the RWS tunnel system are distinguished into quality and functional requirements. To emphasize the quality of tunnel works, RWS divides the quality term into Reliability, Availability, Maintainability, Safety, Health, Environment, Economics and Policy (RAMSHEEP). On the other hand, the functional requirements are linked to the primary objectives of the RWS tunnel system standards which are to allow the traffic to flow smoothly and safely. RWS points out that '' *A tunnel is an integral part of the HoofdWegenNet (HWN). That is why it must meet the requirements set for the HWN for traffic flow in a particular route, but under the preconditions of legislation and regulations specific to tunnels''* (Rijkswaterstaat, 2016). Therefore, the due research is focusing on the top functional requirements a Dutch road tunnel should meet to be analyzed with the associated to climate change risks which may lead to system's function failure.

The integration of a road tunnel system into the main road network is integral. The users of the main road network should not experience any difference when passing through the road tunnel. In this *subchapter*,

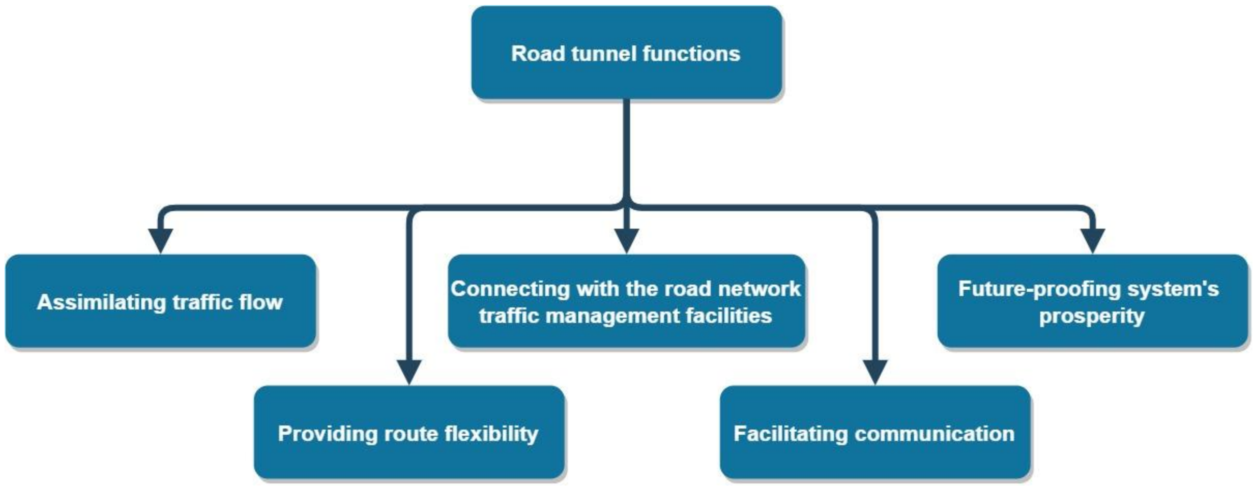


Figure VII: Functional requirements for a road tunnel system. Source: own table

five functions are defined as the main functions of a road tunnel and elaborated in more details under the prior study of RWS tunnel standards and self-assessment of the findings (*Figure VII)*.

I. Function A: Assimilating traffic flow

The traffic flow of the road tunnel system must assimilate the traffic flow that is accommodated in the rest road section where the road tunnel system is part of. In and around the road tunnel system the traffic flow should not be affected by the existence of this tunnel section. The travel time and travel speed can express the traffic flow for a route that has been defined in the national reference framework and regional framework at the location of that specific system.

Moreover, the road tunnel system must carry the same capacity with the main road network in order that any disturbance to be avoided. Focus is made on the tunnel design regarding the number and width of traffic lanes, the emergency lanes, and the speed limits, which must be the same for any road section. The design of any tunnel section must be aligned with the design principles of the New Design Motorways (NOA) directives. Traffic jam in and around a tunnel section is undoubtedly unacceptable. This road section should not cause a bottleneck in terms of traffic flow during normal use conditions. Lane narrowing, lane decrease at the tunnel entrance and/or excessive road inclination in and out of tunnel are indicators of creating congestions and therefore must be avoided. The road user must have clear tunnel entrance visibility and enough time and space to adjust its vehicle speed whether the conditions require so. Guidelines from the NOA impose the minimum requirements in terms of time and space.

Finally, the road tunnels which are aligned with the RWS tunnel standards should have a clear passage height of at least 4.70 meter. Compliance with the guidelines of ''Vervoer over Land van Gevaarlijke stoffen'' (VLG) regarding the categories of land transport of dangerous goods is necessary for a proper road tunnel design based on safety principles especially when the tunnel crosses waterways and residential areas. These are the minimum requirement to allow trucks to safely pass through the tunnel avoiding to damage tunnel's civil structure and tunnel installations which eventually could result in human casualties.

The future climate conditions will definitely show their impact on performing Function A. Frequent extreme weather conditions, groundwater level changes, and land subsidence, as well as their products, are some of the climate change results which could potentially affect the Function I performance and therefore could make the road tunnel system unavailable for use.

II. Function B: Providing route flexibility

Providing flexibility to a tunnel system is important. The traffic load of the main road network for both directions can periodically change and therefore, the tunnel section should be able to adjust on temporary demand capacity by changing the directions of lanes and/or tubes. Alternating traffic directions must allow the traffic to flow without any disturbance for the main road network. This function requirement depends on the surrounding road network and the location of tunnel system which may be prone to traffic congestions on rush hours.

Moreover, the existence of alternative routes is significant for a road tunnel system which becomes unavailable for any reason. In extreme circumstances the traffic flow can be hampered or even blocked. Routes must be tested and appointed suitable for emergency use to meet the requirements of sufficient space, capacity, and traffic control for the surrounding road network.

Therefore, the capability for carrying out traffic management is of high importance. Control scenarios must be available as part of the traffic management to mitigate the chance a traffic jam of the main road network to affect the road tunnel system. This is necessary to comply with the safety standards (Warvw, article 6) and the reliability requirements for a safe escape route in an emergency. Diversion of routes, speed limit and traffic flow fluctuation and limitation of the resulting noise nuisance are some actions that may be taken whether control scenarios for traffic management are deployed.

The future climate conditions will affect the Function B as well. The considerable fluctuations in precipitation volumes which also gradually increase over the next decades, as well as their products, could influence the road pavement sections outside and potentially inside the tunnel structure, the performance of traffic direction management and the performance of the control scenarios for the traffic management for emergencies and congestion avoidance. All these would constitute the road tunnel unavailable for use.

III. Function C: Connecting with the road network traffic management facilities

The processes for traffic handling of a road tunnel system must be seamlessly connected with the processes of the main road network (HWN). These processes are so interwoven that any distinction must be avoided. Especially in extreme circumstances of traffic accident or calamities where the traffic may be diverted, a unity of reacting processes must exist, and any distinction could create frustration to the road users. The processes for monitoring and control, maintenance and overall management are interrelated with among the sections of the network (including a tunnel one) and must be complied with the same protocols and directives. Therefore, the design and operation of a road tunnel system must be based on the road network's operational traffic management and UPP management processes.

In extreme circumstances, the road tunnel and the rest road network must respond united to the traffic needs. The selected future climate WH is prone in weather extremes which could implicitly or explicitly make these systems fail to achieve a united response on these extremes. Individual issues on the road tunnel could lead to insufficient compliance with protocols and directives which is necessary for the connection of the road tunnel’s traffic management facilities with the road network traffic management facilities. For example, issues on the liquid discharge or the ventilation system of the road tunnel would reflect on the experience of the road user. It is important the road user does not feel the insecurity or discomfort when it passes through the tunnel. The overall climate change affects directly or indirectly the road tunnel’s facilities and equipment when the latter cannot deal with the products of that general climate change. Consequently, the united operation of a road tunnel with the rest road network could be jeopardized.

IV. Function D: Facilitating communication

The road tunnel must provide traffic flow information to the road users with important messages regarding the conditions of the outer and inner environment of the tunnel section promptly. The travel and route information must communicate on digital board or via FM radio concerning any temporal speed limitations, traffic congestion, planned or unexpected closings and planned restrictions. Finally, the users of a road tunnel system must have access to mobile network and emergency telephony installations during their passing through. The tunnel should accommodate space for such an equipment and be available to third parties to execute operational and maintenance works.

The climate scenario W_H expects weather conditions that can influence the functionality of some installations that communicate messages to the road users. When the visual and audio guidance becomes insufficient because of malfunctions caused from the weather, then the facilitation of communication is blocked. Moreover, more frequent thunderstorms can weaken more frequently the mobile signal and an increase of the number of road tunnel users as a result of climate change-caused population density increase in the vicinity of a road tunnel alter the needs regarding the needed number of emergency telephone installations. Therefore, the telephone communication becomes insufficient which means again blocking of communication.

V. Function E: Future-proofing system’s prosperity

During the design phase of a road tunnel system, parameters which relate to the annual traffic growth must be taken into consideration. Regional and national future conditions and developments can indicate the needed tunnel infrastructure. Future-proofing the tunnel system is of high importance if considering the required 100-year of minimum lifespan for a typical asset. Therefore, traffic forecasts resulting from traffic models (e.g. New Traffic Model, NTM) must be accommodated by the road tunnel system.

Under the same consideration, the needs of the social environment around the road tunnel are taken into account in the long-term, the tunnel structure remains intact and sufficient space is left available for future expansions. However, the increasing carbon dioxide atmospheric concentration and the increase of humid days that are expected in the future can degrade the civil and soil tunnel structure design. More frequent maintenance works because of faster climate change-imposed deterioration creates nuisance and consequently public condemnation. The overall impact on the climate variables could even jeopardize the possibility of road tunnel extension although prior measures had been taken in that direction. It seems that Function E could be intensely affected by future climate conditions.

5.2. Functional decomposition

A primary consideration in a tunnel system is the definition of the functions that should serve. Afterward, a question is raised regarding the means a tunnel system could achieve these functions and in which level of performance. Every particular function has a system to achieve the function's goals. This system must necessarily be able to satisfy the function specifications – performance requirements of that particular function. When the system underperforms, then the function fails as well.

As we have seen, a complex system, such as a tunnel, consists of lots of functions which in turn consist of many other subfunctions. The functional decomposition is important in this case to effectively define the tunnel system as accurately as possible regarding its subfunctions, subsystems, and at the same time its needed performance. The latter indicates that in any other level of performance, the assigned subsystem would not perform as it should and because of that, the subfunction would fail. Consequently, the main function could not have been achieved as well, which would mean in turn, tunnel system's failure.

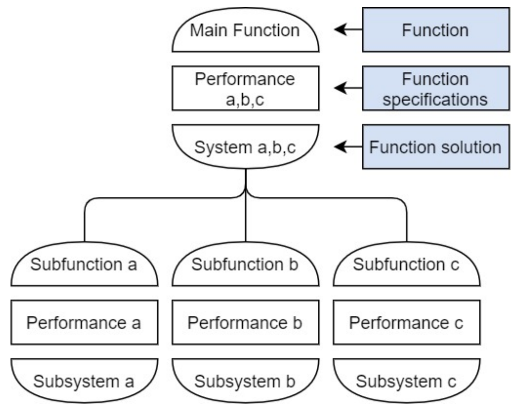


Figure VIII: Hamburger model: Functional decomposition scheme and characteristics, Source: own scheme

The Hamburger model have been used in the engineering domain of aerospace, electrical, mechanical and water management to execute functional decompositions of relevant systems for decision making in asset management. (Zaal, 2009) explains thoroughly in his book the characteristics of the Hamburger model by presenting an explanatory example of a functional decomposition from the domain of water management. *Figure VIII* illustrates the scheme and the characteristics of a typical Hamburger model analysis. In this example, three *Subfunctions (a, b, c)* are achieved by three *Subsystems (a, b, c)* which are assigned to perform the requirements *Performance a, b* and *c* respectively. All these *Subsystems* and *Performances* are the ones that the *Main Function* needs to have.

In the following *subchapters*, the functional decomposition of a road tunnel system by applying the Hamburger model is executed where clearer interpretation of the method and its benefits can be achieved. The decomposition of each function has been executed after a thorough study of the RWS tunnel standards, (Ministry of Transport and Water Management, 2013) and self-assessment of the correlation between the functional and technical requirements laws and regulations for tunnels impose under the prism of potential climate effects on those requirements. Moreover, this analysis supports the functional failure analysis of the system which is presented in *subchapter 3.3*.

5.2.1. Function A: Assimilating traffic flow

The functional decomposition is illustrated in the following *Figure IX* which provide information regarding the *Function Solutions* that are used to perform the relevant *Function* accompanied with the definition of the *Function Specifications.* At this point, it is important to describe each component starting from bottom to top of the scheme.

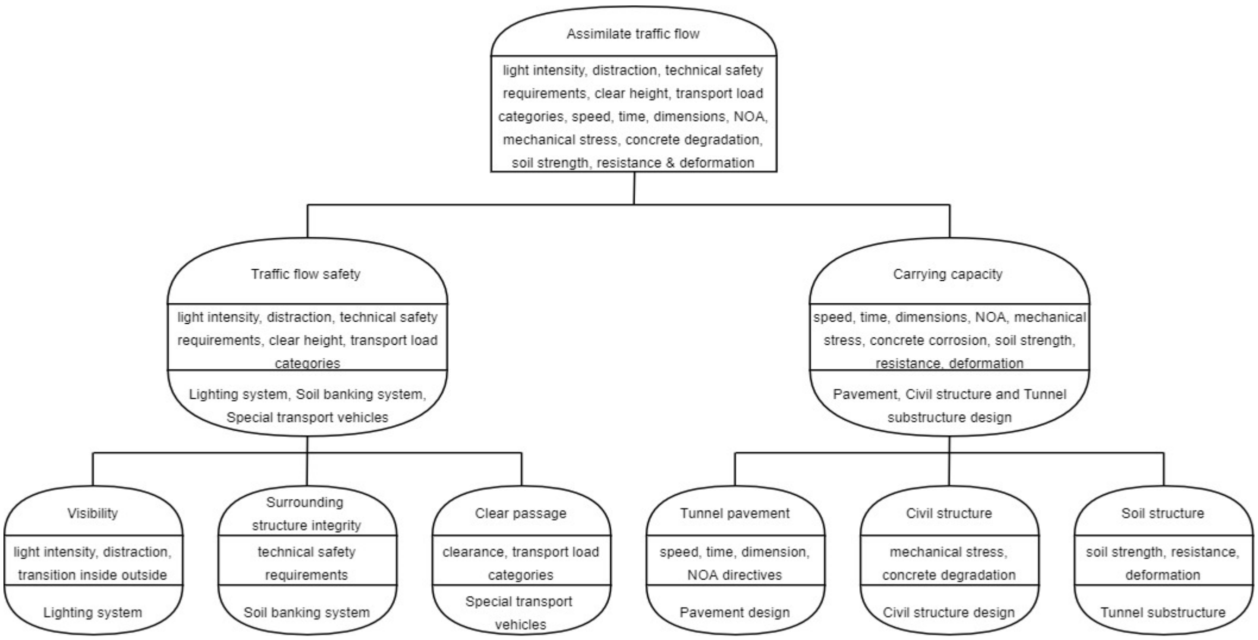


Figure IX: Functional decomposition of Function A: Assimilate traffic flow, Source: own scheme

Set I

- **Visibility:** The lighting system of the tunnel is to provide the road user the necessary visibility when coming in and out of the tunnel. The light intensity must be adjustable to the current weather conditions so that the user smoothly proceeds to this road section without experiencing any inconvenience.

- **Surrounding structure integrity:** The soil banking system consists of retaining walls that hold the massive soil volume in the tunnel entrances. These civil engineering structures are a combination of reinforced concrete elements and soil volumes which must abide by the regulatory directives and law requirements for structural integrity and safety during the service life of the asset. Land subsidence or long periods of drought and intense rainfalls afterwards could make the soil banking system to be unstable and landslide events to occur.

- **Clear passage:** A road tunnel must offer a seamless passage in any sort of transport vehicle; therefore, a tunnel must have sufficient clear height for special vehicles. Any interruption of the regulatory tunnel clearance and in the transport load categories affects that subfunction. The special transport vehicles are the ones that play a decisive role and mostly connected to the clear height of a tunnel. New transportation demands caused from climate change could result in clear height decrease whether more space may be required for the tunnel system's installations.

<u>Set II</u>

- **Tunnel pavement:** It has the function to allow the traffic flow pass through the tunnel. The pavement design is the system that allows that particular subfunction to be fulfilled and the characteristics of that are the speed limit and the travel time for the user and the dimensions of the pavement itself. In case of any differentiation of those specifications and therefore underperformance of the pavement design leads to failure of the subfunction of the tunnel pavement.

- **Civil structure:** The civil engineering structure of the tunnel has the function to bear its weight, the soil loads that it receives from around, and of course the load of the vehicles and tunnel installations. The civil engineering design of the tunnel structure is the system that achieves this specific subfunction and the specifications of this design include the mechanical stress and degradation that the concrete structure is exposed. Any deviation from the function specifications means poor performance and therefore subfunction failure.

- **Soil structure:** The foundation system of a road tunnel structure lays on a compressed layer of soil. The soil structure has the function to bear loads of the over structures and volumes of soil. The soil structure specifications are the soil shear strength, soil resistance, and soil deformation which characteristics and values are project-specifically defined. The tunnel substructure defines these performance requirements and indicates the design of the soil structure. Any future changes on the variables that were taken into account on the design could potentially lead to different values of performance and consequently failure of that particular subfunction.

The Set I elements compose the subfunction ''Traffic flow safety'', its subfunction specifications are the sum of each of the aforementioned specifications and the system that is used for the realization of that particular subfunction ''Traffic flow safety'' consist of the individual aforementioned systems. In the same way, the Set II elements form the subfunction ''Carrying capacity'' the characteristics of which are the sum of the already defined ones as Set II. Completing the functional decomposition analysis, it is concluded that the main function ''Assimilate traffic flow'' is constituted by the subfunctions ''Traffic flow safety'' and ''Carrying capacity'' (*Figure IX*).

5.2.2. Function B: Providing route flexibility

The functional decomposition is illustrated in the following *Figure X* which provide information regarding the *Function Solutions* that are used to perform the relevant *Function* accompanied with the definition of the *Function Specifications.* At this point*,* it is important to describe each component starting from bottom to top of the scheme.

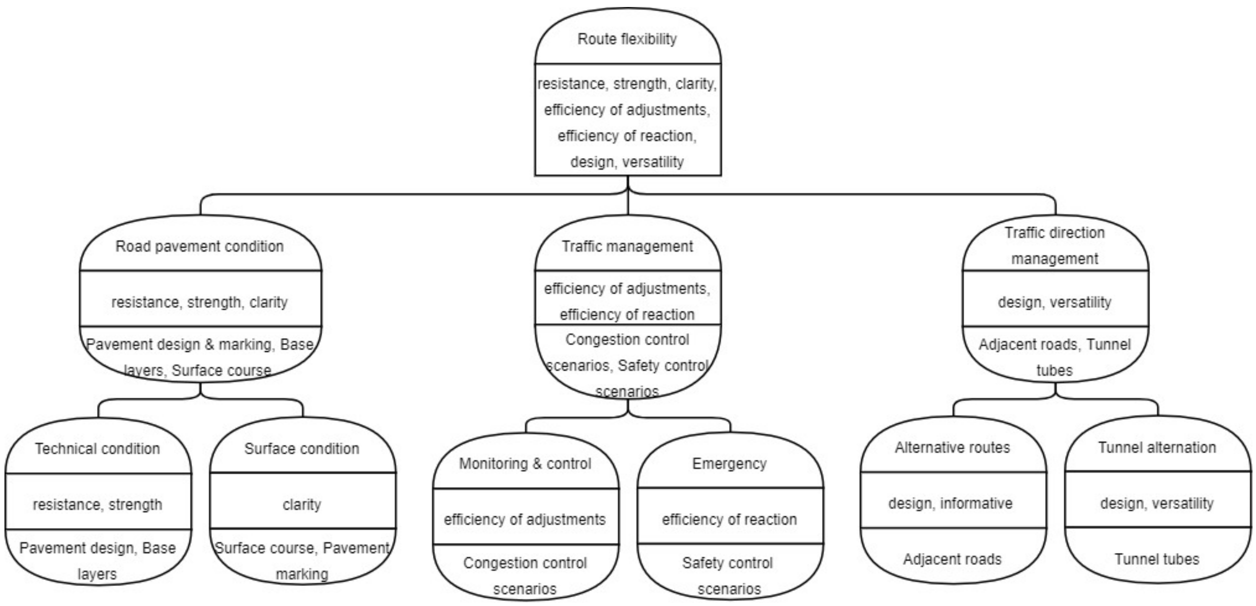


Figure X: Functional decomposition of Function B: Assimilate traffic flow, Source: own scheme

Set I

- **Technical condition:** The road pavement of the tunnel beside the fact that it allows the vehicles to pass through the tunnel, it has also the function to be capable to bear sufficiently the vehicles load, not only inside the tunnel and but also when the vehicles entering it. The technical pavement design is the system that is used to define the technical requirements and the design of the pavement base and the upper asphalt layer of the road parts in the tunnel entrances. The strength and resistance of those structural layers are the specifications that could be affected by the changes of the climate variable of temperature over the years.

- **Surface condition:** The surficial road pavement condition plays an important role in the general pavement conditions of the road tunnel. The surface course inside and outside of the tunnel should be of the same functional and quality level. The clarity of the road pavement marking may be deteriorated faster when it is exposed in more adverse climate conditions. The climate variable of temperature could speed up the degree of deterioration in the following years as a result of general climate change.

Set II

- **Monitoring & control:** It is a function that is necessary for the prevention of traffic congestion events. Congestion control scenarios are used to control the traffic flow within and outside the road tunnel section. The specifications of those scenarios are to perform traffic lighting adjustments and traffic speed adjustments to prevent the cause of high-risk events. Climate extremes rise, so the impact of short extreme weather that can be shown some days may not be faced by those scenarios sufficiently, resulting in creating traffic issues.

- **Emergency:** The road tunnel should be able to react in emergencies. Safety control scenarios are the system that is used to face extraordinary situations that jeopardize the safety of road users and the efficiency of emergency services. These scenarios should be able to react efficiently and in case the solution of route alternation is activated as a result of tunnel flooding after extreme rainfall, emergency services must not be affected. Moreover, the scenarios must respond in cases of tunnel blackout where the majority of tunnel installations cannot operate if an energy generator is not enough or is lacked at all. The climate variable of precipitation is evolving over time and affects this function.

Set III

- **Alternative routes:** The road tunnel should be consisting of surrounding roads that could be potentially be used as alternative routes if the road tunnel becomes unavailable. The traffic load must be served by these adjacent roads if needed. The provision of information to the users is necessary to guide them in the correct directions. The selection and design of those alternative routes should not be jeopardized by future changes, such as the future transformation of some routes into low traffic roads to accomplish CO2 emissions mitigation. Moreover, the provision of information must not be disturbed by extreme weather conditions that threaten with damages on informative boards.

- **Tunnel alternation:** The road tunnel must also be able to alternate the traffic directions within the tunnel tubes. The tunnel tubes are the system that must be designed in such a way to allow the traffic to flow in both directions. This makes it to be versatile. The traffic setting structure is a decisive factor to achieve versatility. The disturbance of this setting is possible to happen through an event of tunnel tube partial flooding or from general climate change impacts. Moreover, frequent maintenance works, that may need to deal with the system's deterioration resulting from climate effects, increase the tunnel's unavailability. In case of demand of traffic alternation within the tunnel, while maintenance works are executed, this would impact the tunnel's functionality.

The Set I elements compose the subfunction ''Road pavement condition'', its subfunction specifications are the sum of each of the aforementioned specifications and the system that is used for the realization of that particular subfunction ''Road pavement condition'' consist of the individual aforementioned systems. In the same way, the Set II elements form the subfunction ''Traffic management'' the characteristics of which are the sum of the already defined ones as Set II. Finally, the Set III elements form the subfunction ''Traffic direction management'' the characteristics of which are again the subfunction specifications and systems that those elements consist of. Completing the functional decomposition analysis, it is concluded that the main function ''Route flexibility'' is constituted by the subfunctions ''Road pavement condition'', ''Traffic management'' and ''Traffic direction management'' (*Figure X*).

5.2.3. Function C: Connecting with the road network traffic management facilities

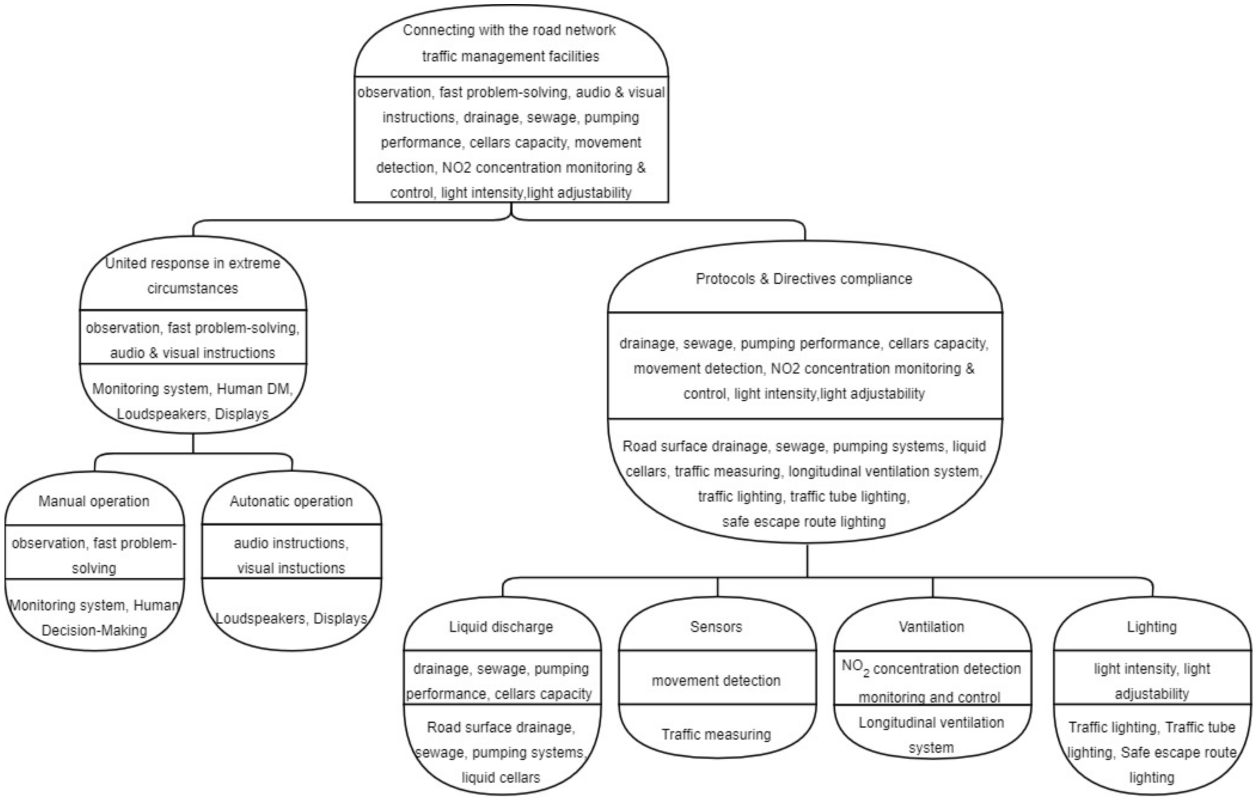


Figure XI: Functional decomposition of Function C: Assimilate traffic flow, Source: own scheme

The functional decomposition is illustrated in the following *Figure XI* which provide information regarding the *Function Solutions* that are used to perform the relevant *Function* accompanied with the definition of the *Function Specifications.* At this point, it is important to describe each component starting from bottom to top of the scheme.

Set I

- **Manual operation:** A road tunnel system operates under a continuous process of traffic monitoring and controlling. Through human monitoring and decision-making, the manual operation of the system is achieved. Optimum observation of abnormalities and fast problem-solving are the specifications of this function to perform the optimal result. However, frequent disturbing events (i.e. flooding) that are caused by unexpected weather conditions for the current season, it may compromise the fast communication of traffic changes, bringing about considerable consequences. The climate scenario WH is the one that such events more frequently can happen.

- **Automatic operation:** A road tunnel system also operates under an automatic and continuous process of traffic monitoring and controlling. The provision of information to the road users is done in sync with every nearby road section of the network. Visual and audio messaging is executed after the automatic observation of abnormalities to avoid traffic congestion and the feeling of insecurity to the users. Any visual and audio instructions on displays and loudspeakers must be consistent especially in this case where they are done automatically. Frequent weather instability observations increase the potential unavailability of the road tunnel as the risk of faulty messaging increases.

Set II

- **Liquid discharge:** The liquid discharge in the road tunnel must be in the same sufficient level as the one in the rest road network. No difference must be shown. The road surface drainage, the sewage system, the pumping systems, and the liquid cellars are the systems that allow this function. The mechanical performance of these systems and the capacity of those discharge cellars indicate the efficiency of this function. Hailstorms and other extreme precipitation events (heavy rainfalls) are the climate variables that are increasing and even doubled the following years which indicate potential influence of achieving sufficiently liquid discharge.

- **Sensors:** They are used for the monitoring of traffic flow by detecting any movement or in many other ways. Sensors are significantly useful to a road tunnel system because of their capabilities to detect whatever humans could hardly do or would need more time. Their specifications depend on the function that they execute, and their performance should not be affected by climate change. Whether the reliability of the sensors changes because of their exposure to different weather conditions than that they are designed, faulty observations will result.

- **Ventilation:** The longitudinal ventilation system is the one that is used to accomplish the optimum ventilation of a road tunnel. Processes of monitoring and control of the NO2 atmospheric concentration in the tunnel are executed for that purpose. Any weakness to perform adequately such processes lead to the failure of cleaning off the inside tunnel air. An increase in the number of vehicles that sufficiently use the tunnel, it increases the smoke concentration inside the tunnel and therefore degrades the performance of the ventilation system. Moreover, the ongoing promotion of electric mobility increases the consequences of a car crash which electric cars may involve as the produced smoke may be denser than the ventilation system is designed to face.

- **Lighting:** Another function of the road tunnel is to be well lit and the lighting signals clear. The systems that are related to this function are the traffic lights, the traffic tube lighting, and the safe escape route lighting. The light intensity and light adjustability play a decisive role to achieve the lighting requirements. The humid weather is an example of a climate condition where the lighting sensors may wear out sooner than it was expected and consequently to fail to adjust the lighting systems to the current external lighting environment.

The Set I elements compose the subfunction ''United response in extreme circumstances'', its subfunction specifications are the sum of each of the aforementioned specifications and the system that is used for the realization of that particular subfunction ''United response in extreme circumstances'' consist of the individual aforementioned systems. In the same way, the Set II elements form the subfunction ''Protocols and directives compliance'' the characteristics of which are the sum of the already defined ones as Set II. Completing the functional decomposition analysis, it is concluded that the main function ''Unity of tunnel's and road network's traffic management system'' is constituted by the subfunctions 'United response in extreme circumstances'' and ''Protocols and directives compliance'' (*Figure XI*).

5.2.4. Function D: Facilitating communication

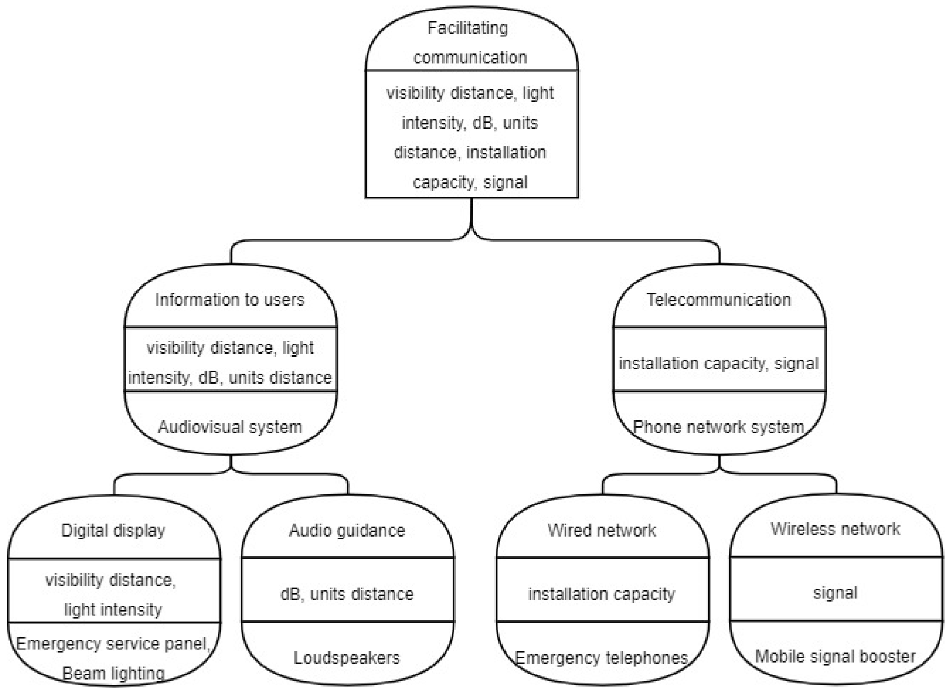


Figure XII: Functional decomposition of Function D: Assimilate traffic flow, Source: own scheme

The functional decomposition is illustrated in the following *Figure XII* which provide information regarding the *Function Solutions* that are used to perform the relevant *Function* accompanied with the definition of the *Function Specifications.* At this point, it is important to describe each component starting from bottom to top of the scheme.

<u>Set I</u>

- **Digital display:** The digital installations at a road tunnel system for the communication of any information to the road users are important elements. The displays, the emergency service panels, and the beam lighting are such systems that are used for this purpose. The visibility distance and light intensity are the specifications of the digital displays. Any deviation from them would lead to underperformance of this subfunction. Intense rainfalls, heat, and ice days are related to climate evolvement and could impact these performance requirements.

- **Audio guidance:** Loudspeakers are used as the means of communication of any information in audio form and provision of any needing audio guidance. The number of loudspeaker units and the volume level play a decisive role in the effectiveness and good performance of this subfunction. Extreme weather conditions that are related to the precipitation could wear down the installations and degrade the required audio performance. Moreover, an increase in the number of users increases the noise as well which means that such installations could constitute inadequate as far their number is concerned.

<u>Set II</u>

- **Wired network:** The system that performs the subfunction of a wired network is the emergency telephones. The existence of them is an integral element in any road section. The road user must have access to telephone whether they are on a need to communicate an emergency. The specification of the wired network inside the tunnel is the number of such telephone installations. The user must spend as little time as possible to reach an emergency telephone, otherwise, the number of installations may be fewer than it should be. Exceeded user occupancy of the road tunnel, where the vehicles are continuously more than the tunnel was designed, the number of telephones may be thought inadequate for proper response in a need. Moreover, climate evolvement shows an increase in extreme events that are likely reasons for tunnel evacuation. Emergency telephones are very likely to be used in such cases as well. An inadequate wired network could make wired communication unavailable and consequently a road tunnel incapable to allow communication with the outer environment.

- **Wireless network:** The system that performs this subfunction is a mobile signal booster. The use of it is necessary to boost the mobile network inside the road tunnel. Therefore, the specification of the wireless network is the signal level that it should be performing. Climate variables, such as thunderstorms, can affect the existence of adequate signal during a storm event. The signal can be lost for a specific period. Without this subfunction, the road tunnel becomes unavailable for mobile communication if the users are inside the tunnel.

The Set I elements compose the subfunction ''Information to users'', its subfunction specifications are the sum of each of the aforementioned specifications and the system that is used for the realization of that particular subfunction ''Information to users'' consist of the individual aforementioned systems. In the same way, the Set II elements form the subfunction ''Telecommunication'' the characteristics of which are the sum of the already defined ones as Set II. Completing the functional decomposition analysis, it is concluded that the main function ''Facilitating communication'' is constituted by the subfunctions ''Information to users'' and ''Telecommunication'' (*Figure XII*).

5.2.5. Function E: Future-proofing system's prosperity

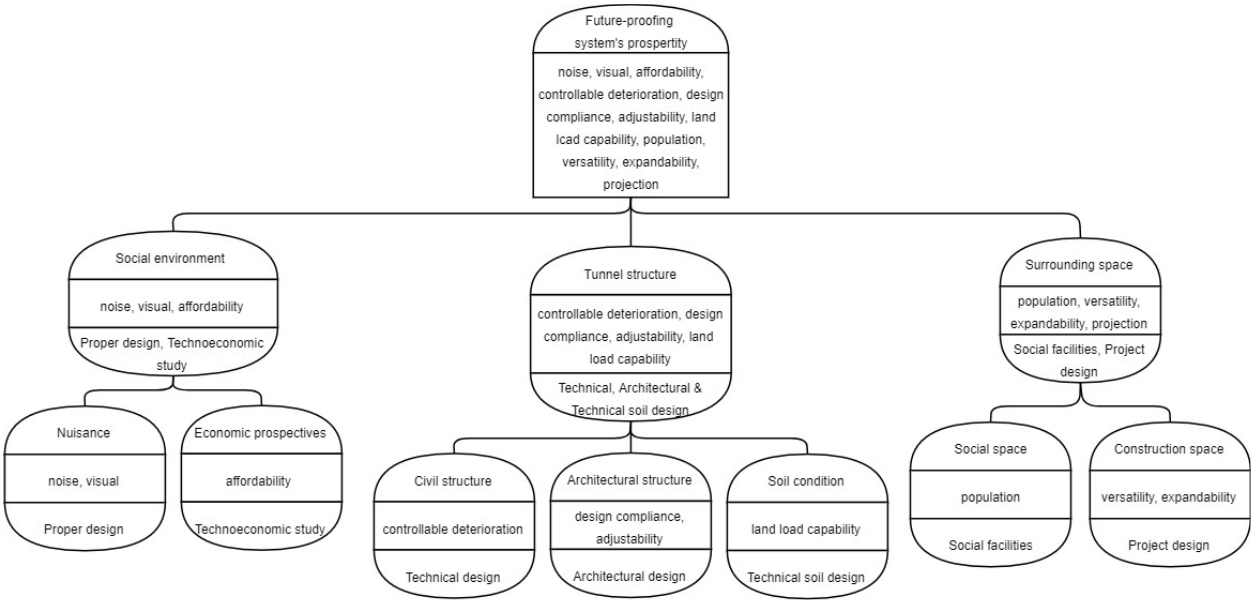


Figure XIII: Functional decomposition of Function E: Assimilate traffic flow, Source: own scheme

The functional decomposition is illustrated in the following *Figure XIII* which provide information regarding the *Function Solutions* that are used to perform the relevant *Function* accompanied with the definition of the *Function Specifications.* At this point, it is important to describe each component starting from bottom to top of the scheme.

Set I

- **Nuisance:** A proper design is the system that is used to deal with nuisance-related issues. The design is about to face the noise and visual disturbance of the inhabitants in the vicinity of the road tunnel system. The increasing commuting because of the overall climate change and possible increase of the population around the tunnel would exceed the limits of nuisance acceptance. This means that the previous design for nuisance prevention can fail to perform well and acts for problem resolution and tunnel's lifespan expansion would make the road tunnel unavailable for use.

- **Economic prospective:** Techno-economic studies are the means to ensure the economic prosperity of the social environment by using the road tunnel system. This is translated as the affordability of the use or not of a particular road tunnel system. Frequent maintenance works are expected if considering the adverse impacts of the climate variables which seem to have over time on a road tunnel. Maintenance works mean a period of tunnel unavailability to perform its functions. More and more users will change their preference to use the route of the tunnel when the latter is frequently closed, and the public will condemn the tunnel's usability. Moreover, the social environment will suffer an economic loss if they need to run a longer distance to reach their destination. All these could doubt the performance of one of the system's functions which is future-proofing tunnel's prosperity.

Set II

- **Civil structure:** The technical design of the concrete structure takes into consideration the need for controllable deterioration of the concrete mass. The environment can be quite vulnerable to the road tunnel civil structure. The climate evolvement shows that carbon dioxide and chloride ions will be concentrated in bigger volumes in the following years and are the ones that weaken the concrete mass. Uncontrollable degradation is possible to happen and must be avoided as this could lead to an unavailable road tunnel.

- **Architectural structure:** The architectural design of the architectural aspect of the structure should be performed in a road tunnel. The design must be complied with the needs and provide enough space for adjustments in the future. The overall climate change seems to create news needs and therefore new demands to be adjusted. All these should be considered in the early phase because any future interventions could make the road tunnel unavailable for operation.

- **Soil condition:** A technical soil design should be performed to ensure the required soil condition for the foundation of a road tunnel system. The land load capability is measuring in this case. Changes in this parameter would be destroyed for the tunnel structure. Climate change affects some variables that influence landmass stability and consequently, the stability of the road tunnel structure. A reasonable result would be the execution of restoration works which in turn would lead to an unavailable tunnel for use.

Set III

- **Social space:** The population density of the vicinity of the road tunnel system characterizes the needs of the society for social space. Social facilities and green areas are the means that are used to fulfill these needs. Potential changes in the population density because of the overall climate change would require new developments of urban recreation. The surrounding space of a road tunnel is used in many cases for such purposes, mainly the area above the tunnel structure. Therefore, any interventions in later, during the tunnel's life cycle, may require from the road tunnel to be closed for the execution of such works.

- **Construction space:** The project design in the early phase must provide adequate construction space for the execution of the construction works. It is also important the consideration of potential future demands for expansion of the existent road tunnel structure. The versatility of the system should be enough to allow the road tunnel system to be adjusted easily. Thus, prosperity and versatility must characterize that system. However, some parameters that emerge from climate change can jeopardize these characteristics. Excessive strain on the existent structure caused by i.e. land subsidence, groundwater level, or even excessive traffic loads should require relevant interventions to relieve the road tunnel structure which in turn may require more space than it was designed for such works. It is obvious that the road tunnel prosperity and consequently availability for operation is in danger.

The Set I elements compose the subfunction ''Social environment'', its subfunction specifications are the sum of each of the aforementioned specifications and the system that is used for the realization of that particular subfunction ''Social environment'' consist of the individual aforementioned systems. In the same way, the Set II elements form the subfunction ''Tunnel structure'' the characteristics of which are the sum of the already defined ones as Set II. Finally, the Set III elements form the subfunction ''Surrounding space'' the characteristics of which are again the subfunction specifications and systems that those elements consist of. Completing the functional decomposition analysis, it is concluded that the main function ''Future-proofing system's prosperity'' is constituted by the subfunctions ''Social environment'', ''Tunnel structure'' and ''Surrounding space'' (*Figure XIII*).

5.3. Modes of functional failure

The next process after the functional decomposition of the five functions of a road tunnel system and the presentation of the expected projections of the climate variables over the next decades is the execution of a failure analysis for each of these functions. A deductive top-down analysis is applied to find out the specific (basic) events that can potentially cause a generic (top) event. The Fault Tree (FT) model is the methodology that is followed for that purpose. A FT is built up of gates and events. The principal types of gate are the ''OR Gate'' and ''AND Gate'' (Vesely, Dugan, Fragole, Minarick, & Railsback, 2002). There are more than these two types of gates, but they are not discussed in the due research and failure analysis.

Moreover, in the FT model, the occurrence of a functional failure is defined as ''Top event''. The occurrence of an event that cannot be caused by other events and initiates a sequence of events that leads to the occurrence of the ''Top event'', is defined as ''Basic Event'' and it lays in the bottom of the hierarchy in a FT diagram. Finally, the occurrence of any other event in between is defined as ''Intermediate event''.

In the following *subchapters*, FT analysis is executed for the five road tunnel functions, categorizing the components into ''Intermediate events'' and ''Basic events'' and finally reflecting them into five different FT diagrams. The explanation of the consideration behind of each component definition, the correlation with the climate change and the associated mathematical expressions are presented in the corresponding section in Appendix. The definition format for the ''Top event'' ,of i.e. *Function A,* is ''TopA#'', for the ''Intermediate event'' is ''INTERA#", and for the ''Basic event'' is ''A#'', where ''#'' is the relevant indicators for each event case.

5.3.1. Fault tree of Function A: Assimilating traffic flow

The failure analysis of Function A constitutes by components which are categorized into fourteen ''Intermediate events'' and twenty ''Basic events''. A short description and visualization of them allows the deeper understanding of the failure mode structure. *Figure XIVI* is the Fault Tree diagram of Function A.

The failure of the subfunction *Carrying capacity* of the functional decomposition of *Function A.* can be caused by the basic events *A1.-A12.* and is summarized as the intermediate event *INTERA1: Failure in carrying capacity.* The failure of the other subfunction *Traffic flow safety* of *Function A.* can be caused by the basic event *A13.-A20.* and is summarized as the intermediate event *INTERA2.: Insufficient traffic flow safety.*

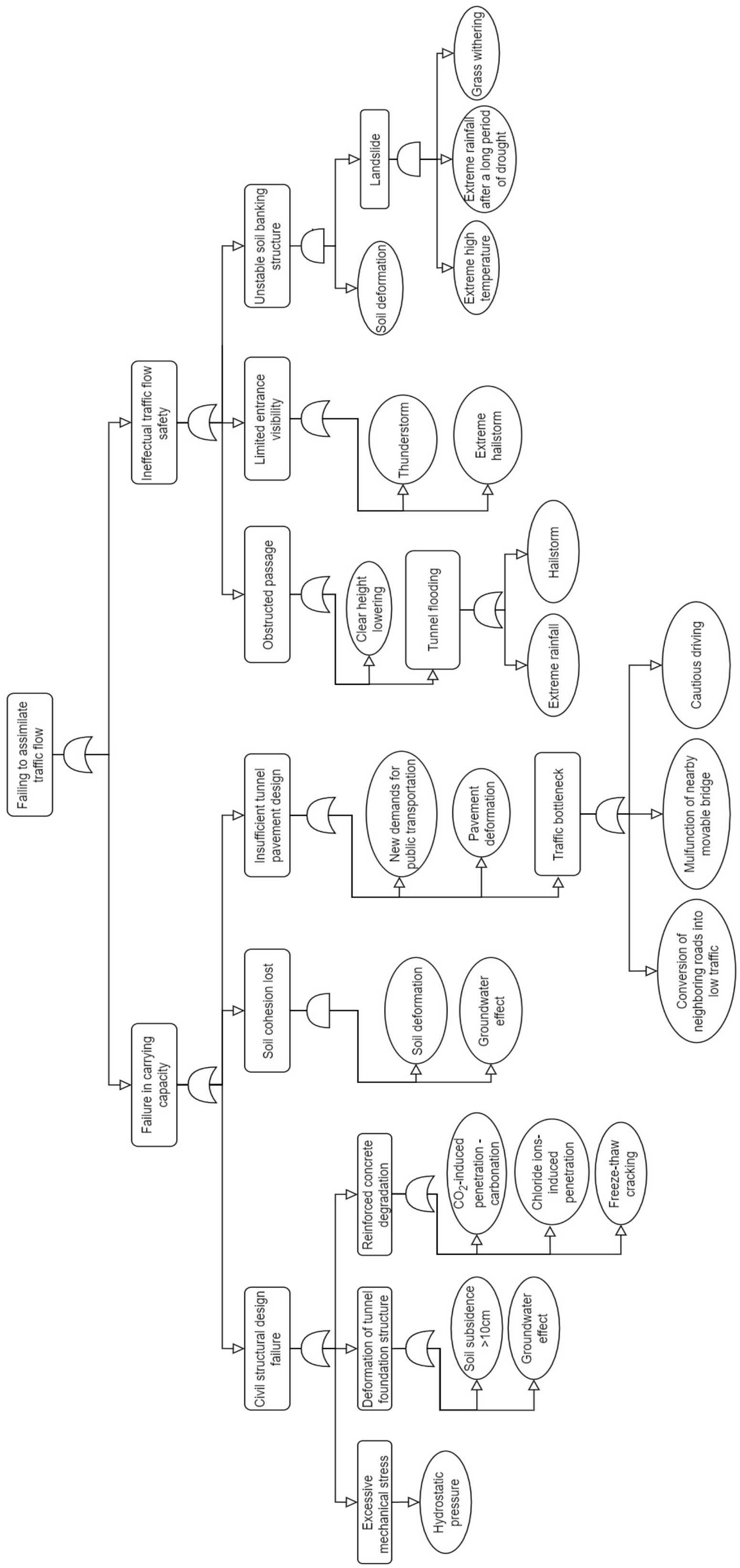


Figure XIV: Failure analysis of Function A under the form of a fault tree, Source: own diagram

5.3.2. Fault tree of Function B: Providing route flexibility

The failure analysis of Function B constitutes by components which are categorized into eight ''Intermediate events'' and fifteen ''Basic events''. A short description and visualization of them allows the deeper understanding of the failure mode structure. *Figure XV* is the Fault Tree diagram of Function B.

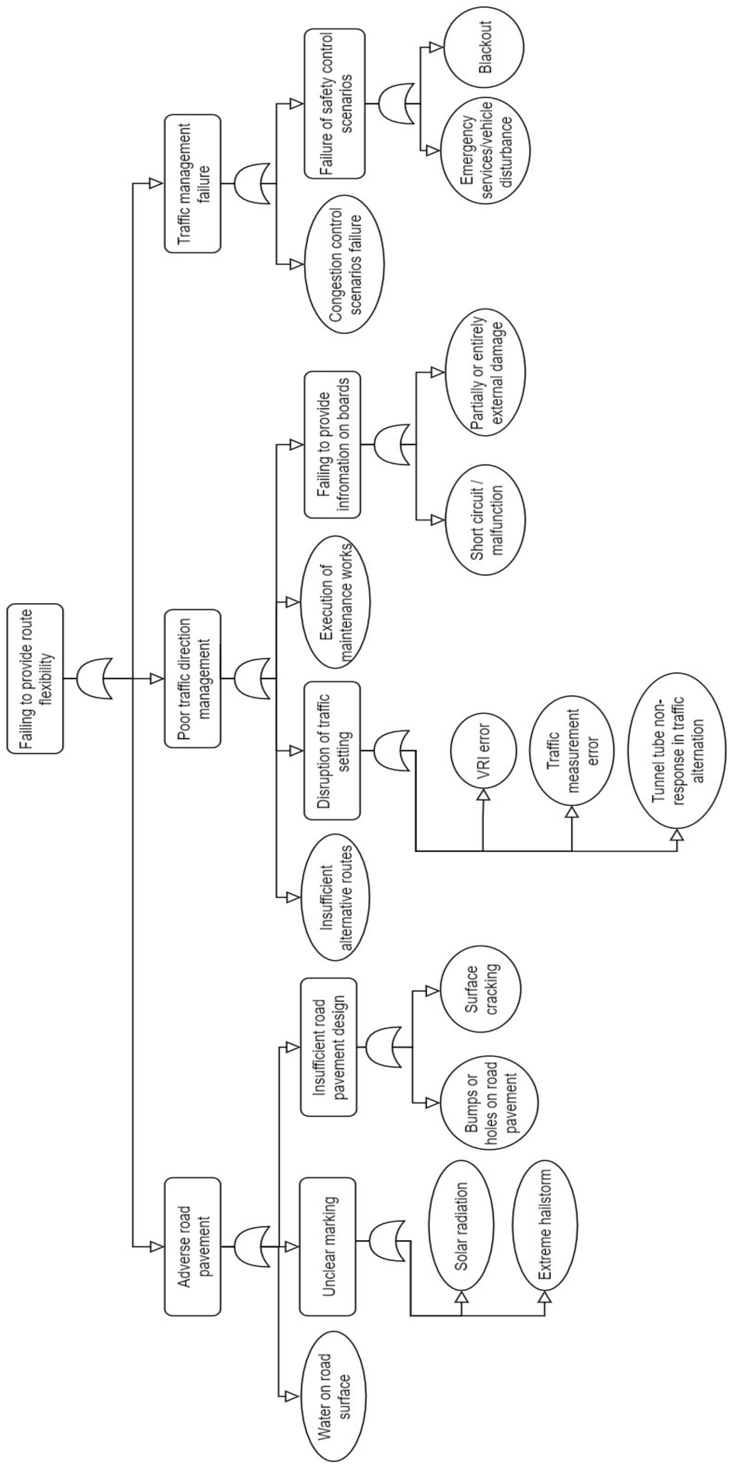


Figure XV: Failure analysis of Function B under the form of a fault tree, Source: own diagram

The failure of the subfunction *Road pavement condition* of the functional decomposition of *Function B.* can be caused by the basic events *B1.-B5.* and is summarized as the intermediate event *INTERB1.: Adverse road pavement.* The failure of the other subfunction *Traffic direction management* of *Function B.* can be caused by the basic events *B6.-B12.* and is summarized as the intermediate event *INTERB2.: Poor traffic direction management.* Finally, the failure of subfunction *Traffic management* can be caused by the basic events *B13.-B15.*

5.3.3. Fault tree of Function C: Connecting with the road network traffic management facilities

The failure analysis of Function C constitutes by components which are categorized into five ''Intermediate events'' and nine ''Basic events''. A short description and visualization of them allows the deeper understanding of the failure mode structure. *Figure XVI* is the Fault Tree diagram of Function C.

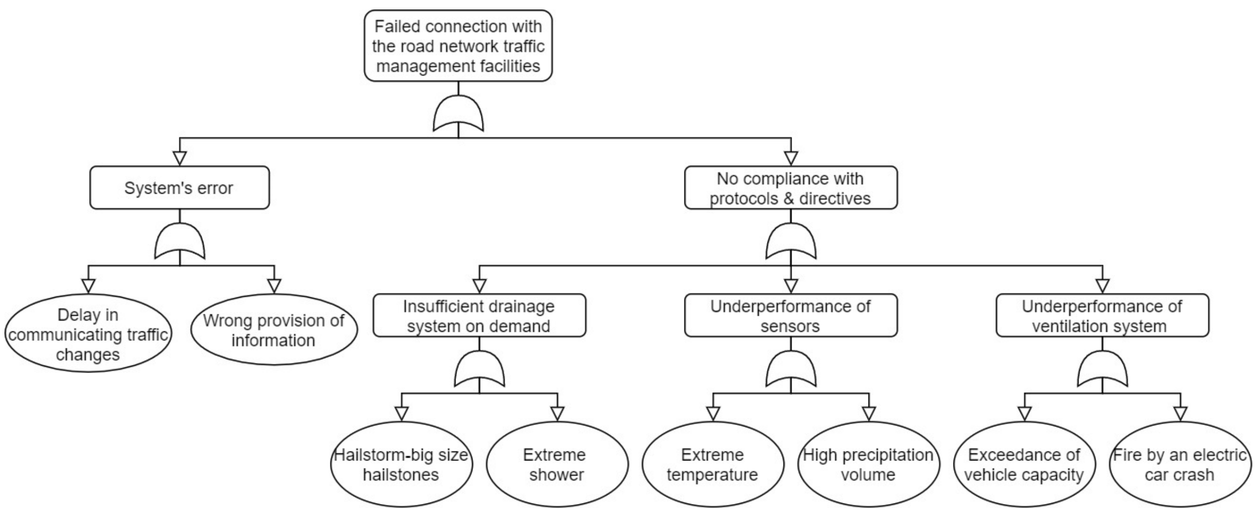


Figure XVI: Failure analysis of Function C under the form of a fault tree, Source: own diagram

The failure of the subfunction *United response in extreme circumstances* of the functional decomposition of *Function C.* can be caused by the basic events *C1.-C2.* and is summarized as the intermediate event *INTERC1: System's error.* The failure of the other subfunction *Protocols & Directives* of *Function B.* can be caused by the basic events *C3.-C8.* and is summarized as the intermediate event *INTERC2.: No compliance with protocols & directives.*

5.3.4. Fault tree of Function D: Facilitating communication

The failure analysis of Function D constitutes by components which are categorized into eight ''Intermediate events'' and nine ''Basic events''. A short description and visualization of them allows the deeper understanding of the failure mode structure. *Figure XVII* is the Fault Tree diagram of Function D.

The failure of the subfunction *Information to users* of the functional decomposition of *Function D.* can be caused by the basic events *D1.-D5.* and is summarized as the intermediate event *INTERD1.: Incapability to provide information to the road users.* The failure of the other subfunction *Telecommunication* of *Function D.* can be caused by the basic events *D6.-D9.* and is summarized as the intermediate event *INTERD2.: Insufficient telephone communication.*

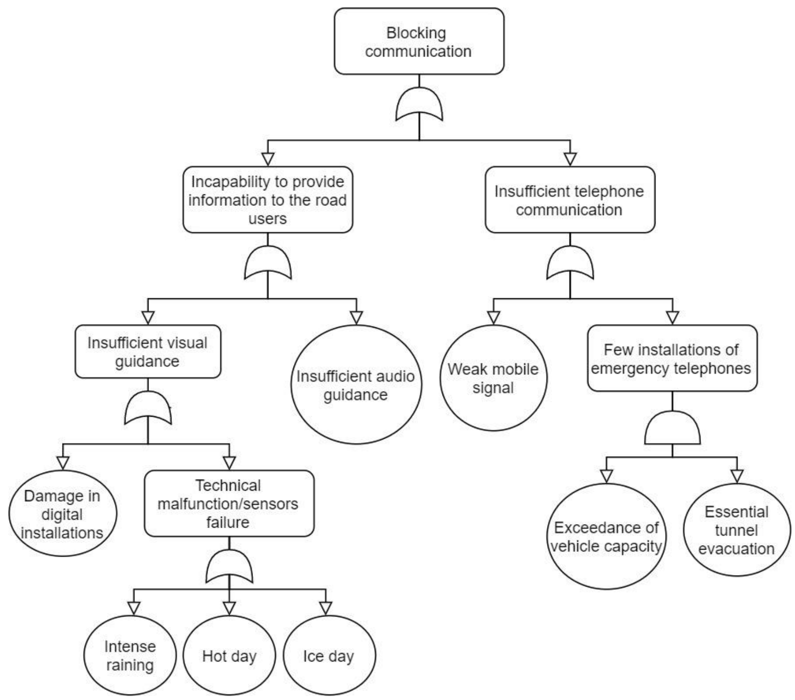


Figure XVII: Failure analysis of Function D under the form of a fault tree, Source: own diagram

This proves that both D7. and D8. events contribute simultaneously to the road tunnel unavailability.

5.3.5. Fault tree of Function E: Failing to future-proof system's prosperity

The failure analysis of Function E constitutes by components which are categorized into four ''Intermediate events'' and eight ''Basic events''. A short description and visualization of them allows the deeper understanding of the failure mode structure. *Figure XVIII* is the Fault Tree diagram of *Function E*. The failure of the subfunction *Social environment* of *Function E.* can be caused by the basic events *E1.-E2.* and is summarized as the intermediate event *INTERE1.: Public condemnation.* The failure of the other subfunction *Tunnel structure* of *Function D.* can be caused by the intermediate event *INTERE2.1.: Uncontrollable deterioration* which in turn is caused by the basic events *E3*. and *E4.,* and the basic events *E5.* and *E6.* and is summarized as the intermediate event *INTERE2.: Tunnel structure design failure.* Finally, the failure of subfunction *Surrounding space* can be caused by the basic events *E7.* and *E8.* And is summarized as the intermediate event *INTERE3.: Lack of sufficient surrounding space for construction adding.*

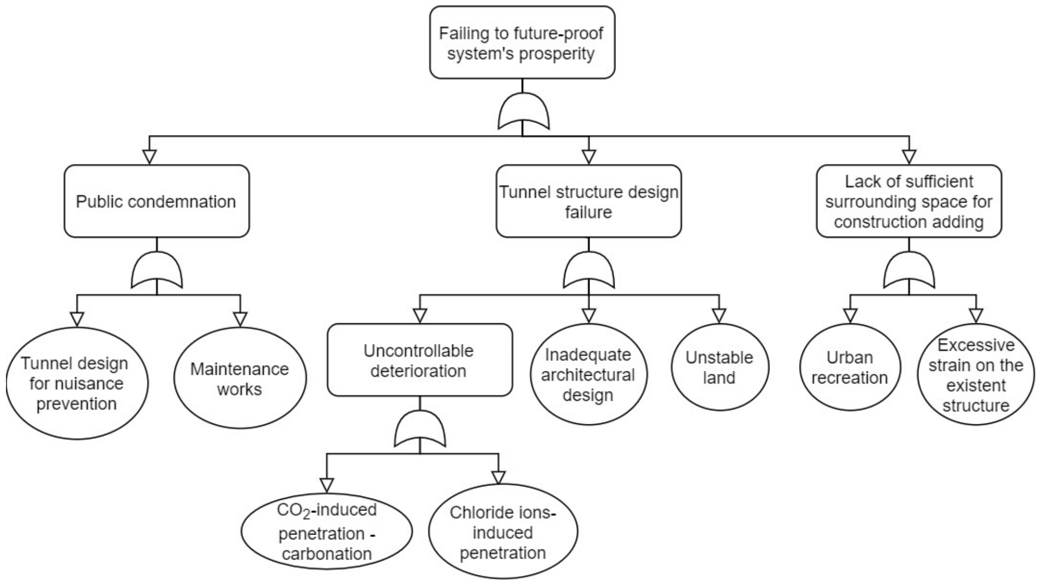


Figure XVIII: Failure analysis of Function E under the form of a fault tree, Source: own diagram

5.4. Conclusion

The Functional Breakdown Structure of a road tunnel, which was presented in *Chapter 5,* was important to be developed after having analyzed the climate change uncertainty because both together completed the execution of the DAPP model first step, *1) Describe current situation, objectives & uncertainties.* The definition of the primary functional requirements *(5.1.)* of a road tunnel in the Netherlands, the identification of the performance and road tunnel systemic requirements *(5.2.)* and finally, the recognition of the modes of failure of those functions *(5.3.)* describe the *objectives* and associated *uncertainties* of road tunnels caused by the *current situation*, which is the climate change effect, as it was already elaborated in *Chapter 4.* In this chapter, 5 primary function requirements were defined, the decomposition of them by using the Hamburger model was performed to identify performance requirements and needs in systems and 59 basic events that lead to functional failure were recognized by implementing the Fault Tree Analysis.

Moreover, it replied to the first part of the Sub Question 1: ''*What are the functions of a road tunnel'',* which is proceeded in *Phase I.* The continuation to the second DAPP model step, *2) Analyze the problem, vulnerabilities & opportunities using transient scenarios,* in *Chapter 6*, is going to respond to the second part of the Sub Question 1: *''To what extent can future climate change impact the system's functional failure'',* and therefore, *Phase I* will be completed.

6. Analysis of the road tunnel system's functions failure modes

In this chapter, the analysis of the road tunnel system's functions is conducted based on their fault tree structures, which were presented in *Chapter 5*, by calculating the potential unavailability rate of a road tunnel to perform its functions when a basic event occurs and the assessment of the related impact of this incident. Firstly,

- In *subchapter 6.1.,* the timeline of the analysis is given to indicate four time periods of 20 years' span starting from 2020 to 2100.
- The methodology of the analysis for the calculation of the quantitative values of unavailability and qualitative values of impact and the identification of the way to correlate them is presented in *subchapter 6.2.*
- The execution of the methodology for the unavailability rate calculation resulting from each basic event and its impact assessment for every function (A-E) and period takes place in *subchapter 6.3.* Finally,
- S*ubchapter 6.4.* executes the methodology for the correlation of information of *subchapter 6.3*. and presents into five charts the unavailability percentage contribution of each basic event in the total unavailability rate resulted from every function to the road tunnel system. The resulted information is combined with the corresponding impact of each basic event and shapes four matrices for each function, one matric for every time period, which indicates the basic events that should be dealt with both preventive and mitigative measures, only preventive or only mitigative or without any adaptation measure.

The outcomes of this chapter reply to the second part of the Sub Question 1: *''To what extent can future climate change impact the system's functional failure'',* which means that *Phase I* is completed and the continuation to *Phase II* for the definition of the preventive and mitigative measures for road tunnel adaptation in *Chapter 7* will be performed.

6.1. Timeline of analysis

Climate change is a phenomenon that is evolving gradually over time. The impact of those changes is either visible in the first place or long later. Long term decision-making process seems to be the most appropriate approach when such dynamics must be faced. At the same time, the sort of infrastructure asset is the one that indicates and potentially confirms the path that should be followed. A road tunnel is an asset that needs long-term decision-making to keep its viability and be adaptive to the new conditions over time. This is quite important because Its lifespan is being designed for many years (100 or even 200 years) of service.

Based on the time reference of the data that have been used for the purposes of this research, the analysis of them in terms of a road tunnel's system and the assumptions that are made for the potential future influences to it refer to the time frame of 80 years. The time frame 2020-2100 is divided into four parts of twenty years. This means that assumptions and actions are made and taken for four different time periods: 2020-2039, 2040-2059, 2060-2079 and 2080-2100. In this way, their interfaces are defined as the tipping points of action, which are needed in the DAPP model.

Figure XIX depicts the chronological line indicating the four time periods and naming the action phases.

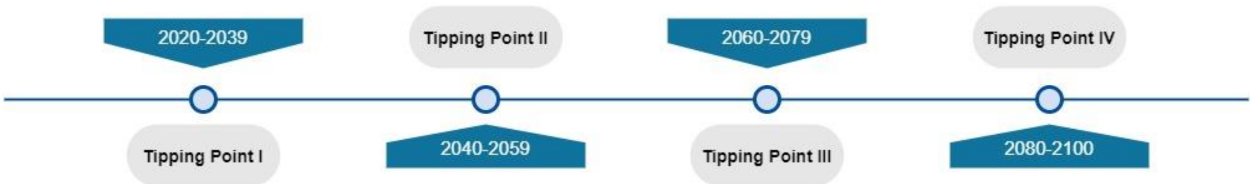


Figure XIX: The timeline divided into four time periods of action, Source: own graph

6.2. Analysis methodology

6.2.1. Road tunnel system unavailability rate analysis

The fault tree structure and its mathematical expressions, as they are proposed in *Chapter 5,* of each function are going to be used for the estimation of the unavailability rates these functions give to the road tunnel if these functions fail to perform. Unavailability of a road tunnel for operation is resulted from the incapability of at least one road tunnel function to be performed. In the following paragraphs, the process for the calculation of the unavailability rate, resulted from a particular basic event, is explained, then the calculation of the overall unavailability rate and finally the calculation of the percentage contribution of each basic event on the overall unavailability rate.

The first step is the assessment of the unavailability rate for every basic event. But firstly, it is necessary to describe the process step by step that is followed repetitively for each basic event. Considering the previously described basic event and its correlation with the climate products, the frequency rate of that event is estimated. The frequency rate is reversely proportional of the mean time between failure (MTBF), which in this case is translated as the mean time between two events when the road tunnel becomes unavailable for use and interventions works are needed to repair the source of the problem. Thus, the MTBF is calculated and expressed into days. Subsequently, the mean time to repair (MTTR), which is referred to the latter action, is assessed based on an assumption for the required time for the execution of the intervention works. Then, the unavailability rate, resulting from that basic event, can be calculated, and is expressed as the ratio: NA= MTTR / (MTBF + MTTR). The process is repeated for each of the basic events of a function fault tree.

The overall unavailability rate of the referring function is calculated based on the mathematical expressions and fault tree structure that have been presented in *Chapter 5.* This rate expresses the unavailability of the road tunnel to be open and operable to the road users when the particular function fails to perform as it was required and some works are needed to make the road tunnel operable again. An Excel spreadsheet has been developed based on the mathematical expressions and fault tree relations of the ''OR Gate'' and ''AND Gate'' between ''Basic events'' and ''Intermediate events'' on corresponding fault tree diagram. In this way, the overall unavailability rate of each function is calculated by using as input the resulted unavailability rates of each basic events.

Finally, the Excel spreadsheet is extended to calculate the percentage contribution of each basic event on this overall unavailability rate. In the book of (Sutton, 2010), a process of six steps is proposed for the calculation of the percentage contribution of a basic event to the system's failure and subsequently to overall risk. So, the process is by the following:

1. *Determine the overall system failure rate using the predicted frequency/probability values for each event.*
2. *Set one event with a failure rate value of zero and recalculate the minimal Cut Set value.*
3. *Determine the change to the Top Event value.*
4. *Reset the event to its former predicted frequency/probability.*
5. *Repeat the above process for each Base Event in turn.*
6. *Rank each event's contribution to risk by comparing the difference that each makes to the Top Event value when its own value is set to zero.*

In our case, the ''*system's failure''* is ''*system's unavailability'',* in step 1 we determine the ''*overall system unavailability rate''* using the '' calculated *unavailability rates for each basic event'',* in step 2, we set one basic event with an ''*unavailability rate value of zero''* and recalculate the minimal Cut Set value (the emerging ''*system's unavailability rate*'', in step 3, we determine the change *''original system's unavailability rate – emerging system's unavailability rate'',* in step 4, we reset the basic event's ''*unavailability rate'',* in step 5, we repeat the process for each basic event and finally in step 6, we rank each event's contribution to the ''*system's unavailability''* by comparing the difference that each makes to the ''*system's unavailability rate''* when its own value is set to zero. So, the process is:

1. *Determine the overall system unavailability rate using the calculated unavailability rates for each basic event.*
2. *Set one basic event with an unavailability rate value of zero and recalculate the minimal Cut Set value (the emerging system's unavailability rate).*
3. *Determine the change original system's unavailability rate – emerging system's unavailability rate.*
4. *Reset the basic event's unavailability rate.*
5. *Repeat the process for each basic event in turn.*
6. *Rank each event's contribution to the system's unavailability by comparing the difference that each makes to the system's unavailability rate' when its own value is set to zero.*

Five Excel spreadsheets have been developed to calculate the unavailability rate of each of the five road tunnel functions and find out the percentage contribution of every ''Basic event'' to the system's unavailability rate. The whole process for the assessment of the road tunnel unavailability rate is repeated for every period as they are defined in *subchapter 6.1.* Finally, one unavailability percentage contribution charts for each road tunnel function is created including the values of every time period to show the evolution of the percentage contribution on system's unavailability for every basic event over time, an example is indicated in *Figure XX*.

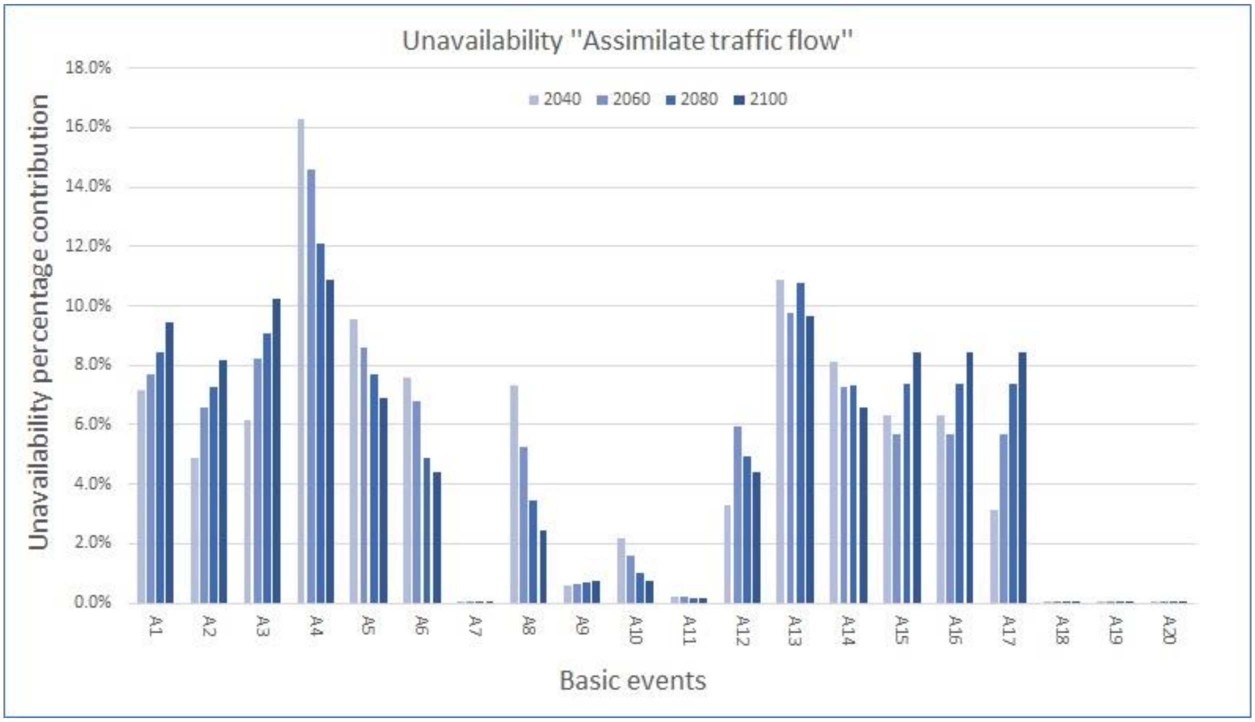


Figure XX: Example chart of basic events' unavailability percentage contribution on road tunnel system's unavailability, Function A, Source: own chart

6.2.2. Basic events' impact on organization values analysis

Organizational values are some ideas that an organization establishes for the correct guidance towards what is important and necessary for the organization (Mueller & Straatmann, 2014). The organization that own and manage a road tunnel asset aims its possession to comply with these values. Any deviation could bring about severe impact on the organization itself. It is comprehensive how significant is the operation of a road tunnel asset to not endanger the viability of its organization during the service life.

Literature study and expert consultation contributed to the definition of five values as the ones an organization must have to keep established.

- **Safety:** Any activity within an organization and interaction with its external environment should be executed under safe conditions.
- **Social Environment**: The operation of an organization has an impact on the social environment. The relationship between the organization and the society must be preserved in qualitative level.

- **Asset quality:** The assets of an organization must be updated and complied with the national regulations and laws regarding functional and quality requirements.
- **Finance:** The viability of an organization also relies on monetary terms. Maintaining financial stability is integral.
- **Reputation:** The reputation of an organization must be kept intact. Any incident that could create bad publicity could subsequently affect the organization's reputation.
- **Availability:** The road tunnel must be operable and the downtime that incidents may cause must be also as little as possible.

The impact that is created when a basic event makes a road tunnel function incapable to be performed and therefore a road tunnel system unavailable for operation is defined qualitatively and quantitively on the organization values. The impact is classified into five categories and their corresponding numerical index. Each category is reflected to six organization values of a typical organization which manages the road tunnel system. *Table III* explains in more details what each impact category means for these six organization values.

Table III: Impact categorization and reflection on six Organization Values, Source: own table

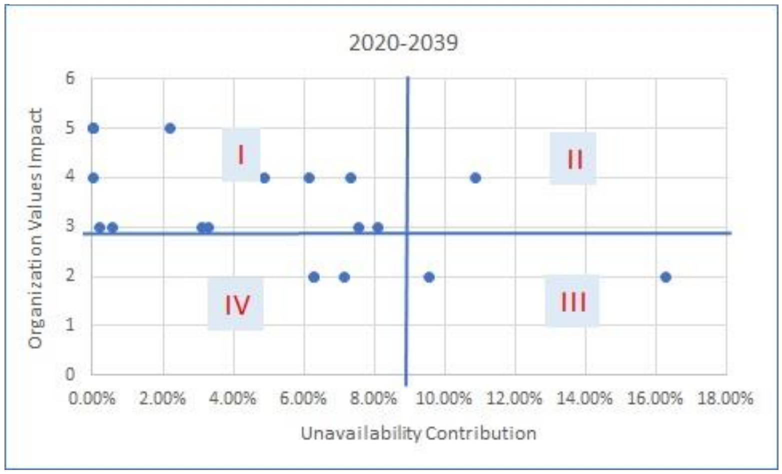
Potential Impact on Organization Values							
Category		Safety	Social Environment	Asset quality	Finance	Reputation	Availability
Negligible	1	No concequences	No disturbance	Compliance with standards, regulations & key performance indicators	No cost/damage	No consequences	1-4 hours downtime
Minor	2	Discomfort, first aid incident	No complains or few individual complains	Minor effects on asset's appearance, shortly non compliance of organization's requirements	Small cost/damage < €100k	No public disturbance, without media attention	Less than 1 day downtime
Limited	3	Light injury	Clear effects on local users, local users disturbance	Temporary deviation from service level agreements, occasionally unavailable	Moderate cost/damage €100k-500k	Local press, critical questions on asset organization	More than 1 day to less than 1 week downtime
Serious	4	Serious injury, non-permanent injury	Extended effects of regional users, regional disturbance	Recoverable effect, exceeding the legal requirements of asset's structure performance, often unavailable	Major cost/damage €500k-1m	Regional press, critical questions on public authorities	More than 1 week to less than 1 month downtime
Critical	5	Very serious injury, disabled, fatality	National users' disturbance	Unrecoverable effect exceeding the legal requirements of asset's structure performance, out of use	Excessive cost/damage > €1m	National press, awareness of governmental authorities	More than 1 month downtime

6.2.3. Unavailability percentage contribution – Organization Values impact matrix

The outcome of the analyses as they are described in *subchapters 6.2.1.* and *6.2.2.* is combined into the *Unavailability percentage contribution-Organization Values impact matrix.* Every function concludes in four such matrices, one for each period. The following *Table IV* is used to explain what kind of information is get from the formulation of such a matrix.

The blue spots represent the basic events that contribute to the road tunnel system's unavailability. The matrix is divided into four quadrants, I, II, III, and IV. Every spot is in one of these four quadrants characterizing its contribution to road tunnel's unavailability and its impact on organization values when the road tunnel system becomes unavailable because of that basic event.

Table IV: Example of Unavailability percentage contribution-Organization Values matrix, Source: own table



The quadrants of the matrix will indicate later in *Phase II* the need of defining preventive and mitigative measures to face the unavailability cause and the impact, respectively. In quadrant I, it is motivated only a mitigative measure to be taken, in quadrant II, both a preventive and mitigative measure, in quadrant III, only a preventive and in quadrant IV, no measure. The robustness of those measures will be indicated by the chart of unavailability percentage contribution, as it was pointed out in *subchapter* 6*.2.1.* An increasing percentage contribution of a basic event means an increasing trend of robustness on the proposed measures/actions (preventive and mitigative) over time. On the other hand, a decreasing percentage contribution indicates the exact opposite and in stable contribution means a repeat on actions in every period.

In the following *subchapter 6.3,* the implementation of the proposed methodology in *subchapter 6.2* in the time periods of *subchapter 6.1* is carried out for the road tunnel system's functions A, B, C, D and E.

6.3. Basic events unavailability and impact assessment in every time slot

In this subchapter, the values of the assumed unavailability rate of each basic event of each function referring to every period are given which have been assessed based on the ratio: NA= MTTR / (MTBF + MTTR) which has been discussed in *subchapter 6.2.1*. Moreover, the impact on the organizational values in the case that a road tunnel becomes unavailable is given for each basic event which is assumed as the same for every time period and is assessed based on the described methodology in *subchapter 6.2.2*. Finally, a thorough description is provided to explain the reasoning behind these assessments which are stated in Appendices of *subchapter 6.3.*

6.3.1. Function A: Assimilating traffic flow

The unavailability of that tunnel function can be caused by twenty independent and different events during the lifetime of that road section. The following table shows that the basic event *A15-Hailstorm* can result in unavailable road tunnel more than 20% of the ratio MTTR and MTTR+MTBF in the first time period 2040, reaching out even more than 30% in 2100 and is the only basic event that mostly cause such an extent of unavailability. On the other hand, the basic events of *A7-Soil deformation*, *A9-Pavement deformation, A18-Extreme high temperatures, A19-Extreme rainfall after a long period of drought,* and

A20-Grass withering will lead to an unavailable road tunnel very few times the following decades, even not at all in the last three cases. Finally, the impact totally varies between negligible and critical level, but mostly seems to be critical.

6.3.2. Function B: Providing route flexibility

The unavailability of that tunnel function can be caused by fifteen independent and different events during the lifetime of that road section. The basic event of *B12-Partially or entirely external damage* can considerably often shut down a road tunnel for reparation works as the rate varies between 32% and 41% and is thought the most important event to be considered. There are also some basic events (*B1-Water on road surface, B7-VRI error, B8-Traffic measurement error*) with high unavailability rates which, however, decline over time and many others with very little rates that do not exceed 5%. As far as the impact is concerned, half of the cases are minor for the organization values of a road tunnel and the rest to vary between limited and critical level, mostly in low-unavailability rate basic events.

6.3.3. Function C: Connecting with the road network traffic management facilities

The unavailability of that tunnel function can be caused by eight independent and different events during the lifetime of that road section. For that function, we see that the basic event *C3-Hailstorm* could cause little road tunnel unavailability instead of the high unavailability rate which is observed in the function of Assimilating traffic flow for the same basic event. The *C8-Fire by an electric car crash* seems to cause frequent issues to the road tunnel for the function with very high impact too (critical). For the rest of events, there is a variety of rates and impact level.

6.3.4. Function D: Facilitating communication

The unavailability of that tunnel function can be caused by eight independent and different events during the lifetime of that road section. This is also a case where a difference among others is seen for a basic event (*D3-Hot day*). At the same moment, three basic events with little unavailability rate, less than 1%, could cause severe effects on the organization values (critical) which therefore are considered as important elements of the analysis too.

6.3.5. Function E: Future-proofing system's prosperity

The unavailability of that tunnel function can be caused by eight independent and different events during the lifetime of that road section. The half of basic events show considerable unavailability rates, more than 12% reaching out even about 25%, which attract the attention. It worth saying that the impact of all basic events is categorized as critical which in turn indicates the special care that should be given for that function of a road tunnel system.

6.4. Development of the *Unavailability Percentage Contribution-Organization Values Impact* matrix

The assessment outcomes of each function (*subchapter 6.3)* regarding the impact on organization values and unavailability rates for every period caused by every basic event are introduced as input in four Excel spreadsheets, one for every period. Every spreadsheet calculates the road tunnel's system's unavailability rate of the function for a particular period. By following the steps of *subchapter 6.2.1*, the basic events' unavailability percentage contribution on the road tunnel system's unavailability is calculated. These values are summarized in a chart indicating the evolution of the unavailability percentage contribution caused by every basic event on the road tunnel system's unavailability. Finally, four matrices for each function are developed to depict in which quadrant a basic event is located based on its caused impact and unavailability percentage contribution. The assessment for every basic event of the respective chart and matrices outcome indicates what kind of measures should be defined as response actions over time in Phase II.

In the following subchapter, the matrices are developed based on the aforementioned methodology for the functions A-E.

6.4.1. Function A: Assimilating taffic flow

The basic event *A15-Hailstorm* seems to highly contribute to the system's unavailability as it is depicted in *Figure XXII* showing an increasing trend the next decades starting from approximately 25% and reaching out almost 33% of the total unavailability rate referring to the particular function on the road tunnel system. In total, five basic events, *A1-Hydrostatic pressure, A2-Soil subsidence >10cm, A3-Groundwater effect, A16-Thunderstorm* and *A17-Extreme hailstorm,* show an increasing trend and seven, the *A4-Carbonation/CO_2-induced penetration, A5-Chloride ions-induced penetration, A6-Freeze-thaw cracking, A8-New demands for public transportation, A9-Pavement deformation, A10-Conversion of neighboring roads into low traffic* and *A14-Extreme rainfall*, the exact opposite. On the other hand, the contribution of basic event *A12-Cautious Driving* and *A13-Lowering* clear height fluctuates over time. However, it is worth mentioning that *A7-Soil deformation*, *A11-Malfunction of nearby movable bridge*, *A18-Extreme high temperatures, A19-Extreme rainfall after a long period of drought* and *A20-Grass withering* contribution is negligible based on the chart.

Figure XXI provide information on how the basic events move about within the matrix over time. For example, the basic event *A15-Hailstorm*, is located in the quadrant III in all time periods. This means that, the focus should be made on taking both preventive and mitigative measures, so up to four preventive and four mitigative measures are expected to be defined in total to be able to deal with the particular matter each time period. It is important to say that, it is not mandatory to define actions for each time period, but it is preferable to find ones that deal with multiple time periods.

Therefore, only preventive measures will be difened for the basic event *A15-Hailstorm*, neither preventive nor mitigative for the the basic events *A11-Malfunction*, *A12-Cautious Driving*, *A14-Extreme rainfall*, *A16-Thunderstorm* and *A17-Extreme hailstorm* and only mitigative measures for the rest of beasic events.

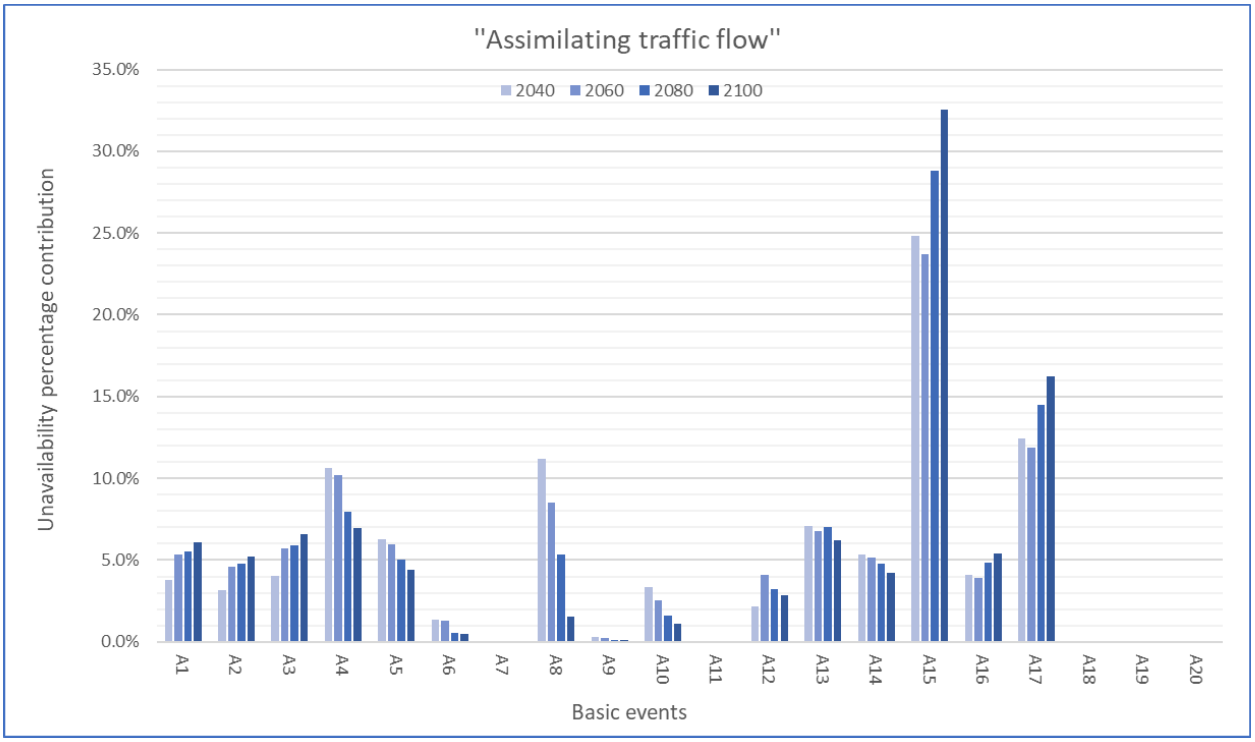


Figure XXII: Evolution of unavailability percentage contribution over time of each basic event to function A unavailability

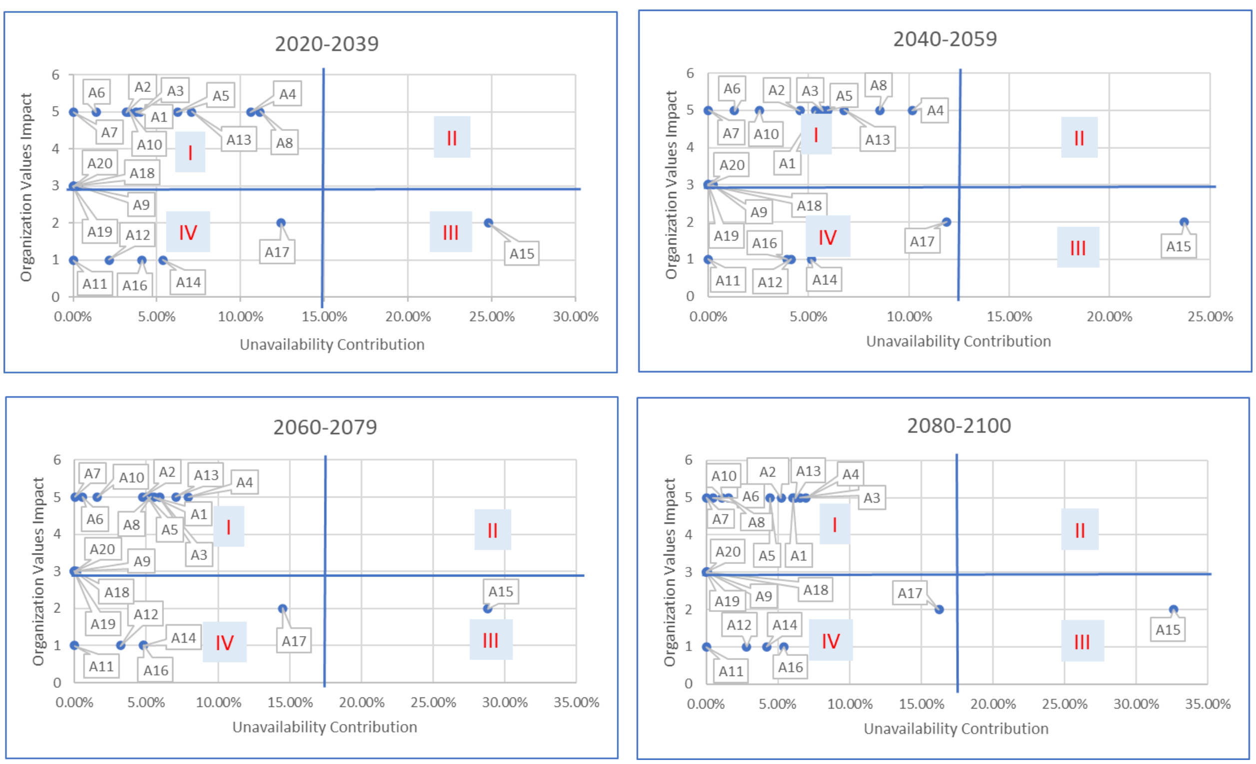


Figure XXI: Basic events of Function's A fault tree indicated as blue spots on four Unavailability percentage contribution-Organization Values Impact matrices. The location of them in four different quadrants provides useful information for the definition of preventive and mitigative measures

6.4.2. Function B: Proving route flexibility

The basic event *B12-Partially or entirely external damage* is the greater contributor over time in road tunnel system unavailability for use, as it is depicted in *Figure XXIII.* In the time periods of 2040 and 2060, *B12* contribution seems stable at 32%, but in the following years, it is gradually increasing having a proportion of even about 42% in 2100. Moreover, it is the only basic event that its contribution grows to compare with the rest of the basic events. Seven basic events of them, *B1-Water on road surface, B2-Solar radiation, B6-Insufficient alternative routes, B7-VRI error, B8-Traffic measurement error, B9-Tunnel tube non response in traffic alternation order,* and *B10-Execution of maintenance works*, show a downward trend over time with only three of them to be considered as big contributors. The rest of the basic events slightly contribute to the road tunnel's unavailability within the century.

The combination of the information of *Figure XXIV* with the impact categorization of each basic event if it makes a road tunnel unavailable for operation is synopsized in the four matrices of *Figure XXIV.* It is observed that all basic events remain in the same quadrant over time, except the basic event *B1* which in the first thee time period is located in quadrant III, but in the time period 2100, it is relocated in quadrant IV. In this case, up to three preventive measures should be defined to satisfy the time periods 2040, 2060 and 2080 without proposing a measure for 2100 period. *B1* is an example of basic event that its contribution evolves in such a way over time that no measures are proposed as necessary for some time frame.

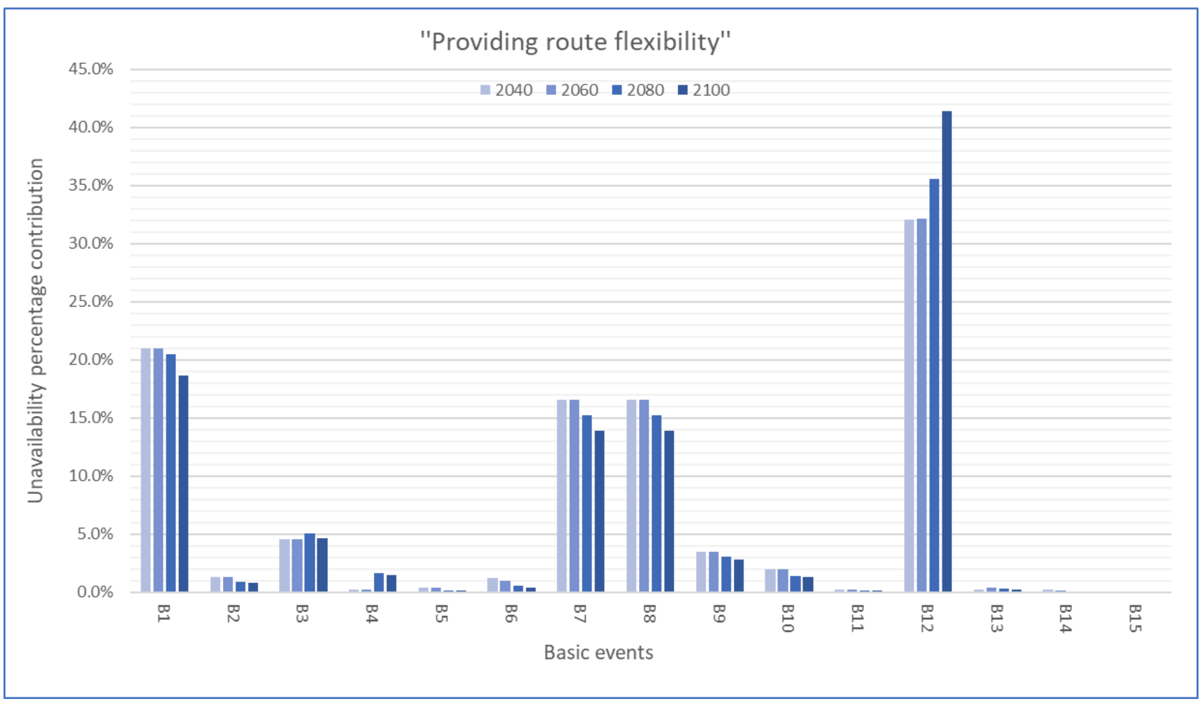


Figure XXIII: Evolution of unavailability percentage contribution over time of each basic event to function B unavailability

Therefore, only preventive measures will be defined for the basic event B1 (not for 2100), preventive and mitigative measures for *B12*, only mitigative measures for the basic events *B4- Bumps or holes on road pavement, B5- Surface cracking, B6-Insufficient alternative routes, B10-Execution of maintenance works* and *B14-Emergency service/ Vehicle disruption* and for the rest of basic events neither preventive nor mitigative measures are going to be defined and taken over the next decades.

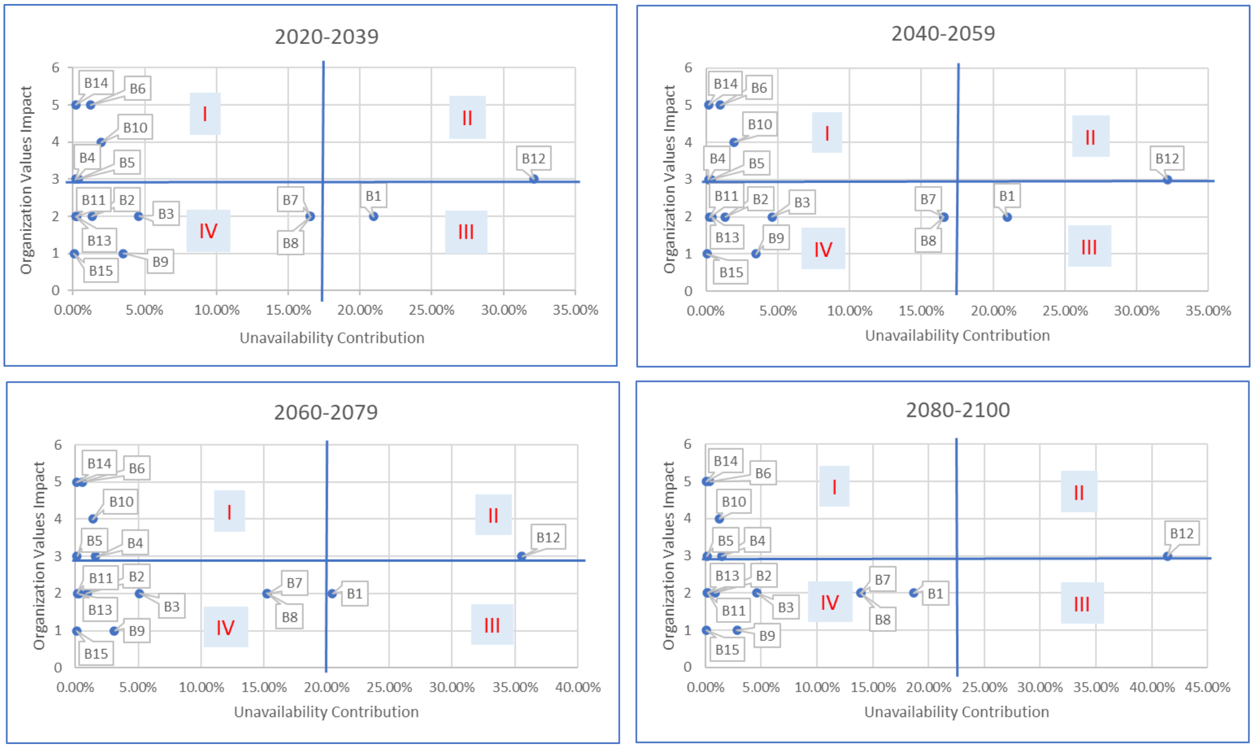


Figure XXIV: Basic events of Function's B fault tree indicated as blue spots on four Unavailability percentage contribution-Organization Values Impact matrices. The location of them in four different quadrants provides useful information for the definition of preventive and mitigative measures

6.4.3. Function C: Connecting with the road network traffic management facilities

Three basic events play a primary role in the road tunnel system unavailability as it is emerging from function C. Basic events *C1- Delay in communicating traffic changes, C4- Extreme shower* and *C8- Fire by an electric car crash* constitute more than 70% of the total unavailability rate of TopC event and their contribution fluctuates over time apart from *C4*, that shows a downward trend. The rest of them contributes little on the overall rate and, in general, remains stable over the following years (*Figure XXVI)*.

Correlating the unavailability percentage contribution with the corresponding impact of the caused unavailability on the organization values, the four matrices of *Figure XXV* emerge for every period of adaptation. The basic event *C8* is the only one that up to four preventive and four mitigative measures could be defined as it remains within the boundaries of quadrant II. Moreover, only mitigative measures are going to be defined, up to four for each basic event, for *C5-Extreme temperature, C6-High precipitation volume,* and *C7- Exceedance of vehicle capacity*. On the other hand, *C1, C2-Wrong provision of information,* and *C3-Hailstorm* are not taken into consideration because their importance does not indicate any need for adaptation measures. Finally, the basic event *C4-Extreme shower* is the only one that moves from quadrant II (2020-2039, 2040-2059) to quadrant I (2060-2079, 2080-2100) which means that up to four mitigative measures should be defined and up to two preventives for the first two time periods. In this function, no basic event is in quadrant III.

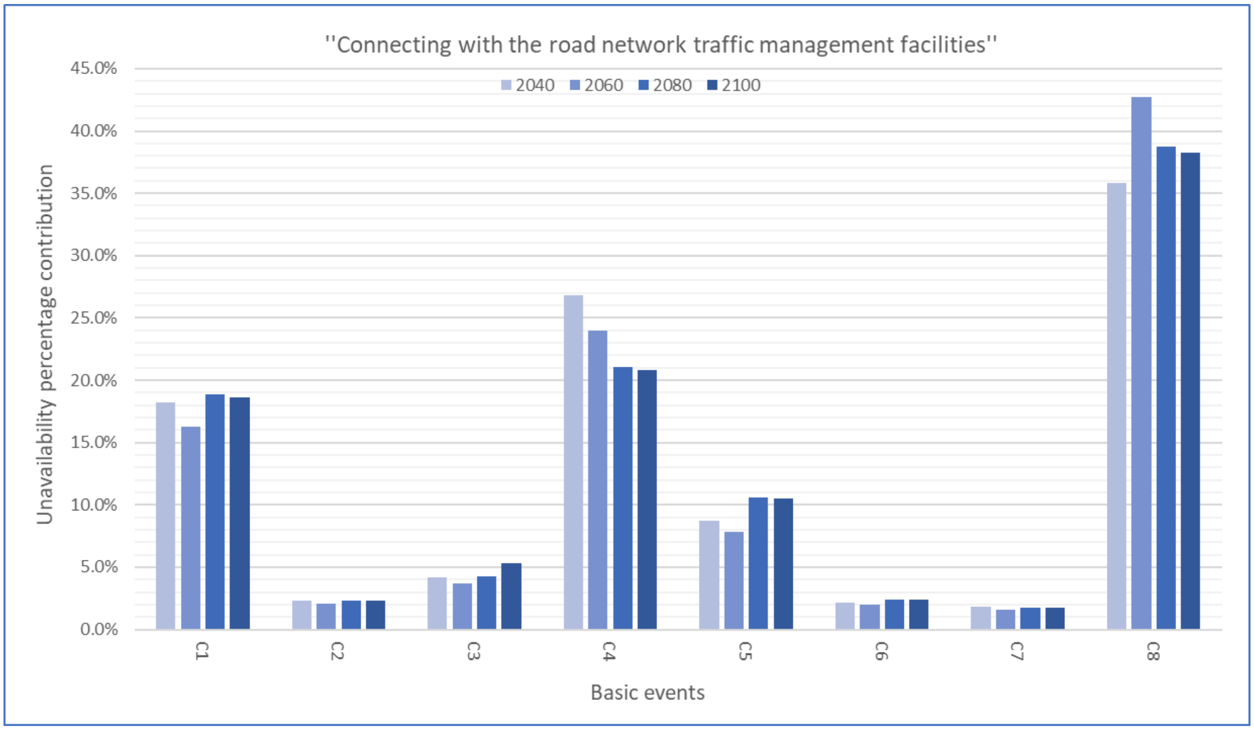


Figure XXVI: Evolution of unavailability percentage contribution over time of each basic event to function C unavailability

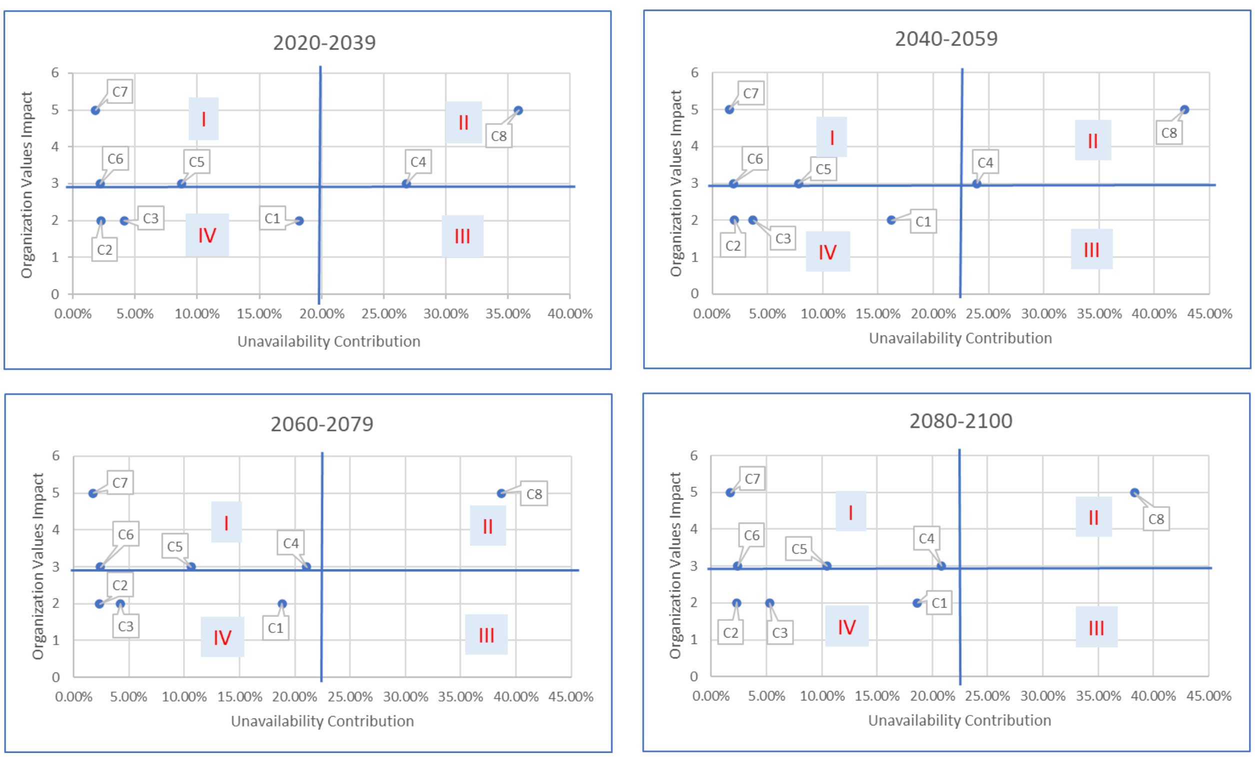


Figure XXV: Basic events of Function's C fault tree indicated as blue spots on four Unavailability percentage contribution-Organization Values Impact matrices. The location of them in four different quadrants provides useful information for the definition of preventive and mitigative measures

6.4.4. Function D: Facilitating communication

In this case, only one basic event, *D3-Hot day*, seems to dominate mostly and contribute to the total unavailability rate, almost 60%. The basic event *D1-Damage in digital installations* and *D2- Intense raining* are the next ones that contribute between 15% and 20%. However, three basic events do not contribute almost at all to the road tunnel unavailability rate caused by TopD (*Figure XXVIII)*.

The matrices of *Figure XXVIII* indicate that only *D3* is the one that both a preventive and a mitigative measure for each period should define. Moreover, only mitigative measures for each time frame should be defined for *D4-Ice day, D7-Exceedance of vehicle capacity,* and *D8-Essential tunnel evacuation*; despite the fact that the percentage contribution of the last two ones is very close to zero, the associated impact on organization values is expected to be critical, which is the highest and quite significant category in the ranking. Finally, for the rest of the basic events, neither preventive nor mitigative measures for adaptation are thought significant to be taken.

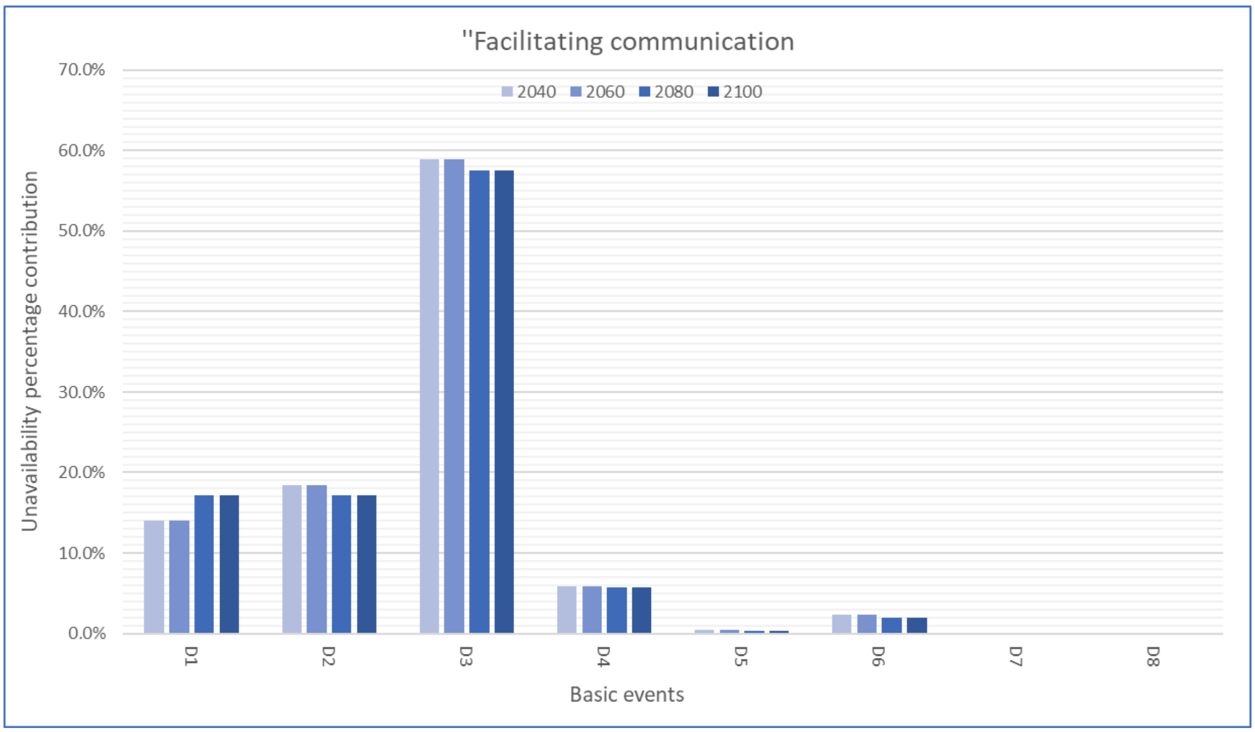


Figure XXVII: Evolution of unavailability percentage contribution over time of each basic event to function D unavailability

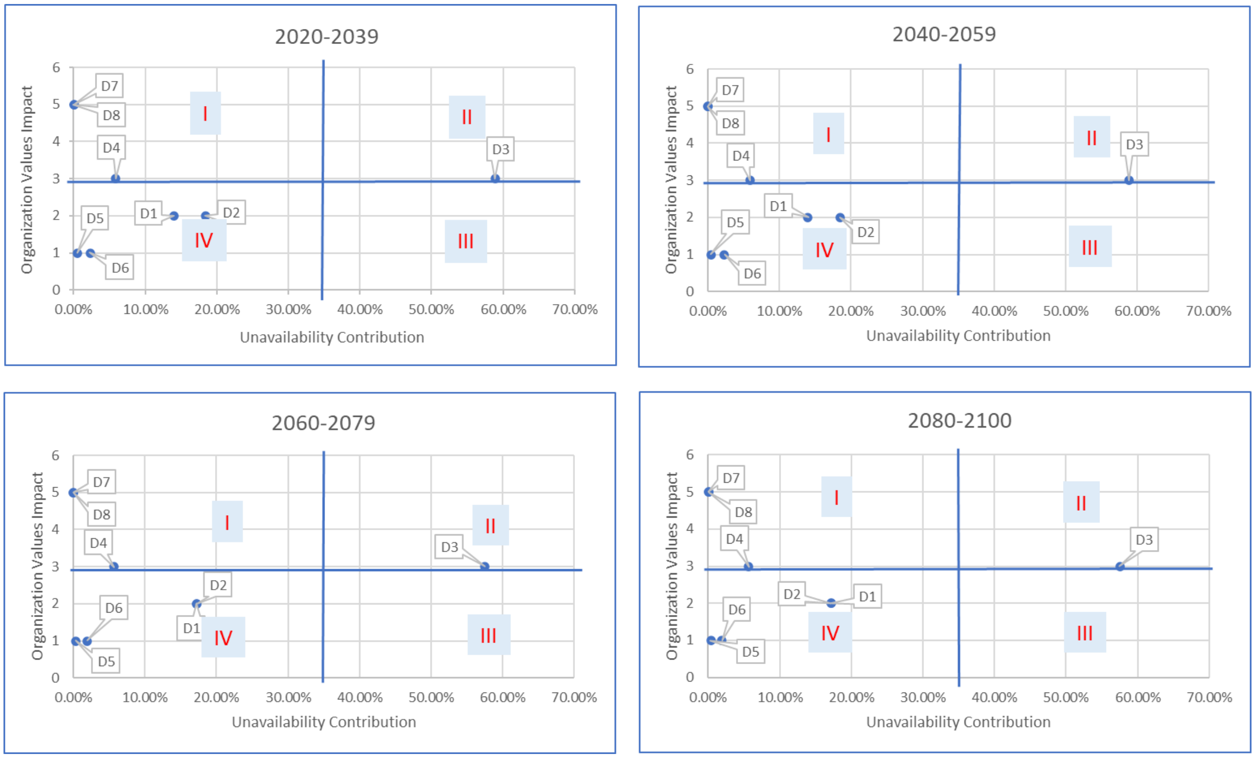


Figure XXVIII: Basic events of Function's D fault tree indicated as blue spots on four Unavailability percentage contribution-Organization Values Impact matrices. The location of them in four different quadrants provides useful information for the definition of preventive and mitigative measures

6.4.5. Function E: Future-proofing system's prosperity

There are two major contributors in the road tunnel system unavailability rate caused by non-performance of function E, *E2-Maintenance works* and *E5-Inadequate architectural design* which together proportionate almost the half of the total rate. Moreover, the evolvement of their contribution fluctuates over time as it is illustrated in *Figure XXX* which means that these two remain at the same quadrant for every period. At the same time, four basic events (*E1-Tunnel design for nuisance prevention, E3- CO_2-induced penetration-carbonation, E4- Chloride ions-induced penetration,* and *E7-Urban recreation*) show a decreasing trend over the following years and only two basic events (*E6-Unstable land* and *E8-Excessive strain on the existent structure*) gradually their contribution increases.

Looking at *Figure XXIX,* the *E3* encourages the definition of up to two preventive measures for the time periods of 2020-2039 and 2040-2059 and up to four mitigative measures as it is in quadrant II. *E1* is also located in quadrant II but only for the period 2040-2059, in the rest ones remains in quadrant I. It is an interesting case because it indicates the definition of up to four mitigative measures and only one preventive measure for the period 2040-2059, which is believed as of high importance to be done.

Only mitigative measures should be defined for *E4, E6, E7-Urban recreation,* and *E8* and both preventive and mitigative measures for *E2-Maintenance works,* and *E5-Inadequate architectural design*, again up to four different measures if it is doable.

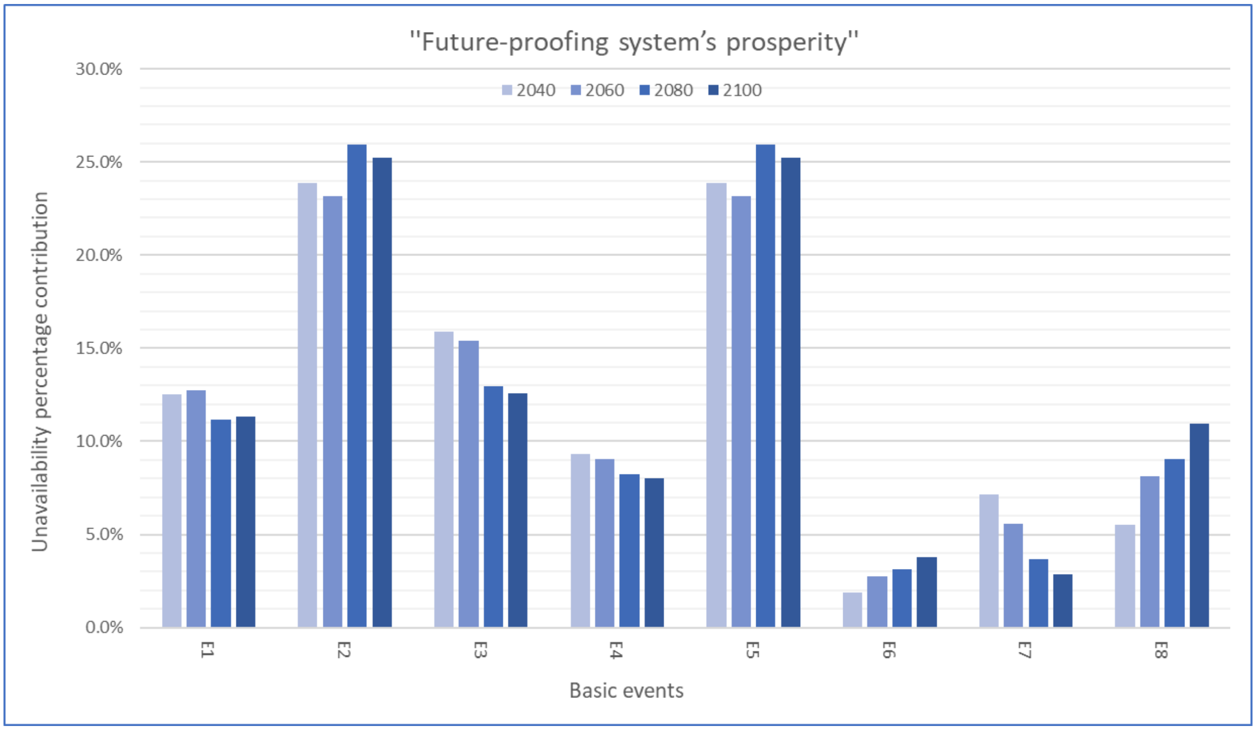


Figure XXX: Evolution of unavailability percentage contribution over time of each basic event to function E unavailability

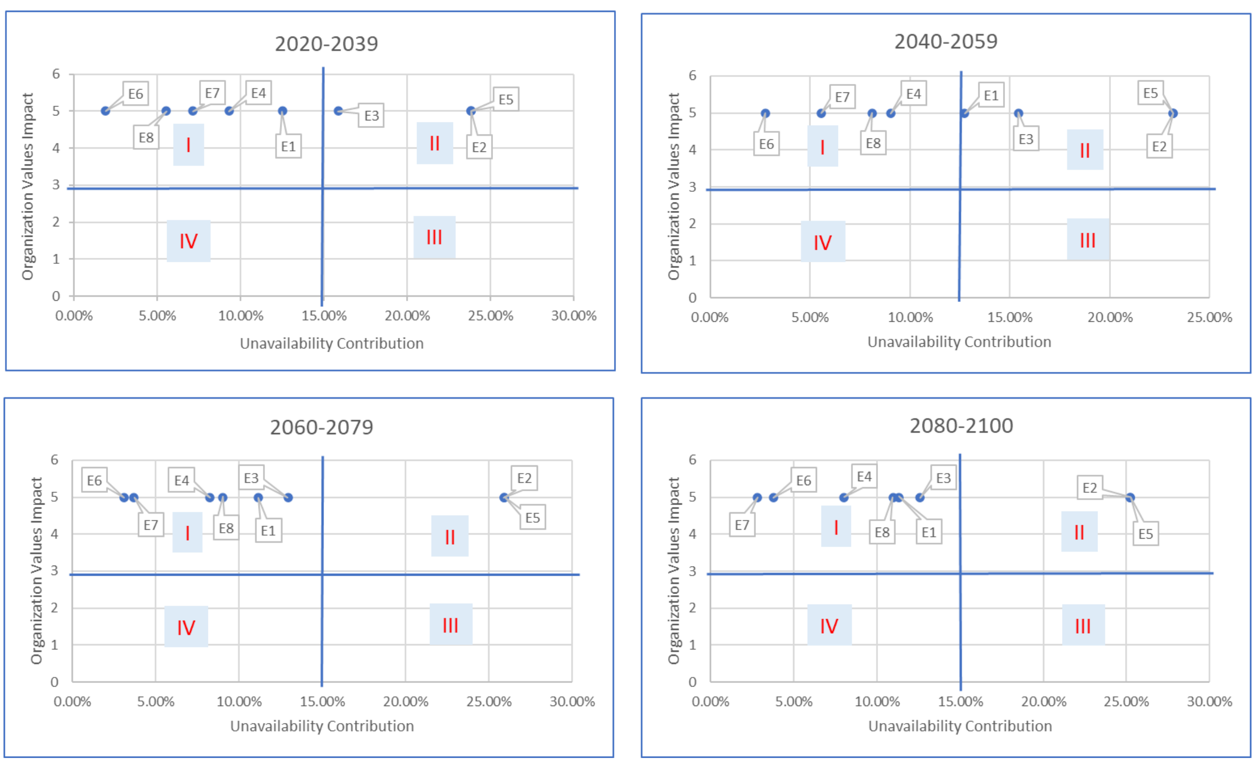


Figure XXIX: Basic events of Function's E fault tree indicated as blue spots on four Unavailability percentage contribution-Organization Values Impact matrices. The location of them in four different quadrants provides useful information for the definition of preventive and mitigative measures

6.5. Conclusion

The analysis of the road tunnel system's functions failure modes was developed in this chapter to complete the execution of the DAPP model second step, *2) Analyze the problem, vulnerabilities & opportunities using transient scenarios.* The definition of the timeline of analysis *(6.1.),* the explanation of the methodology *(6.2.)* to perform the *problem analysis*, the execution of this methodology by using *transient scenarios* (frequency and response time) to assess, quantitatively, road tunnel unavailability and qualitatively, resulting impact on road tunnel organization values *(6.3.)* and the combination of these information concluded to the actual adaptation needs of a road tunnel to prevent functional failures and to mitigate the associated impact, if failure occurred *(6.4.).*

More precisely, the analysis was referred to the period 2020-2100 which was divided into 4 periods of 20-year range. Every basic event was assessed regarding its potential frequency to occur in every period. Moreover, a subjective estimation of the time that a road tunnel would need to become operative again after having functionally failed by each basic event's occurrence was made. Thus, the last two assessments allowed the calculation of the unavailability rate resulting from each basic event for every period. At the same time, the qualitative assessment of the associated impact on road tunnel organization values by this caused unavailability was performed. Eventually, the development of the ''Unavailability Percentage Contribution - Organization Values Impact'' matrices by correlating the gained information allowed the decision-maker to conclude to the basic events that must be addressed in the adaptation plans, and specifically to conclude whether only cause prevention or only impact mitigation or both adaptation measures and strategies are required to be defined.

Chapter 6 replied to the second part of the Sub Question 1: *''To what extent can future climate change impact the system's functional failure'',* which means that *Phase I* was completed and the continuation to *Phase II* for the definition of the preventive and mitigative measures for road tunnel adaptation in *Chapter 7* will be performed.

Phase II

<u>Sub Question 2 response</u>

In *Phase II*, the second sub-research question is attempting to be answered

'' What actions could be taken to prevent these failures and mitigate consequences?''

responding to the 3rd and 4th step of DAPP model (*Figure I.).*

Chapter 7. BowTie visualization for unavailability response

- Introduction in BowTie methodology by explaining the tool's structure and use (*7.1.*).
- Analysis of the outcome of *Phase I,* measures definition for cause prevention and impact mitigation and measures visualization with BowTie diagrams for every indicated period (7.*2.*).

7. BowTie visualization for unavailability response

In this chapter, the BowTie visualization for unavailability response is conducted to define and depict preventive and mitigative measures, and their sell-by-date to prepare the road tunnel system adaptation to the new demands.

- In *subchapter 7.1.,* the BowTie methodology is explained by presenting its elements, elements' role, and the way of visualizing the results. Then,
- In *subchapter 7.2.*, the definition and visualization of measures is executed for every functional requirement and BowTie is repeated as many times as it has been indicated in *Chapter 6.*

The outcomes of this chapter reply to the Sub Question 2: '*What actions could be taken to prevent functional failures and mitigate consequences?''.* It means that *Phase II* is completed and the continuation to *Phase III* for the modelling of the adaptation strategies and creation of the map for preventive actions and the map for mitigative actions in *Chapter 8* will be performed.

7.1. BowTie methodology and terminologies definition

The adaptation measures are visualized by using the diagrams of the methodological tool of BowTie analysis and is implemented up to four times (as the number of time periods) for every of the five established road tunnel functions. The BowTie analysis diagram in the due research consists of the following elements:

- Top event: It is the main element that is caused by other events and cause an impact. It is the incapability of a function to perform as it is required by the unavailability rate that is created by every single event and subsequently, this unavailability rate leads to an associated impact on the road tunnel system. It is labeled as ''Top#'', where ''#'' is the associated letter of function, there are five top events, and are stated in the middle of the BowTie diagram.
- Basic event: The events that cause the function's underperformance and are stated on the left side of the diagram. It is labeled with the letter of the associated function and a number which represents it (e.g. the 10^{th} basic event of function A is indicated as A10).
- Categories of impact: The categories of associated impact on organization values that are resulted by these events when the top event occurs. They are located on the right side of the diagram.
- Preventive measures: They are the measures that prevent the top event and stated in the middle of basic events and top event.
- Mitigative measures: They are the measures that mitigate the caused impact on organization values.

The whole process is visualized in such a way that reminds a bowtie. The purpose of the BowTie methodology is to provide a structured approach for identifying cause and impact mitigation measures visualization to shape later the strategic map of adaptation to the new demands.

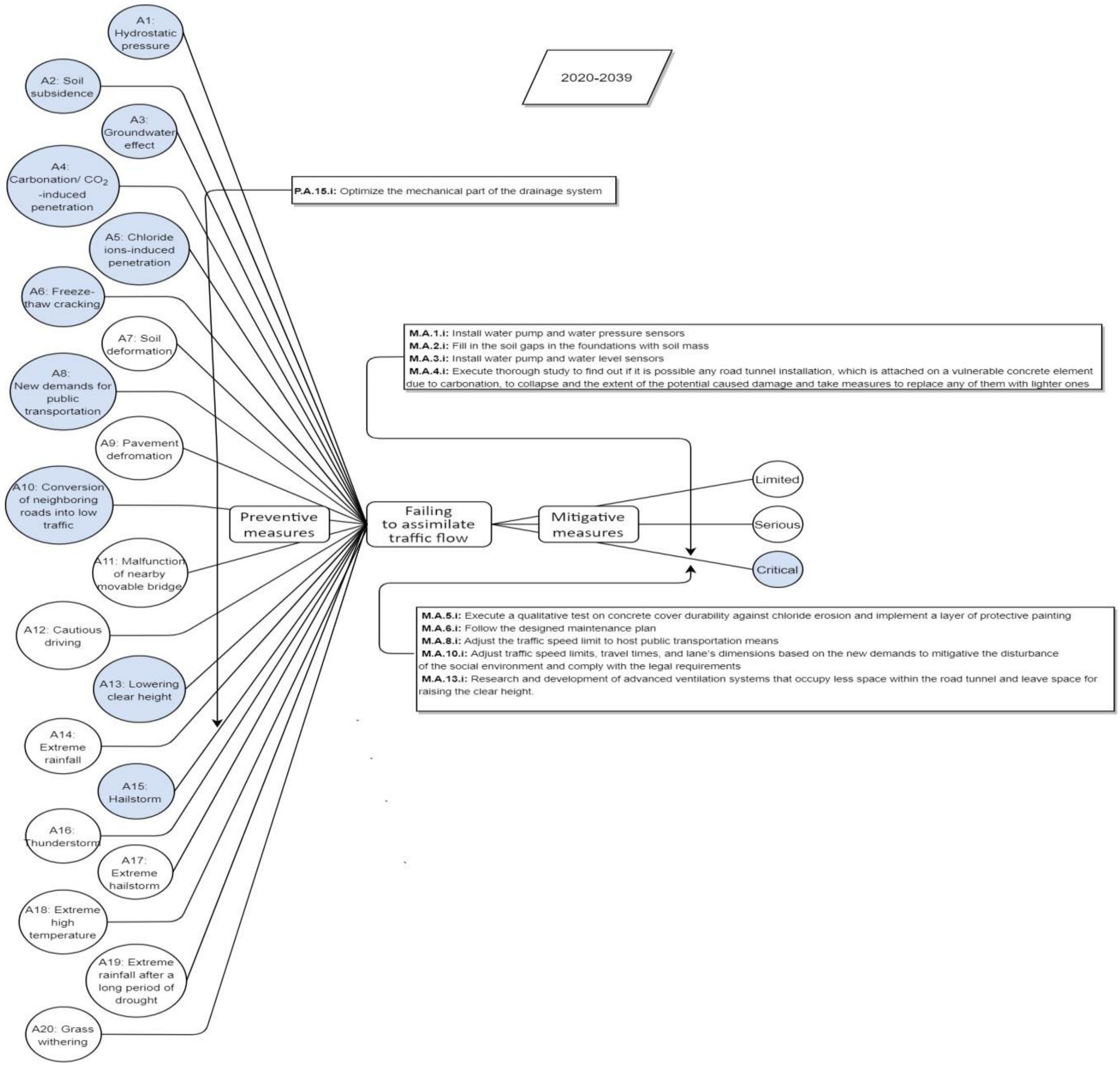
7.2. Adaptation measures

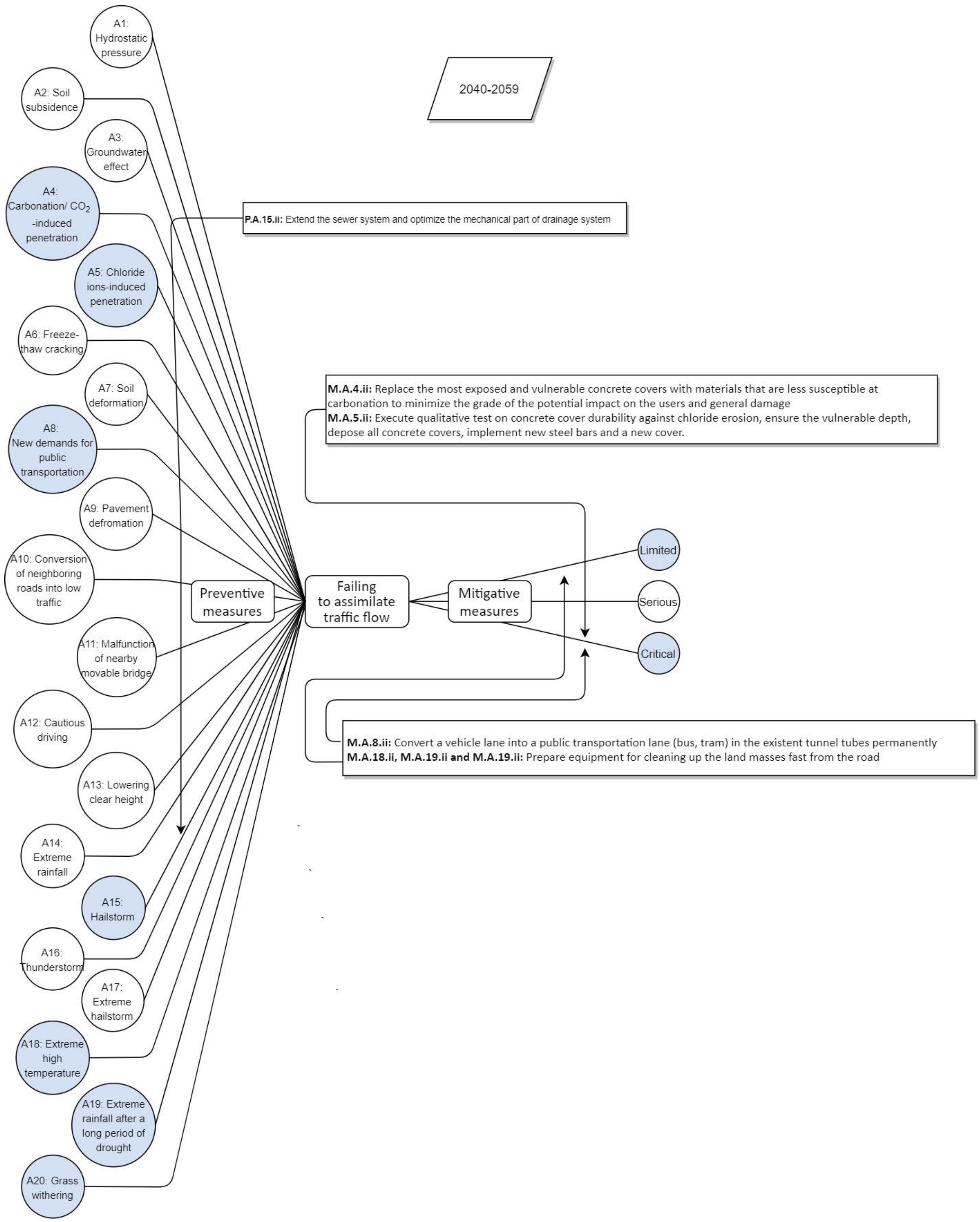
In the subchapter *6.4.,* the analysis concluded which basic events in every case of function require both preventive and mitigative measures, or only preventive, or only mitigative and which basic events do not require any measure to be proposed and taken. In this subchapter, the definition of the actual measures is attempting by using the BowTie model. The basic events that are colored into blue indicate that those are the basic events that are involved either in imposing preventive measures or mitigative measures or both. At the same time, the categories of impact that require measures are thee, ''*Limited'', ''Serious'',* and *''Critical''*. The categories that are colored into blue indicate that those are the impact that require to be mitigated.

The sell-by date of preventive measures is given and related with the time periods. It is considered that a proposed measure in a specific period, it is a measure that would be valid to deal with the associated issue of that period. It does not mean that a preventive measure of 2080-2100 is more robust than one of 2060-2079, but that the first one is eligible for 2080-2100 and the other one for the 2060-2079. However, in some cases, the preventive measure of 2080-2100 could sufficiently fulfill the requirement of prevention for the period of 2060-2079 which is noticeable when something extra is added on the proposed measure of 2060-2079.

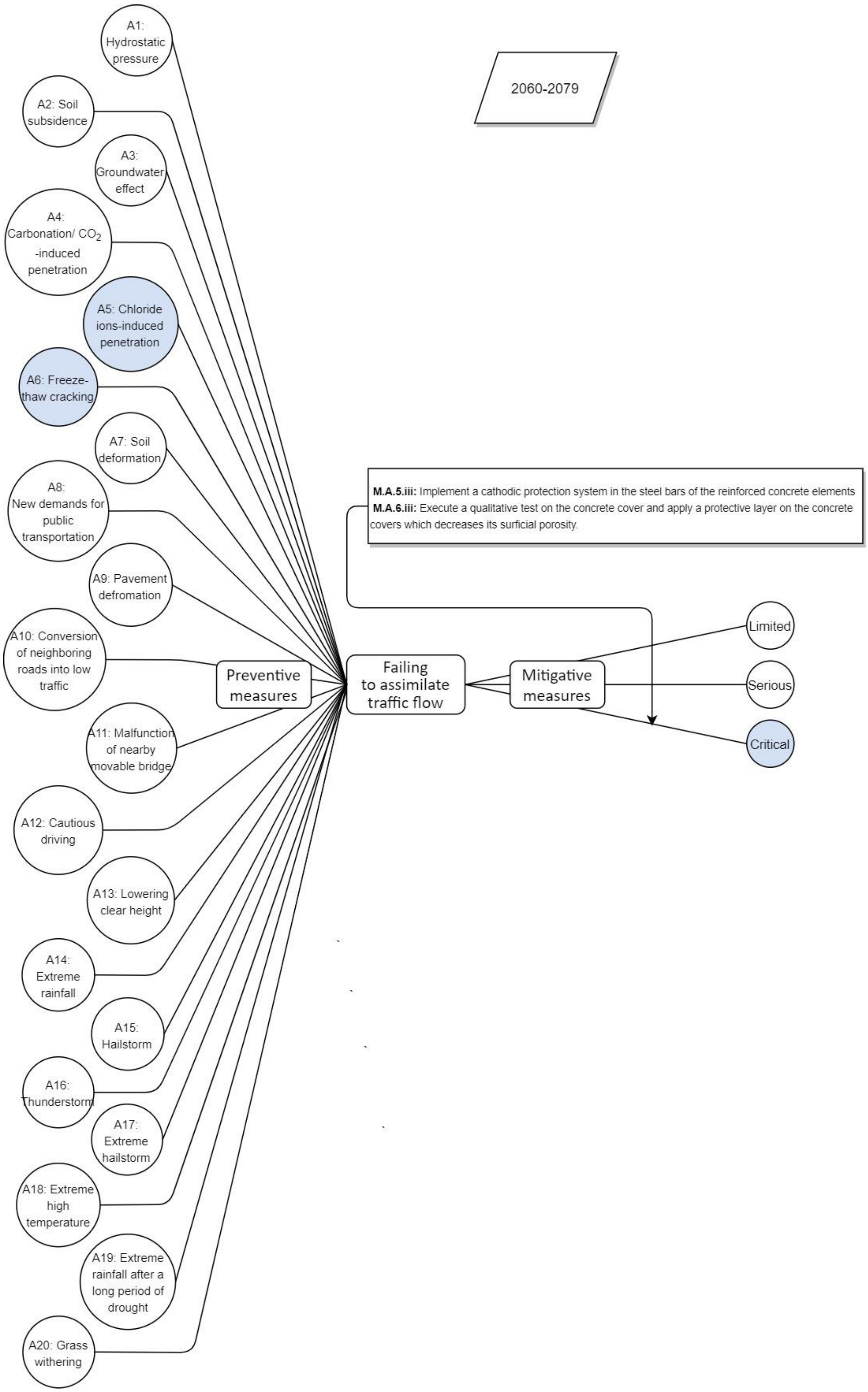
On the other hand, the sell-by-date of mitigative measures is related with the time periods and implies the lifespan of that action. Because of the fact that the potential impact remains the same, regardless of the moment occurs, a mitigative measure of the time period 2020-2039 means that the lifespan of it is 20 years, if applied today, and a measure of 2040-2059 would be of 40 years' lifespan. Based on this point of view, the adaptation measures are presented with BowTie diagrams in the following subchapters.

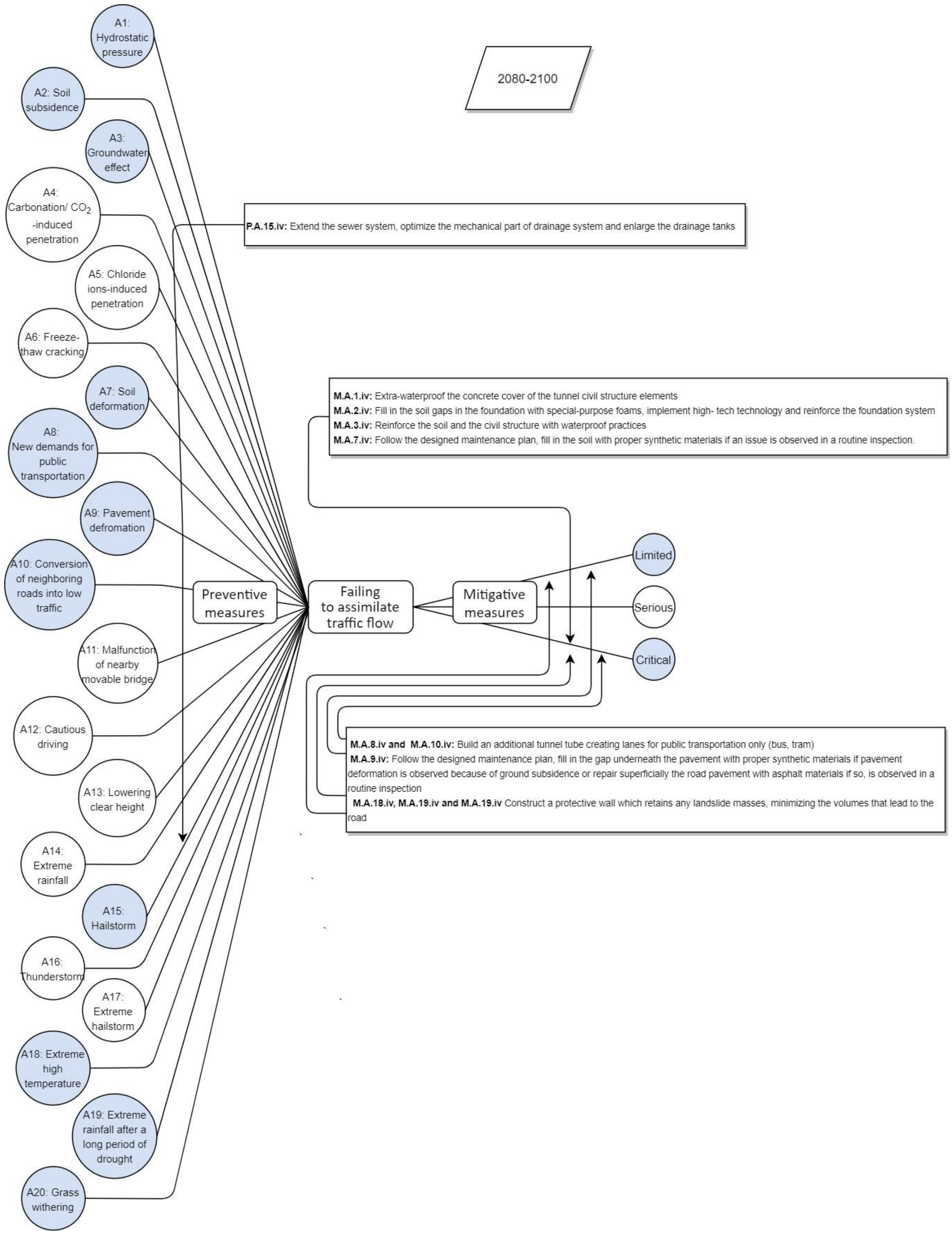
7.2.1. Function A: Assimilating taffic flow



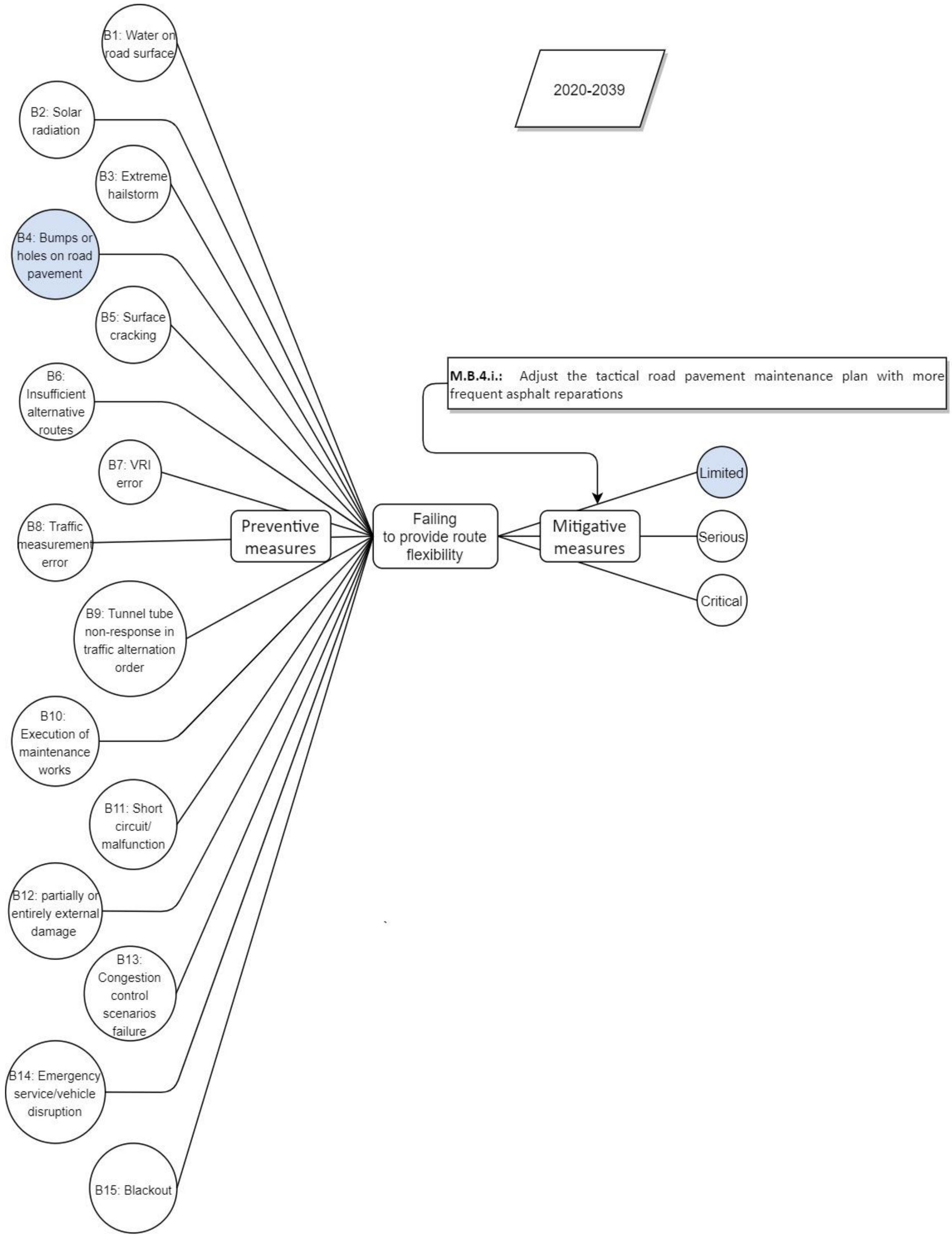


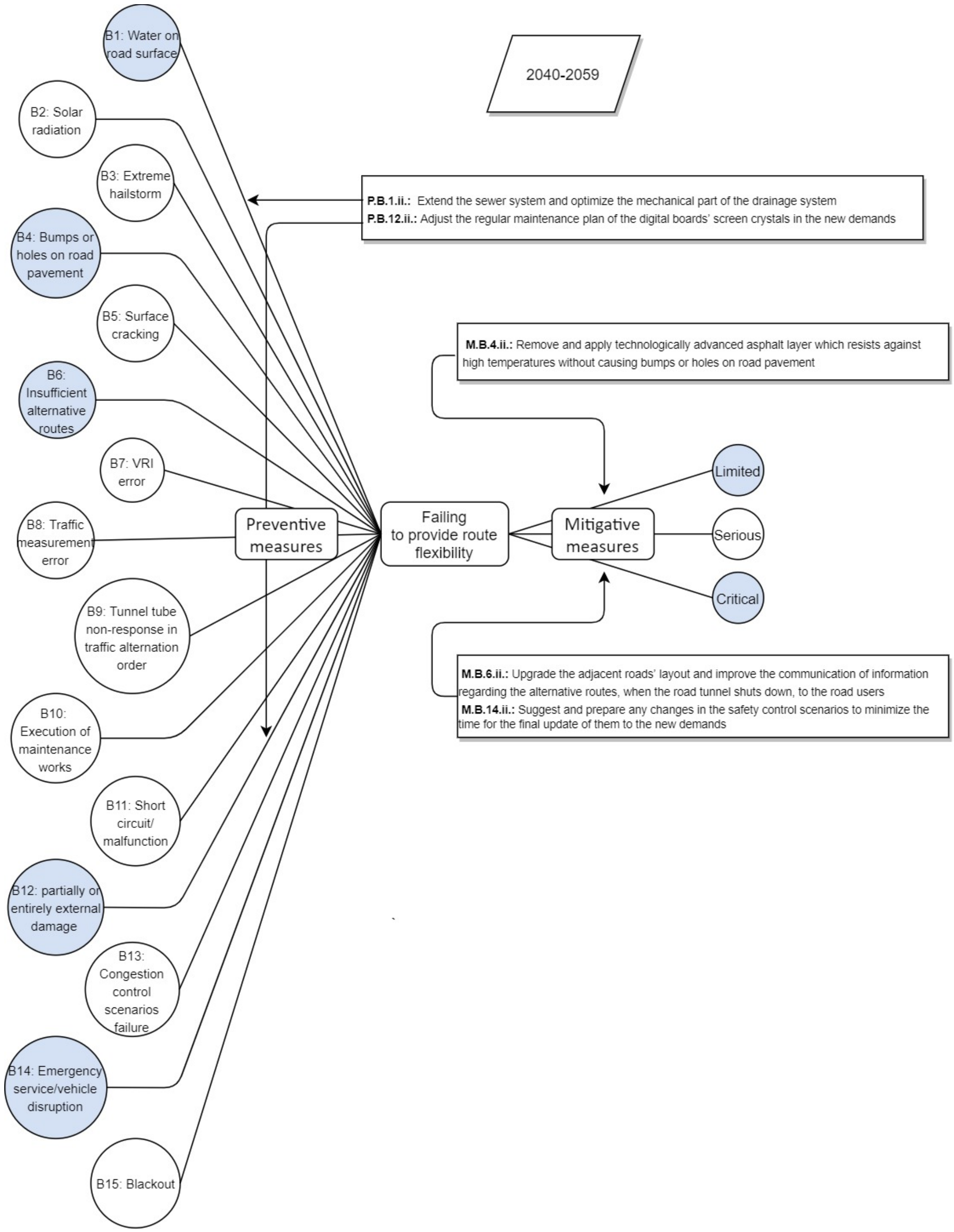
2040-2059
A1: Hydrostatic pressure
A2: Soil subsidence
A3: Groundwater effect
A4: Carbonation/ CO_2 -induced penetration
A5: Chloride ions-induced penetration
A6: Freeze-thaw cracking
A7: Soil deformation
A8: New demands for public transportation
A9: Pavement defromation
A10: Conversion of neighboring roads into low traffic
A11: Malfunction of nearby movable bridge
A12: Cautious driving
A13: Lowering clear height
A14: Extreme rainfall
A15: Hailstorm
A16: Thunderstorm
A17: Extreme hailstorm
A18: Extreme high temperature
A19: Extreme rainfall after a long period of drought
A20: Grass withering
P.A.15.ii: Extend the sewer system and optimize the mechanical part of drainage system
M.A.4.ii: Replace the most exposed and vulnerable concrete covers with materials that are less susceptible at carbonation to minimize the grade of the potential impact on the users and general damage
M.A.5.ii: Execute qualitative test on concrete cover durability against chloride erosion, ensure the vulnerable depth, depose all concrete covers, implement new steel bars and a new cover.
Preventive measures
Failing to assimilate traffic flow
Mitigative measures
Limited
Serious
Critical
M.A.8.ii: Convert a vehicle lane into a public transportation lane (bus, tram) in the existent tunnel tubes permanently
M.A.18.ii, M.A.19.ii and M.A.19.ii: Prepare equipment for cleaning up the land masses fast from the road

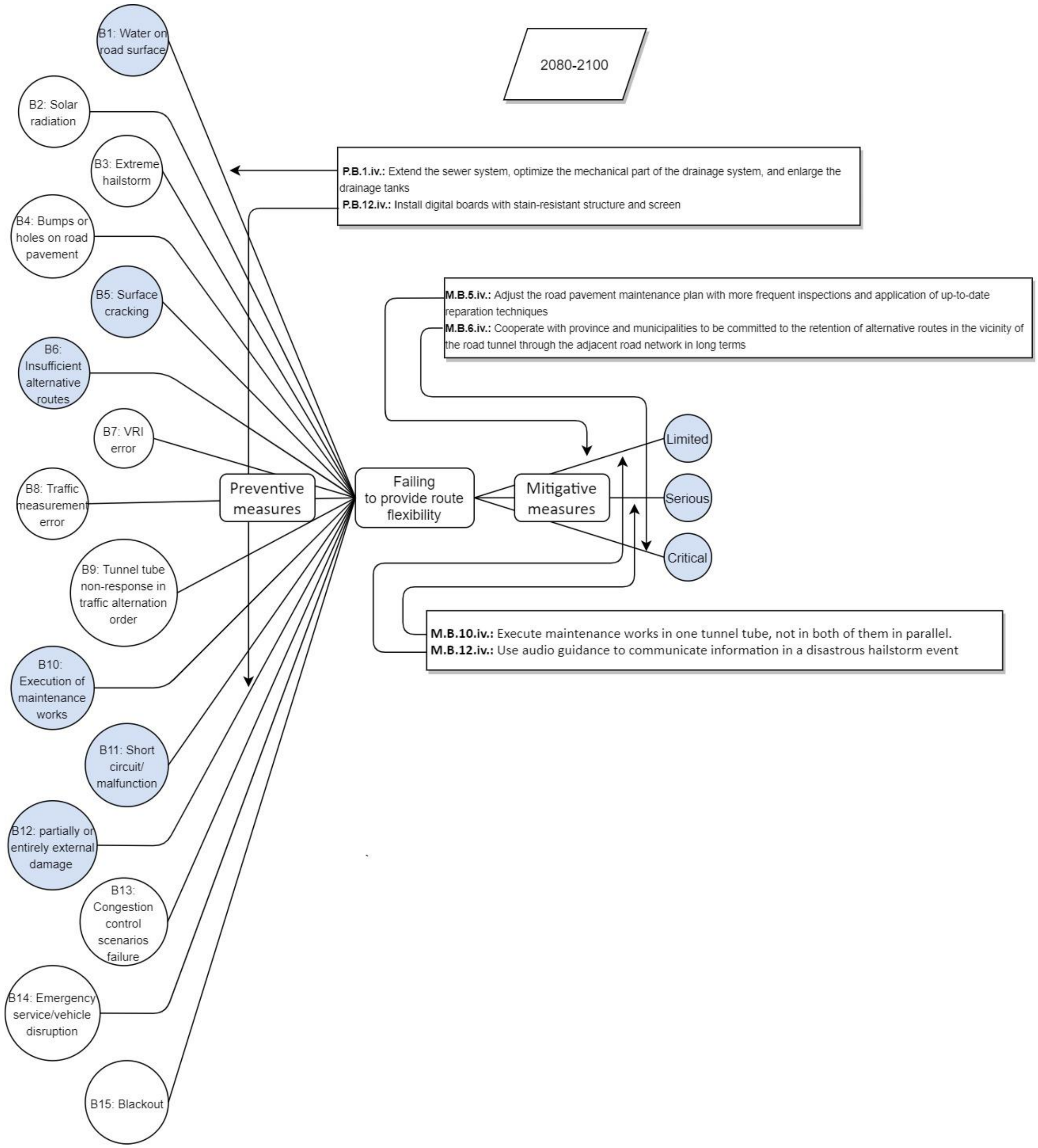

2060-2079
A1: Hydrostatic pressure
A2: Soil subsidence
A3: Groundwater effect
A4: Carbonation/ CO_2 -induced penetration
A5: Chloride ions-induced penetration
A6: Freeze-thaw cracking
A7: Soil deformation
A8: New demands for public transportation
A9: Pavement defromation
A10: Conversion of neighboring roads into low traffic
A11: Malfunction of nearby movable bridge
A12: Cautious driving
A13: Lowering clear height
A14: Extreme rainfall
A15: Hailstorm
A16: Thunderstorm
A17: Extreme hailstorm
A18: Extreme high temperature
A19: Extreme rainfall after a long period of drought
A20: Grass withering
Preventive measures
Failing to assimilate traffic flow
Mitigative measures
M.A.5.iii: Implement a cathodic protection system in the steel bars of the reinforced concrete elements
M.A.6.iii: Execute a qualitative test on the concrete cover and apply a protective layer on the concrete covers which decreases its surficial porosity.
Limited
Serious
Critical


2080-2100
A1: Hydrostatic pressure
A2: Soil subsidence
A3: Groundwater effect
A4: Carbonation/ CO_2 -induced penetration
A5: Chloride ions-induced penetration
A6: Freeze-thaw cracking
A7: Soil deformation
A8: New demands for public transportation
A9: Pavement defromation
A10: Conversion of neighboring roads into low traffic
A11: Malfunction of nearby movable bridge
A12: Cautious driving
A13: Lowering clear height
A14: Extreme rainfall
A15: Hailstorm
A16: Thunderstorm
A17: Extreme hailstorm
A18: Extreme high temperature
A19: Extreme rainfall after a long period of drought
A20: Grass withering
Preventive measures
Failing to assimilate traffic flow
Mitigative measures
Limited
Serious
Critical
P.A.15.iv: Extend the sewer system, optimize the mechanical part of drainage system and enlarge the drainage tanks
M.A.1.iv: Extra-waterproof the concrete cover of the tunnel civil structure elements
M.A.2.iv: Fill in the soil gaps in the foundation with special-purpose foams, implement high- tech technology and reinforce the foundation system
M.A.3.iv: Reinforce the soil and the civil structure with waterproof practices
M.A.7.iv: Follow the designed maintenance plan, fill in the soil with proper synthetic materials if an issue is observed in a routine inspection.
M.A.8.iv and M.A.10.iv: Build an additional tunnel tube creating lanes for public transportation only (bus, tram)
M.A.9.iv: Follow the designed maintenance plan, fill in the gap underneath the pavement with proper synthetic materials if pavement deformation is observed because of ground subsidence or repair superficially the road pavement with asphalt materials if so, is observed in a routine inspection
M.A.18.iv, M.A.19.iv and M.A.19.iv Construct a protective wall which retains any landslide masses, minimizing the volumes that lead to the road

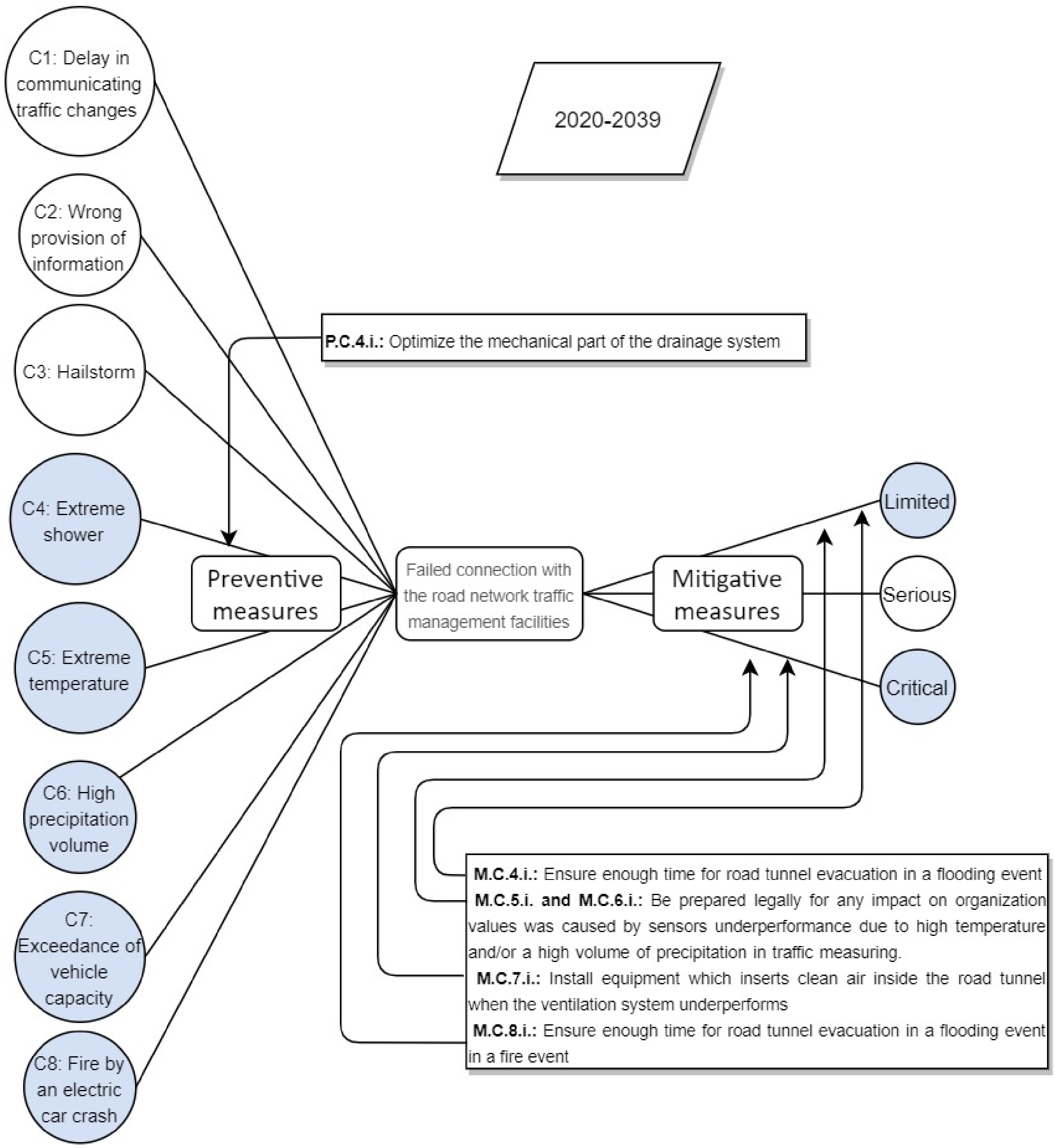
7.2.2. Funtion B: Proving route flexibility

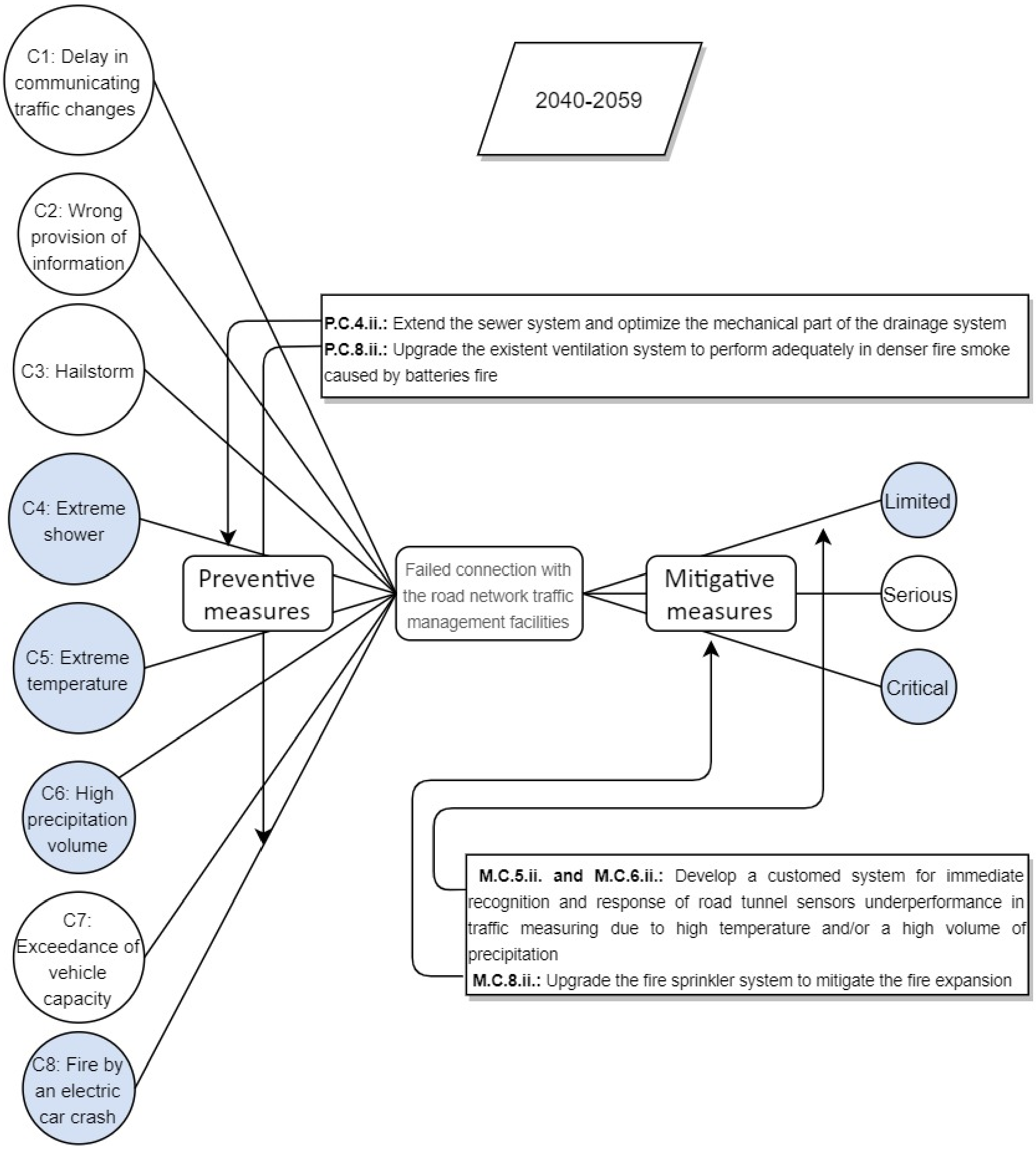


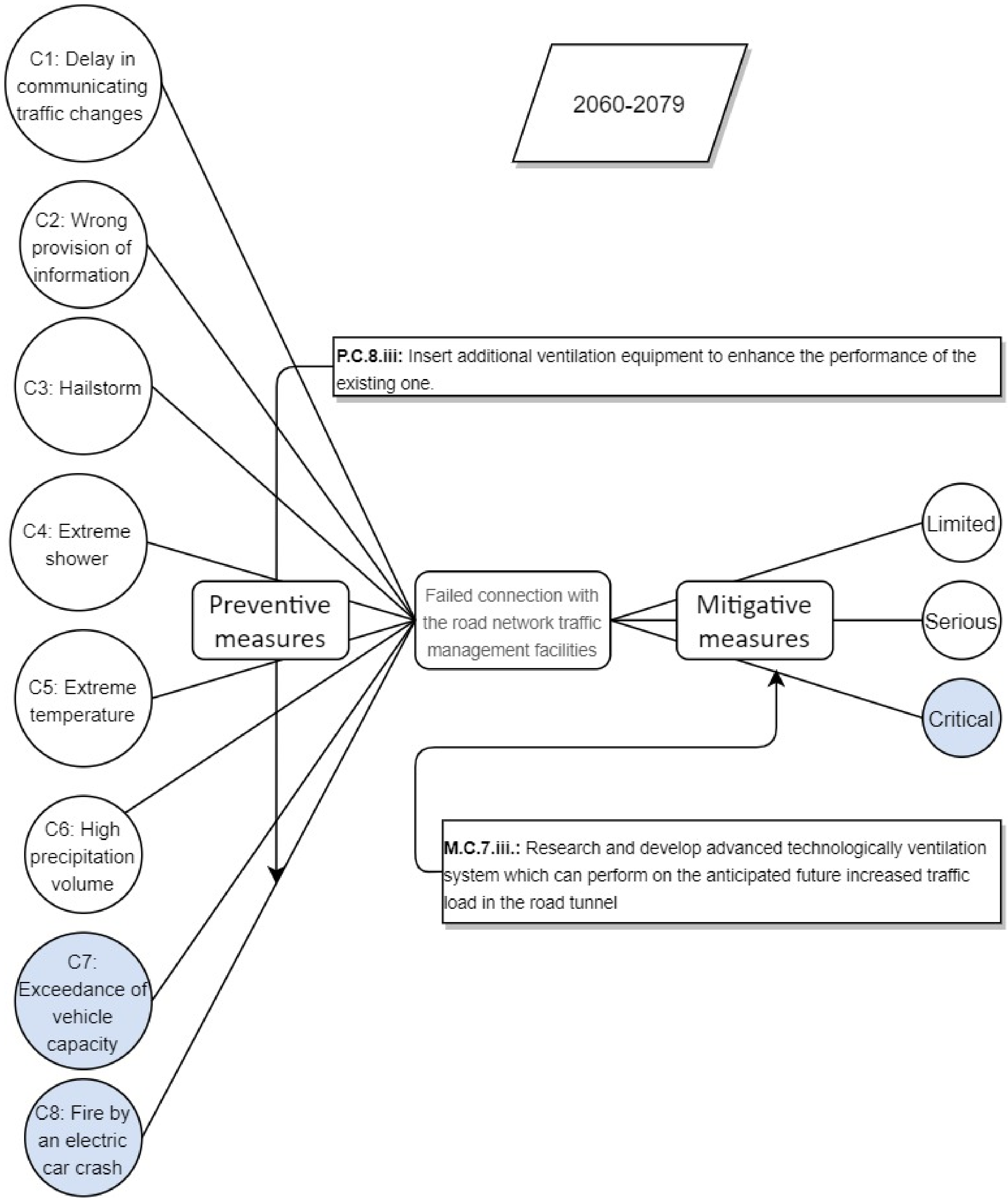

2040-2059
B1: Water on road surface
B2: Solar radiation
B3: Extreme hailstorm
B4: Bumps or holes on road pavement
B5: Surface cracking
B6: Insufficient alternative routes
B7: VRI error
B8: Traffic measurement error
B9: Tunnel tube non-response in traffic alternation order
B10: Execution of maintenance works
B11: Short circuit/ malfunction
B12: partially or entirely external damage
B13: Congestion control scenarios failure
B14: Emergency service/vehicle disruption
B15: Blackout
P.B.1.ii.: Extend the sewer system and optimize the mechanical part of the drainage system
P.B.12.ii.: Adjust the regular maintenance plan of the digital boards' screen crystals in the new demands
Preventive measures
Failing to provide route flexibility
Mitigative measures
M.B.4.ii.: Remove and apply technologically advanced asphalt layer which resists against high temperatures without causing bumps or holes on road pavement
Limited
Serious
Critical
M.B.6.ii.: Upgrade the adjacent roads' layout and improve the communication of information regarding the alternative routes, when the road tunnel shuts down, to the road users
M.B.14.ii.: Suggest and prepare any changes in the safety control scenarios to minimize the time for the final update of them to the new demands


2080-2100
B1: Water on road surface
B2: Solar radiation
B3: Extreme hailstorm
B4: Bumps or holes on road pavement
B5: Surface cracking
B6: Insufficient alternative routes
B7: VRI error
B8: Traffic measurement error
B9: Tunnel tube non-response in traffic alternation order
B10: Execution of maintenance works
B11: Short circuit/ malfunction
B12: partially or entirely external damage
B13: Congestion control scenarios failure
B14: Emergency service/vehicle disruption
B15: Blackout
Preventive measures
Failing to provide route flexibility
Mitigative measures
Limited
Serious
Critical
P.B.1.iv.: Extend the sewer system, optimize the mechanical part of the drainage system, and enlarge the drainage tanks
P.B.12.iv.: Install digital boards with stain-resistant structure and screen
M.B.5.iv.: Adjust the road pavement maintenance plan with more frequent inspections and application of up-to-date reparation techniques
M.B.6.iv.: Cooperate with province and municipalities to be committed to the retention of alternative routes in the vicinity of the road tunnel through the adjacent road network in long terms
M.B.10.iv.: Execute maintenance works in one tunnel tube, not in both of them in parallel.
M.B.12.iv.: Use audio guidance to communicate information in a disastrous hailstorm event

7.2.3. Function C: Connecting with the road network traffic management facilities

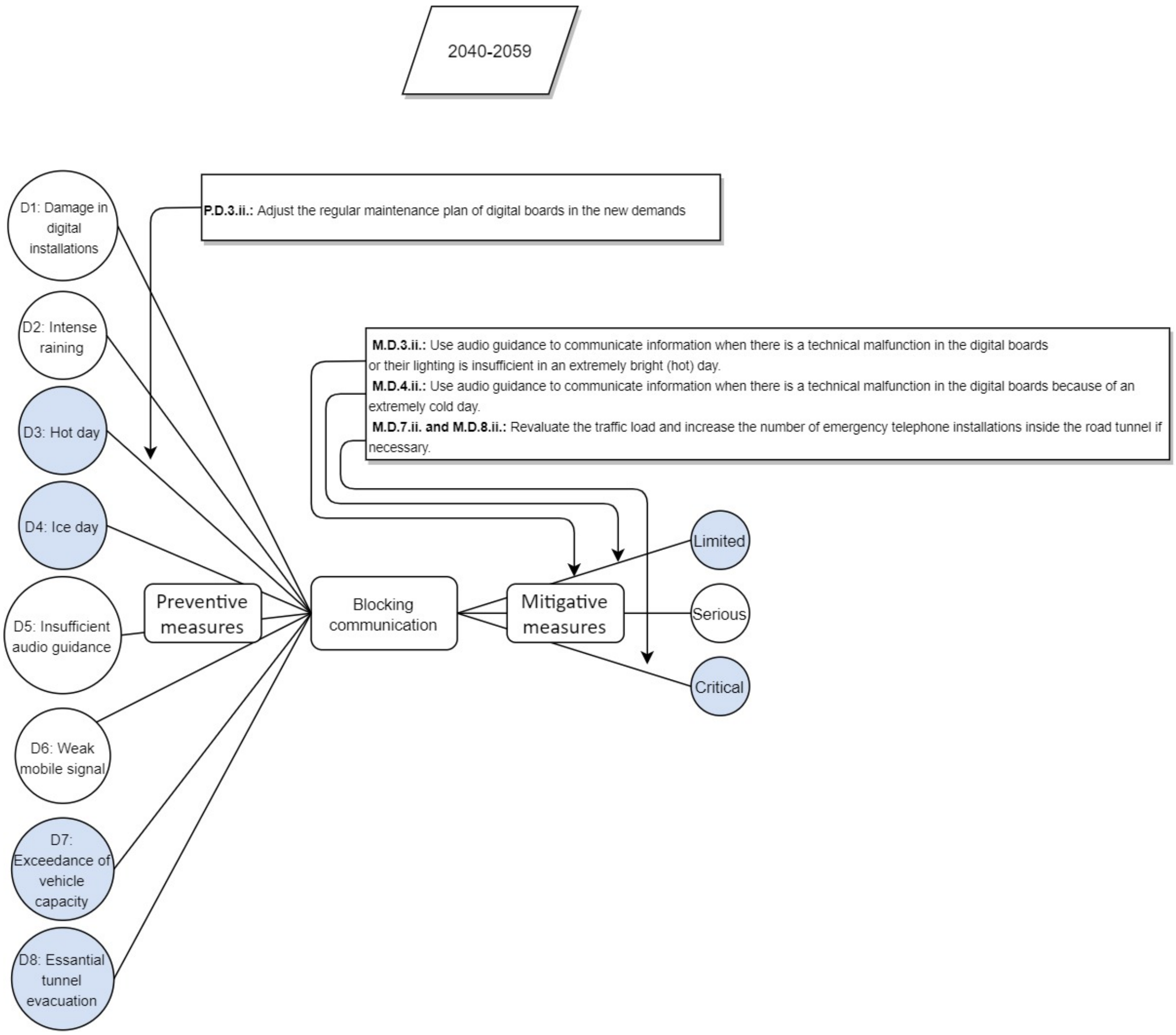


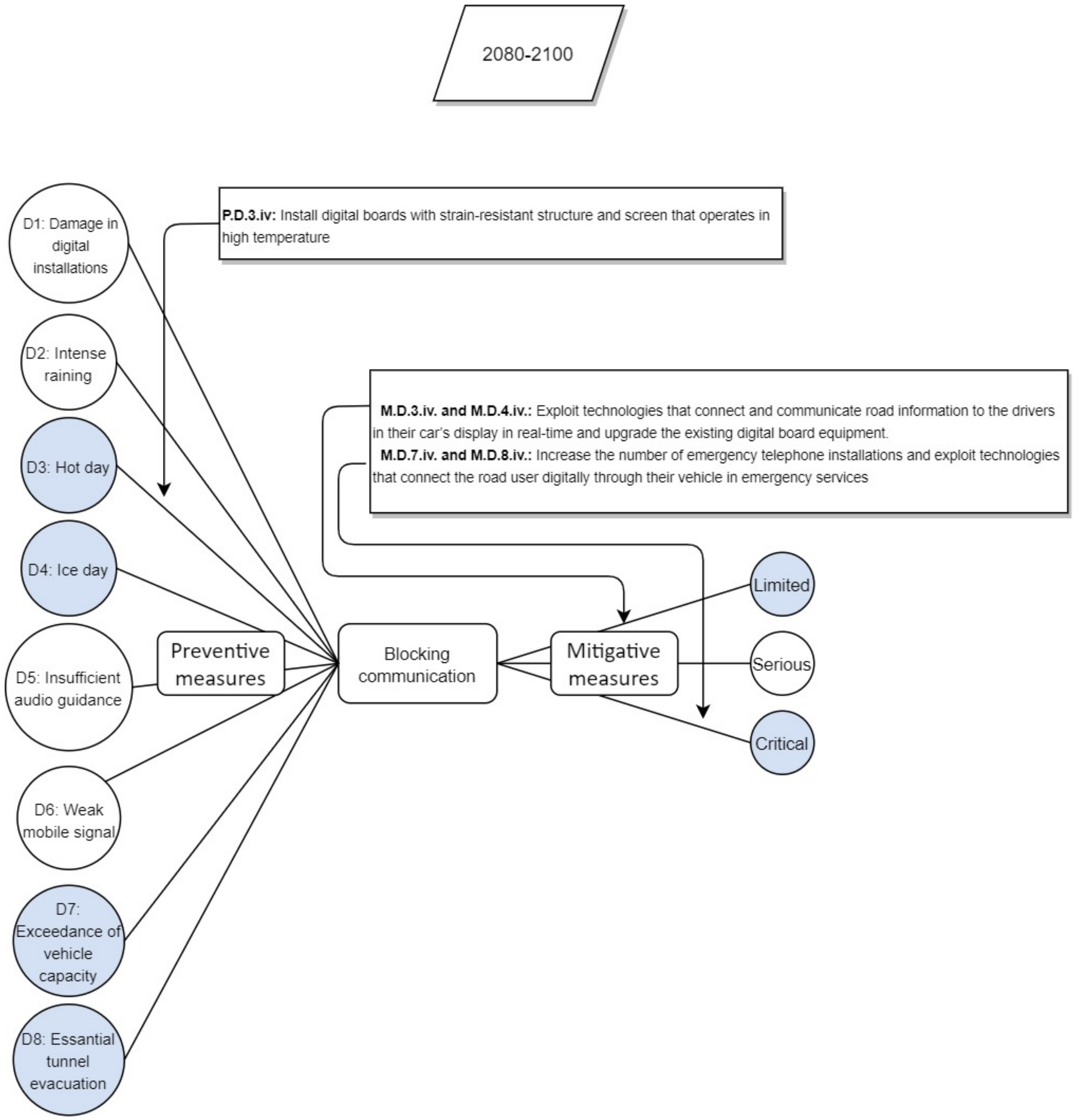

2040-2059
C1: Delay in communicating traffic changes
C2: Wrong provision of information
C3: Hailstorm
C4: Extreme shower
C5: Extreme temperature
C6: High precipitation volume
C7: Exceedance of vehicle capacity
C8: Fire by an electric car crash
P.C.4.ii.: Extend the sewer system and optimize the mechanical part of the drainage system
P.C.8.ii.: Upgrade the existent ventilation system to perform adequately in denser fire smoke caused by batteries fire
Preventive measures
Failed connection with the road network traffic management facilities
Mitigative measures
Limited
Serious
Critical
M.C.5.ii. and M.C.6.ii.: Develop a customed system for immediate recognition and response of road tunnel sensors underperformance in traffic measuring due to high temperature and/or a high volume of precipitation
M.C.8.ii.: Upgrade the fire sprinkler system to mitigate the fire expansion


2060-2079
C1: Delay in communicating traffic changes
C2: Wrong provision of information
C3: Hailstorm
C4: Extreme shower
C5: Extreme temperature
C6: High precipitation volume
C7: Exceedance of vehicle capacity
C8: Fire by an electric car crash
Preventive measures
P.C.8.iii: Insert additional ventilation equipment to enhance the performance of the existing one.
Failed connection with the road network traffic management facilities
Mitigative measures
Limited
Serious
Critical
M.C.7.iii.: Research and develop advanced technologically ventilation system which can perform on the anticipated future increased traffic load in the road tunnel


2080-2100
C1: Delay in communicating traffic changes
C2: Wrong provision of information
C3: Hailstorm
C4: Extreme shower
C5: Extreme temperature
C6: High precipitation volume
C7: Exceedance of vehicle capacity
C8: Fire by an electric car crash
Preventive measures
Failed connection with the road network traffic management facilities
Mitigative measures
M.C.4.iv.: Provide protective equipment in a flooding event
M.C.5.iv. and M.C.6.iv.: Share the maintenance risks of road tunnel sensors for traffic measuring with a specialized third party
M.C.8.iv.: Use fire-resistant materials to cover the ventilation system equipment
Limited
Serious
Critical

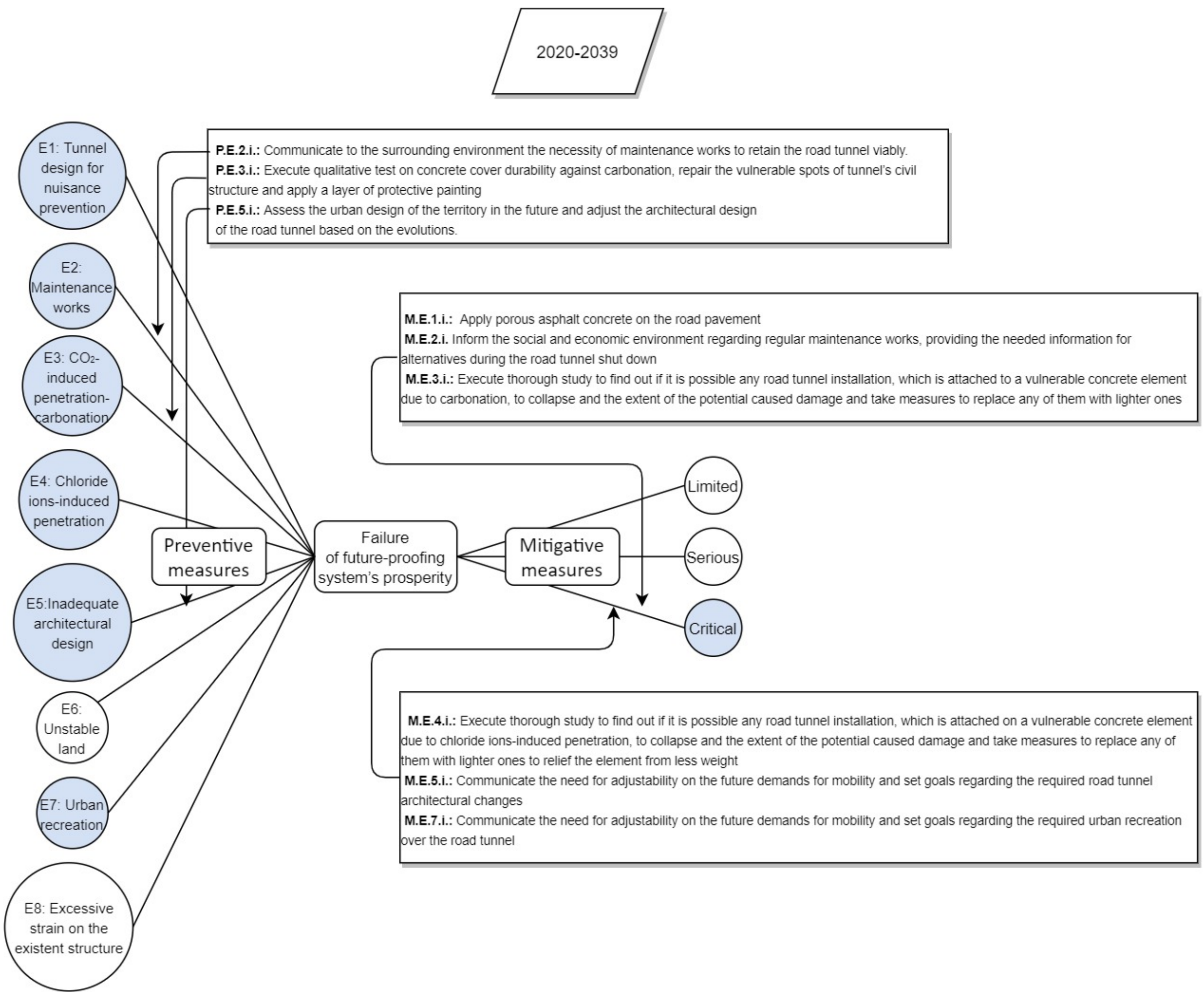
7.2.4. Function D: Facilitating communication

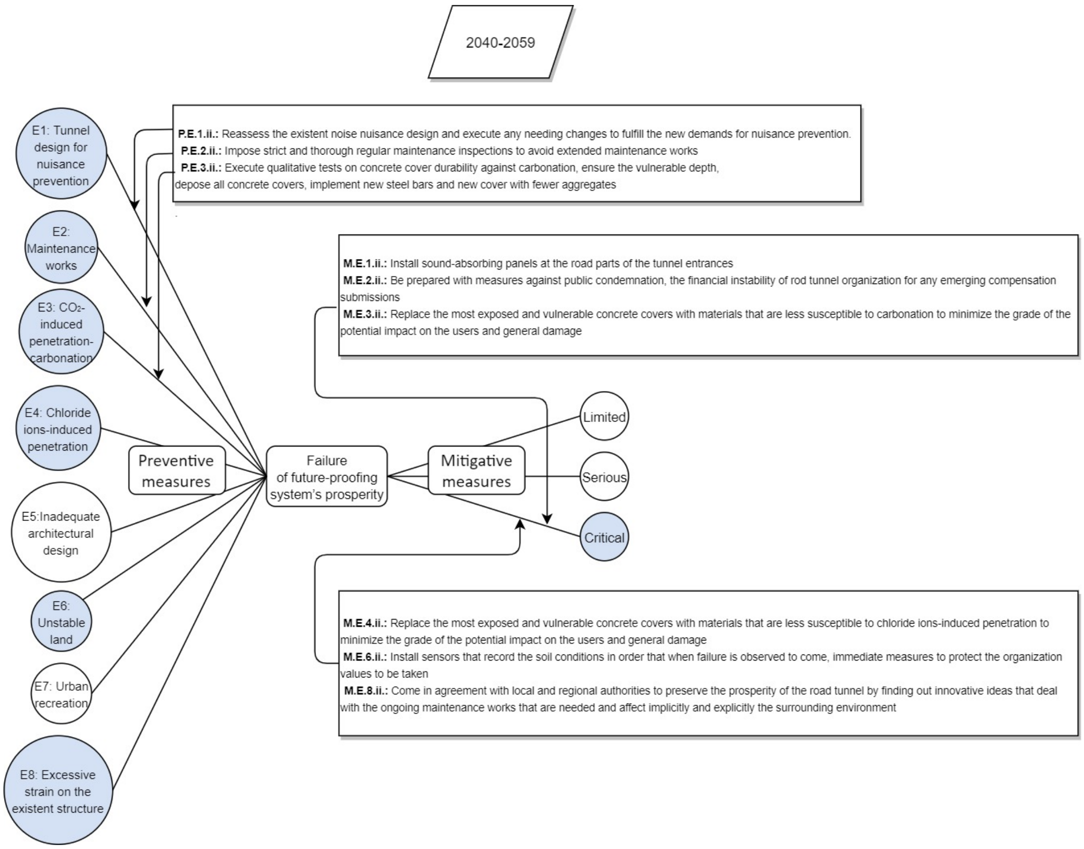




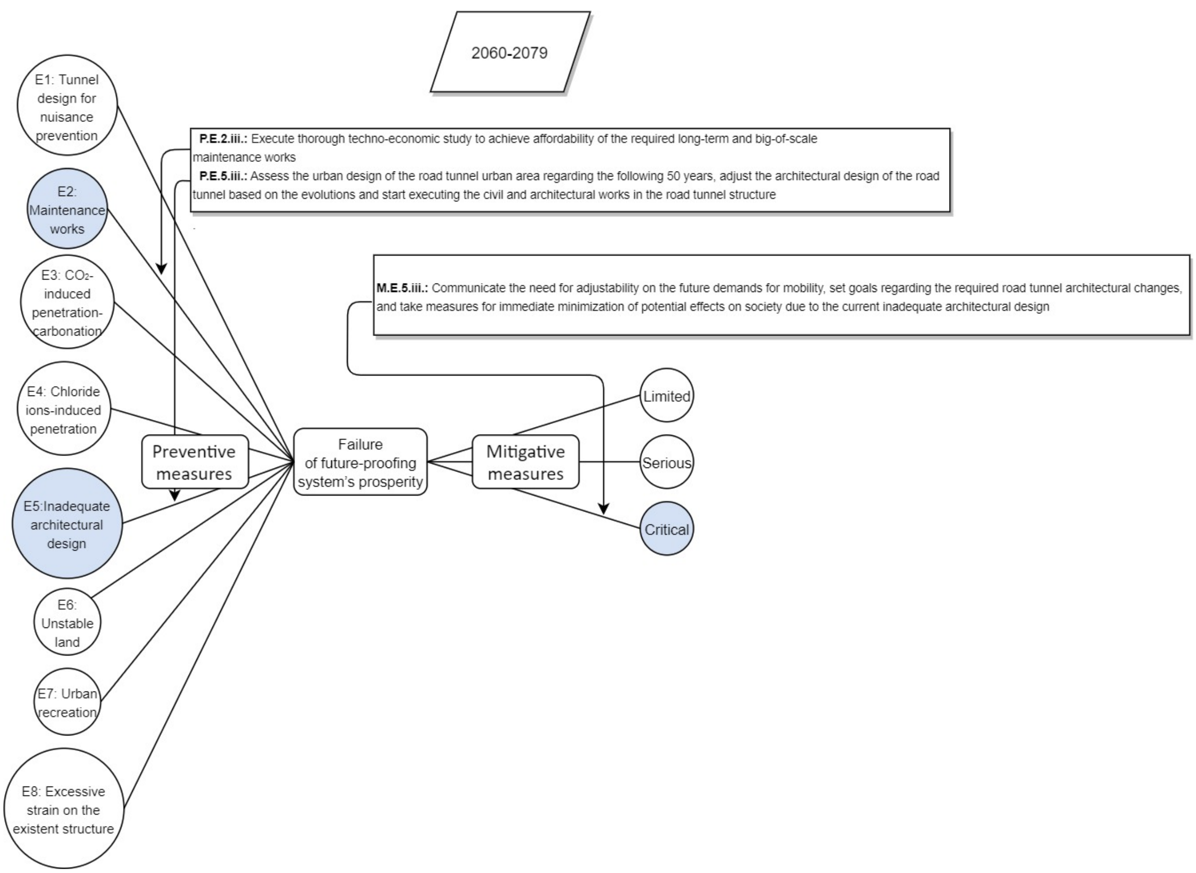
2080-2100
P.D.3.iv: Install digital boards with strain-resistant structure and screen that operates in high temperature
M.D.3.iv. and M.D.4.iv.: Exploit technologies that connect and communicate road information to the drivers in their car's display in real-time and upgrade the existing digital board equipment.
M.D.7.iv. and M.D.8.iv.: Increase the number of emergency telephone installations and exploit technologies that connect the road user digitally through their vehicle in emergency services
D1: Damage in digital installations
D2: Intense raining
D3: Hot day
D4: Ice day
D5: Insufficient audio guidance
D6: Weak mobile signal
D7: Exceedance of vehicle capacity
D8: Essantial tunnel evacuation
Preventive measures
Blocking communication
Mitigative measures
Limited
Serious
Critical

7.2.5. Function E: Future-proofing system's prosperity

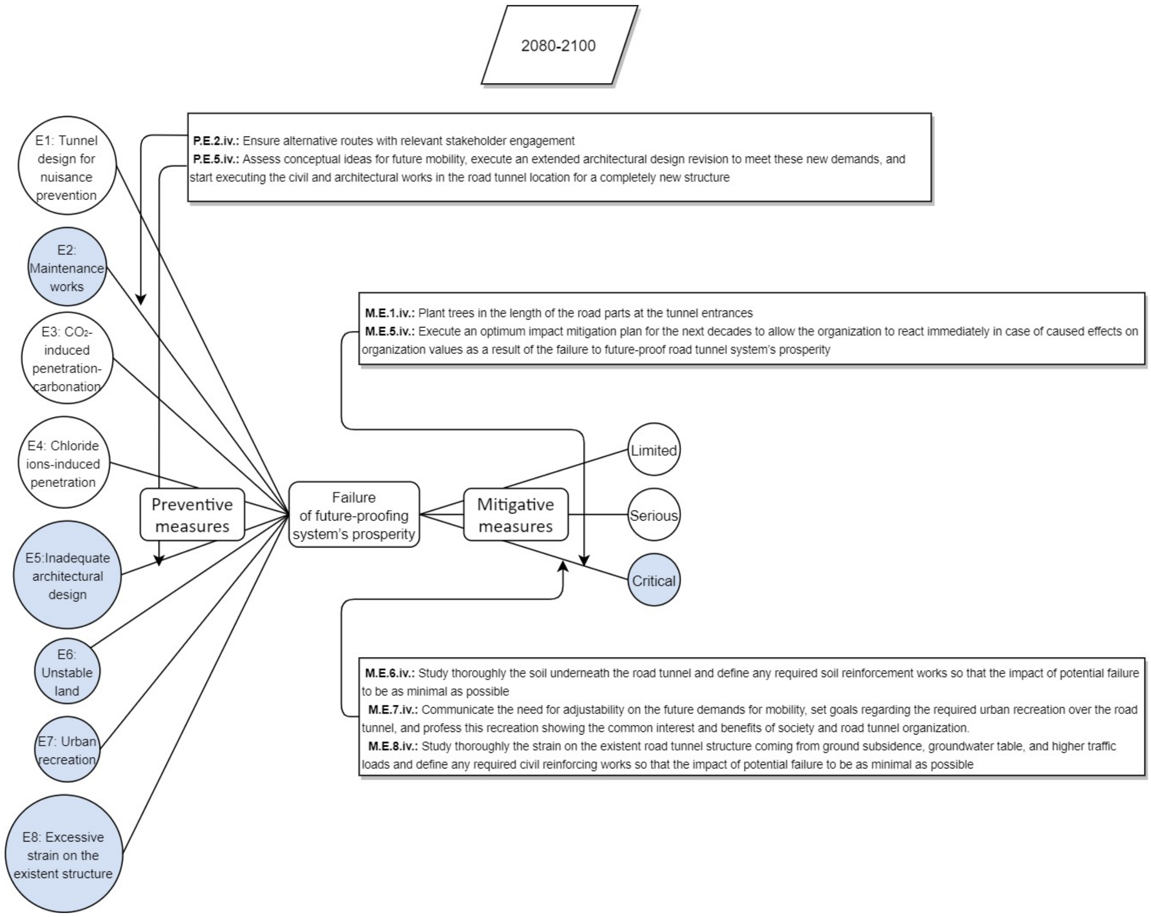




2040-2059
P.E.1.ii.: Reassess the existent noise nuisance design and execute any needing changes to fulfill the new demands for nuisance prevention.
P.E.2.ii.: Impose strict and thorough regular maintenance inspections to avoid extended maintenance works
P.E.3.ii.: Execute qualitative tests on concrete cover durability against carbonation, ensure the vulnerable depth, depose all concrete covers, implement new steel bars and new cover with fewer aggregates
M.E.1.ii.: Install sound-absorbing panels at the road parts of the tunnel entrances
M.E.2.ii.: Be prepared with measures against public condemnation, the financial instability of rod tunnel organization for any emerging compensation submissions
M.E.3.ii.: Replace the most exposed and vulnerable concrete covers with materials that are less susceptible to carbonation to minimize the grade of the potential impact on the users and general damage
E1: Tunnel design for nuisance prevention
E2: Maintenance works
E3: CO2-induced penetration-carbonation
E4: Chloride ions-induced penetration
E5:Inadequate architectural design
E6: Unstable land
E7: Urban recreation
E8: Excessive strain on the existent structure
Preventive measures
Failure of future-proofing system's prosperity
Mitigative measures
Limited
Serious
Critical
M.E.4.ii.: Replace the most exposed and vulnerable concrete covers with materials that are less susceptible to chloride ions-induced penetration to minimize the grade of the potential impact on the users and general damage
M.E.6.ii.: Install sensors that record the soil conditions in order that when failure is observed to come, immediate measures to protect the organization values to be taken
M.E.8.ii.: Come in agreement with local and regional authorities to preserve the prosperity of the road tunnel by finding out innovative ideas that deal with the ongoing maintenance works that are needed and affect implicitly and explicitly the surrounding environment



2060-2079
E1: Tunnel design for nuisance prevention
P.E.2.iii.: Execute thorough techno-economic study to achieve affordability of the required long-term and big-of-scale maintenance works
P.E.5.iii.: Assess the urban design of the road tunnel urban area regarding the following 50 years, adjust the architectural design of the road tunnel based on the evolutions and start executing the civil and architectural works in the road tunnel structure
E2: Maintenance works
M.E.5.iii.: Communicate the need for adjustability on the future demands for mobility, set goals regarding the required road tunnel architectural changes, and take measures for immediate minimization of potential effects on society due to the current inadequate architectural design
E3: CO2-induced penetration-carbonation
E4: Chloride ions-induced penetration
Preventive measures
Failure of future-proofing system's prosperity
Mitigative measures
Limited
Serious
Critical
E5:Inadequate architectural design
E6: Unstable land
E7: Urban recreation
E8: Excessive strain on the existent structure



7.3. Conclusion

The BowTie visualization for unavailability response was conducted to define and visualize preventive and mitigative measures, and their sell-by-date to prepare the road tunnel system adaptation to the new demands and in that way the execution of the DAPP model third and fourth step, 3*) Identify actions and 4a) Assess efficacy, sell-by-date of actions with transient scenarios, 4b) Reassess vulnerabilities and opportunities* were completed. The explanation of the BowTie methodology and its characteristics *(7.1.)* were necessary to perform the *identification* and visualization of the adaptation measures *(7.2.)*. Moreover, the setting of the *sell-by-date of those adaptation actions* was also part of this chapter by giving time ranges of actions expected start and finish. The *reassessment of vulnerabilities and opportunities* was continuously considered when defining the actions to assure the positive contribution of those actions as solutions on the actual problems.

In total, 23 preventive and 63 mitigative measures were defined, some of them dealing with multiple basic events. For instance, the mitigative measure of basic event D3 for the period 2080-2100 could be used as mitigative measure of the basic event D4 for the same period too, therefore, one measure satisfies two basic events. Finally, there were basic events that advised up to four mitigative measures to be taken, but in practice, even two could satisfy longer periods. For instance, the basic event D8 indicates up to four mitigative measures, but eventually, two measures are thought necessary, one for 40 years' lifespan (2040-2059) and one for 80 years' lifespan (2080-2100).

Chapter 7 replied to the Sub Question 2: '*What actions could be taken to prevent functional failures and mitigate consequences?''.* It means that *Phase II* was completed and the continuation to *Phase III* for the modelling of the adaptation strategies, by receiving as input the outcomes of this chapter, will perform the creation of the map for preventive actions and the map for mitigative actions in *Chapter 8.*

Phase III

<u>Sub Question 3 response</u>

In *Phase III*, the third sub-research question is attempting to be answered

'' What are the potential dynamic pathways that model the life cycle strategies and to what extent do these pathways result in decision-making information that policymakers might use?''

responding to the 5th and 6th step of DAPP model (*Figure I.).*

'' What are the potential dynamic pathways that model the life cycle strategies?''

Chapter 8. Modeling of adaptation strategy

- Formulation of sequential actions of prevention and mitigation for every basic event (*8.1.*).
- Formulation of sets of sequential actions naming them as Action Sets (*8.2.*).
- Shape of strategic maps for cause prevention and impact mitigation (*8.3.*).

''To what extent do these pathways result in decision-making information that policymakers might use?''

Chapter 9. Research results

- What did Dynamic Adaptive Policy Pathways model bring new in the domain of road infrastructure management (*9.1.*).
- Do the experts validate the research results, and do they conclude whether pathways result in useful decision-making information? (*9.2.*).

8. Modelling of adaptation strategy

In this chapter, the modelling of adaptation strategies is conducted by introducing as input the outcomes of the *Chapter 7*, to create the strategic map of preventive actions and the one of mitigative actions.

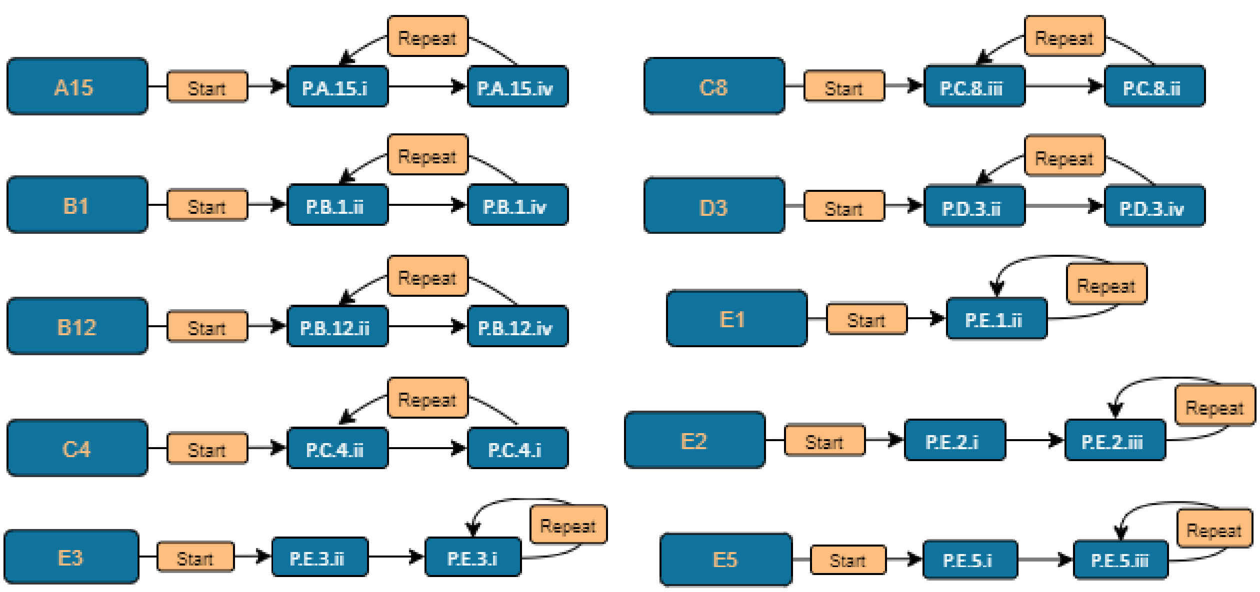
- The formulation of sequential preventive and mitigative actions in *subchapter 8.1.,* and
- The grouping of them into Action Sets in *subchapter 8.2.* shape the potential dynamic pathways that model the life cycle strategies.
- These strategies are elaborated into adaptation pathway maps for cause prevention and impact mitigation in *subchapter 8.3*.

The outcome of this chapter replies to two out of three parts of the Sub Question 3: ''*What are the potential dynamic pathways that model the life cycle adaptation strategies? and which ones are preferred to be followed''.* In *Chapter 9*, the research work validation through experts interviewing will answer the third part of the Sub Question 3 of *Phase III* which is*, ''To what extent do these pathways result in decision-making information that policymakers might use?''.*

8.1. Formulation of sequential actions

8.1.1. Preventive measures

The formulation of sequential actions, referring to a basic event, is executed by observing the timely evolvement of the unavailability percentage contribution of that basic event on the road tunnel unavailability. The relevant chart of unavailability percentage contribution, which is illustrated in subchapter *6.4,* indicates the order in which the actions should be taken. In other words, the preventive measures are prioritized in such a way that reflect the contribution evolvement, which tend to increase, decrease, or remain stable. However, not all the measures are thought necessary to be implemented. Some measures could be enough and capable for more than one period. Therefore, based on those charts of subchapter *6.4.,* the following orders of actions are proposed for every basic event:



The basic events A15, E2, and E5 are the ones that use their two out of three proposed preventive measures and the rest of basic events use all their proposed preventive measures. The tipping point of action change is indicated by the action that has previously been chosen. To make it clearer, for the basic event A15, the P.A.15.iv is implemented after the P.A.15.i. and starts when some years before 2040, a study will have been conducted to see when the P.A.15.iv is necessary to start. In the map, a time range will be depicted by giving the span where action could potentially start to be applied. The earliest start could be in the 20% of the implementation time of the previously applied action and the latest start could be in the 20% of the implementation time of the previously applied action later. This means that an action that started in 2020 and its lifespan is expected till 2040, the action change should be conducted no earlier than 2036 but not later than 2044. In this way, it would be known when the next measure should be taken, earlier or later than it was expected relying on the climate change conditions of that future moment. The corresponding tipping points for 2060 are, 2052 and 2068, for 2080 are, 2068 and 2092 and for 2100 are 2084 and 2106. The selection of the percentage 20% is typical and it could be higher or lower, always relying on the case of the road tunnel and adverse climate condition changes.

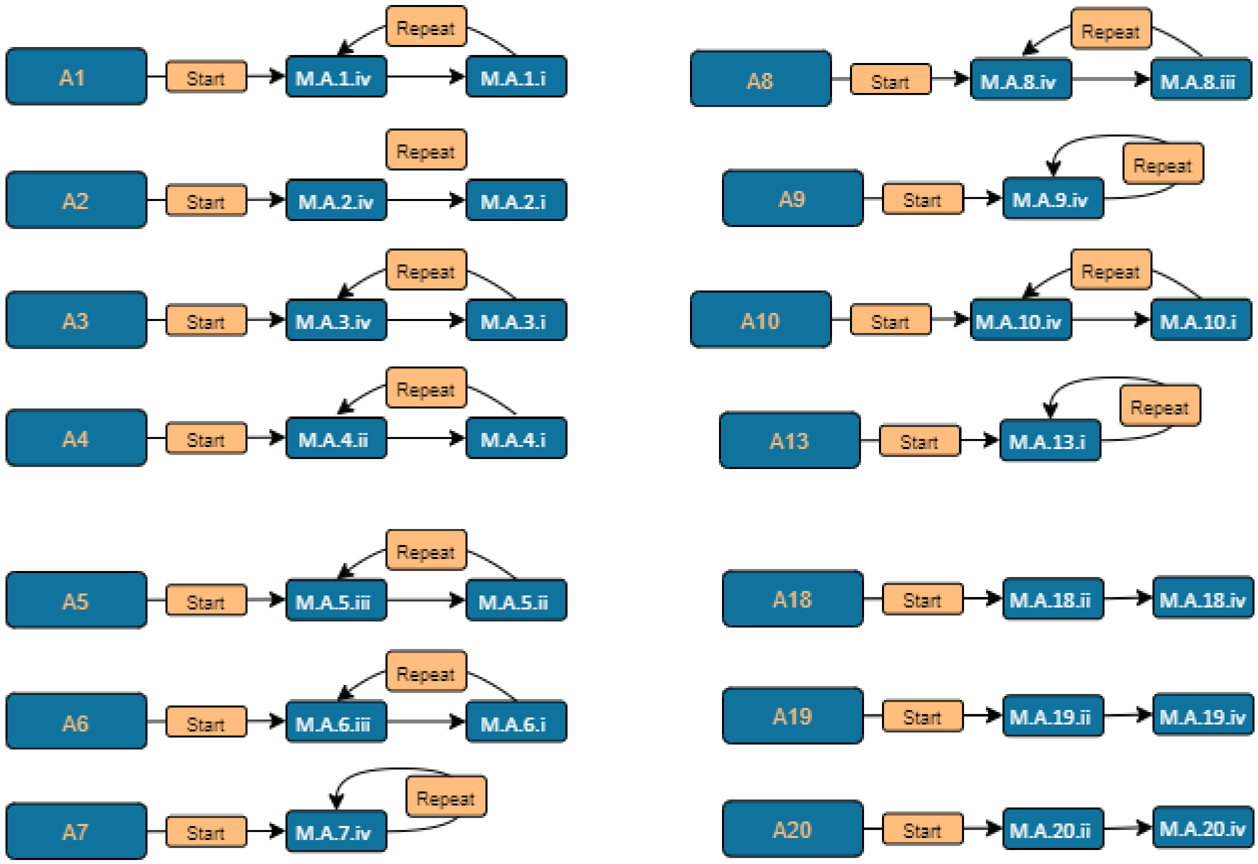
Later in subchapter *8.2.,* the basic events, which are expected to follow the same order of preventive measures' application, are found out and these measures are grouped into action sets of each period. Further explanation is elaborated in the relevant subchapter.

8.1.2. Mitigative measures

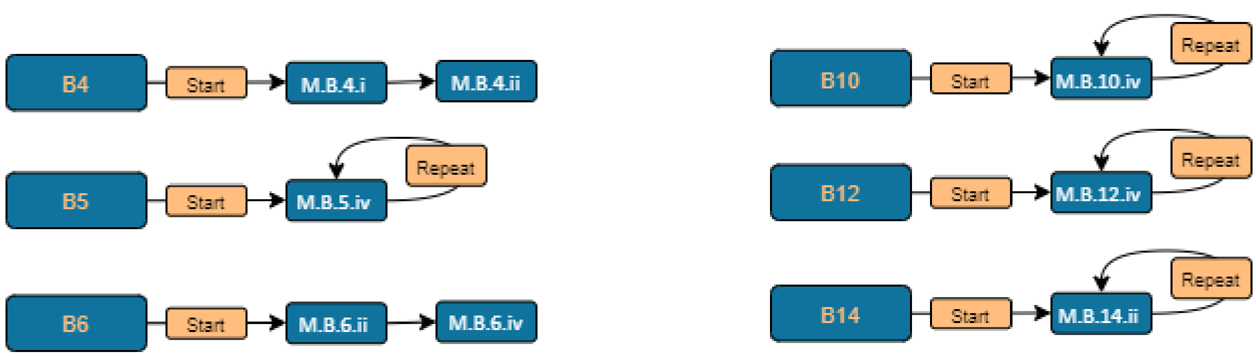
The formulation of sequential actions in this case is executed by scoring the proposed measures of every basic event. As it has been known, every basic event which is assigned to propose mitigative measures, up to four measures are proposed, one for every period. This means that a mitigative measure of 2040-2059 has a lifespan of 40 years and a measure of 2060-2079 has 60 years of lifespan. Therefore, measures of different lifespan are defined in every basic event with different contribution on mitigating the impact on organization values. For example, a proposed mitigative measure can have a positive impact on preserving the organization value of safety, a neutral impact on preserving the value of reputation and so on. By scoring every measure on its contribution to preserve these values and subsequently to mitigate the impact of the corresponding basic event on them, it supports the process of taxonomizing the measures in preference order.

In Appendix-subchapter 8.1., five tables are elaborated which estimate the score of each proposed measure in its corresponding period. These tables are developed in Excel and the mathematical expression for the score calculation is equal of the sum of the six individual scores divided by six (the number of organization values). Based on these tables, the following orders of actions are proposed for every basic event:

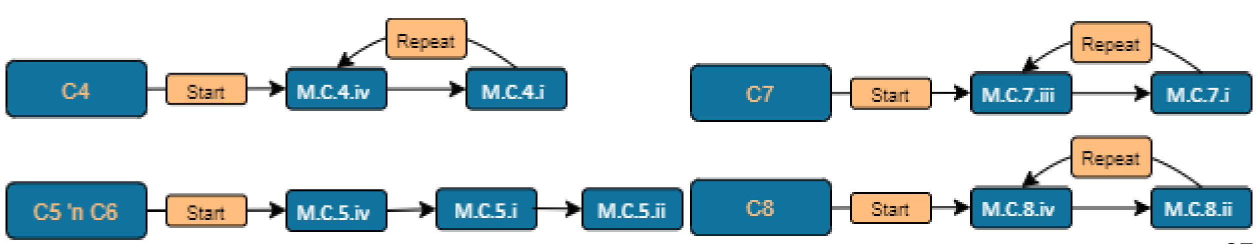
- Function A



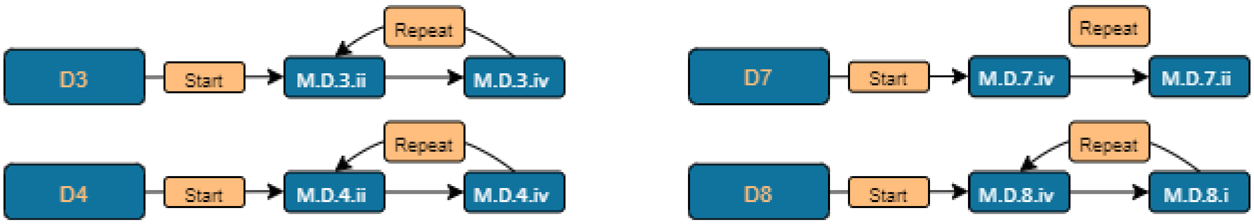
- Function B



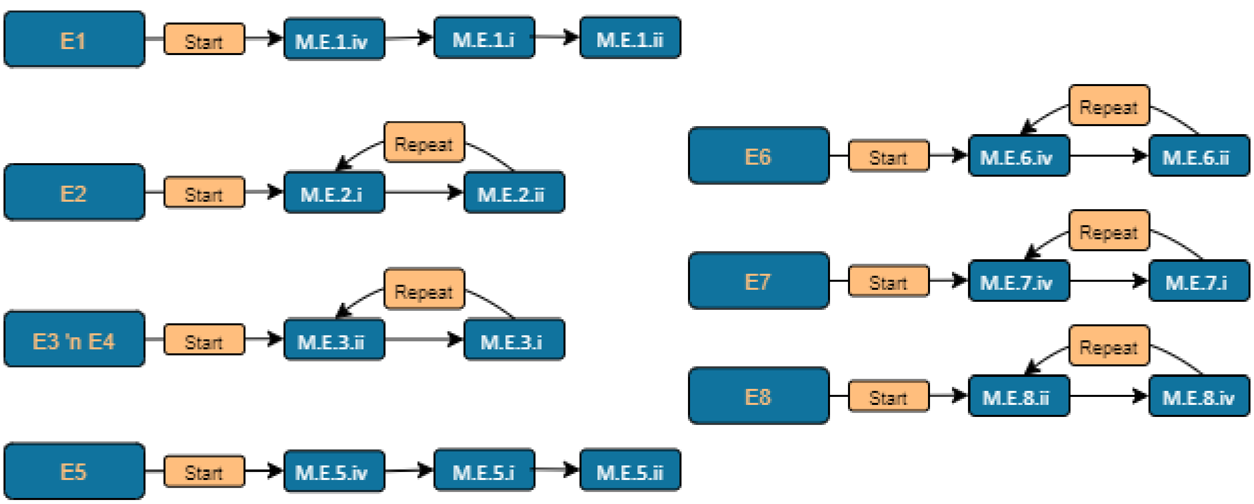
- Function C



- Function D



- Function E



The mitigative measures of C5 and C6 are exactly same measures that satisfy both basic events and the same for the case of E3 and E4 mitigative measures. Moreover, some measures suggest repeat of them when the first circle is done, for example when the sequential actions of A1 are executed, then the action starts from the M.A.1.iv measure again. The sequential actions that do not suggest a repeat of action mean that either the period of mitigative measures application exceeds quite a lot the timeline of analysis or it is not necessary the taking of measures again.

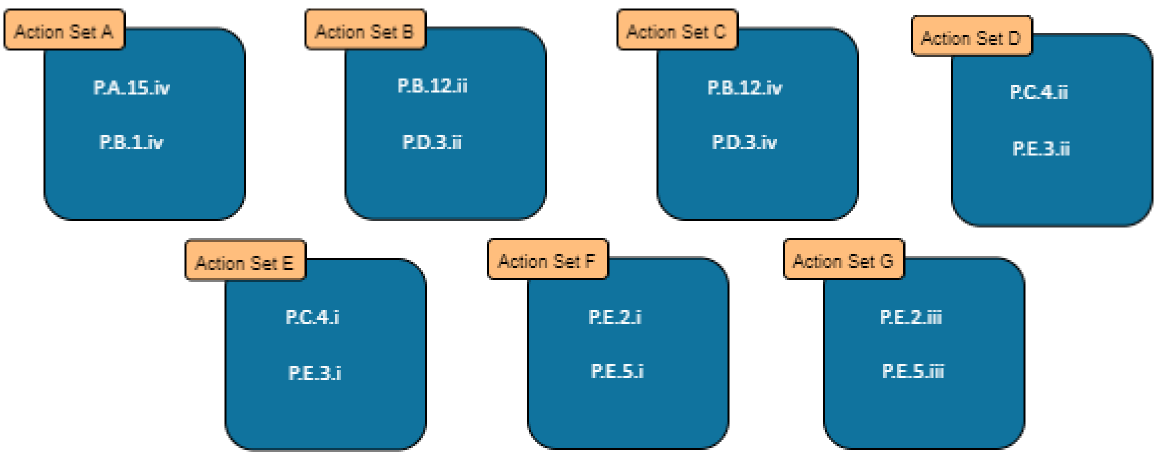
In the map, the time ranges are the same as in the case of prevention. Finally, in subchapter *8.3.,* the basic events, which are expected to follow the same order of preventive measures' application, are found out and these measures are grouped into action sets of each period. Further explanation is elaborated in the relevant subchapter.

8.2. Sets of sequential actions

Grouping of measures that follow the same order of execution is the content of the subchapter. In subchapter 8.2.1. the action sets of prevention are presented and so on in the subchapter 8.2.2. for mitigation.

8.2.1. Measure sets of prevention

The groups are formulated by collecting the sequential actions that follow the same application order timely. The format is ''Action Set #'', where ''#'' is the letter indicator. The following group are presented:



Moreover, there are five independent measures that are not grouped,

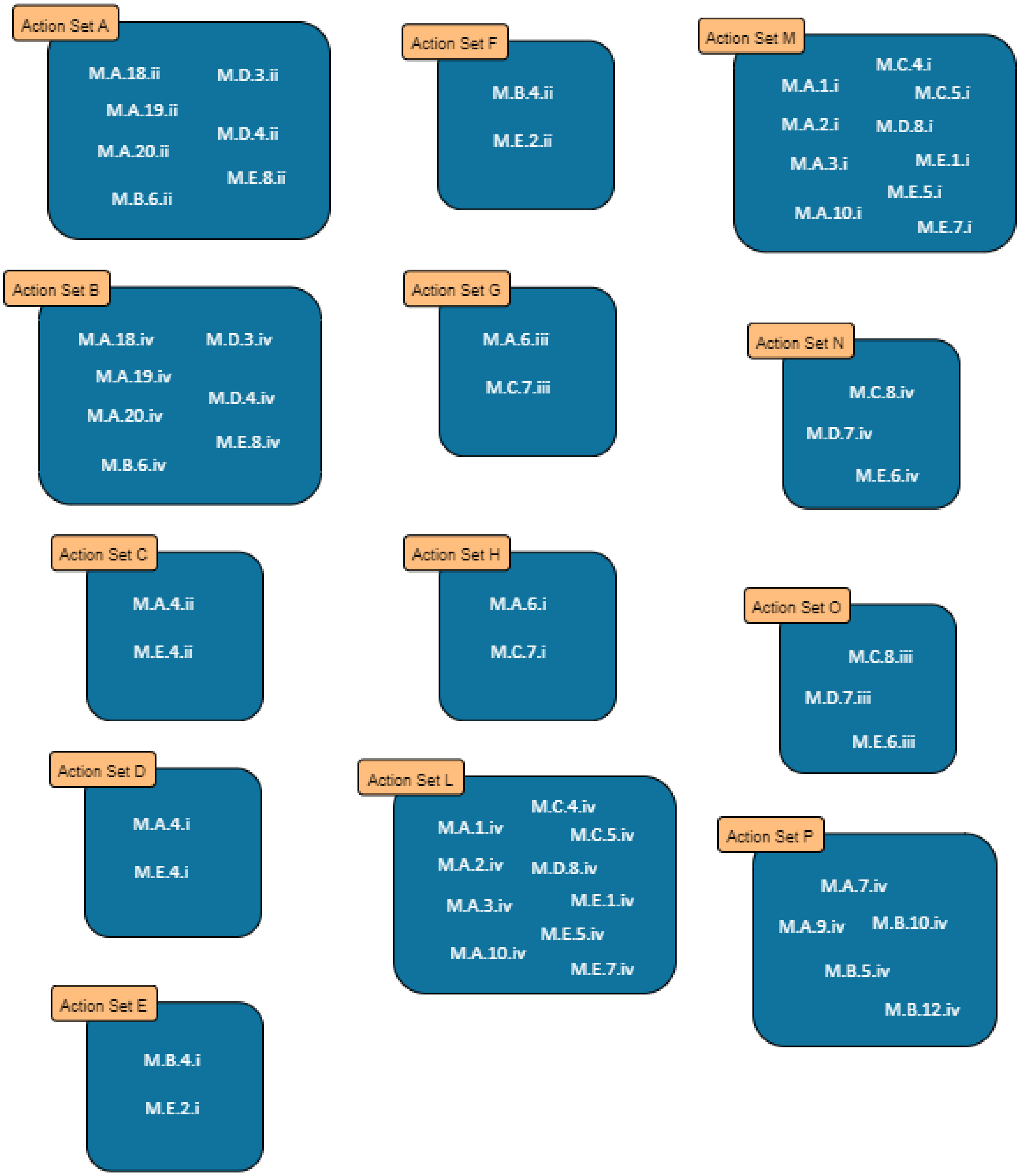
- P.A.15.i.
- P.B.1.ii.
- P.C.8.ii.
- P.C.8.iii.
- P.E.1.ii.

Finally, there are four independent measures that are not suggested to be included in the strategy.

- P.A.15ii.
- P.E.2.ii.
- P.E.2.iv.
- P.E.5.iv.

8.2.2. Measure sets of mitigation

The groups are formulated by collecting the sequential actions that follow the same application order timely. The format is ''Action Set #'', where ''#'' is the letter indicator. The following group are presented:



Moreover, there are four independent measures that are not grouped because they do not match with any of the other measure orders.

- M.A.5.ii.
- M.A.5.iiii.
- M.A.8.iii.
- M.A.8.iv.

Finally, there are five independent measures that are suggested to be excluded from the strategy.

- M.A.5.iii.
- M.C.5.ii.
- M.C.6.ii.
- M.D.7.ii.
- M.E.1.ii.

8.3. Pathways map

The visualization of those Action Sets into a strategic map of adaptation for cause prevention and another one for impact mitigation takes place in this subchapter. The main research goal, the creation of a strategic plan through dynamic pathways map is achieved and further explanation of the map's formulation, and the strategic flexibility that occurs.

8.3.1. Map for Preventive Actions

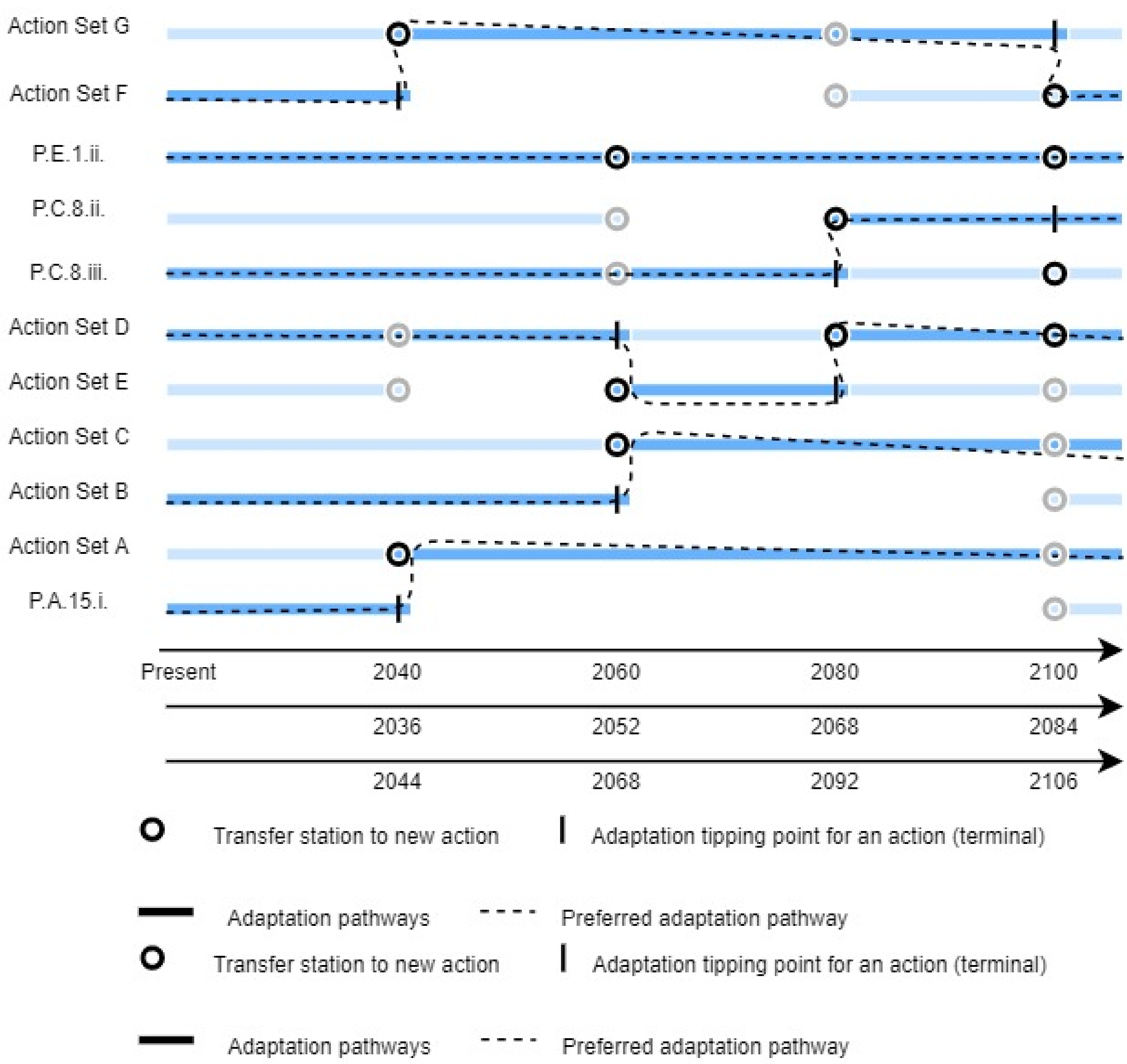


Figure XXXI: Strategic plan for adaptation - preventive actions

Having set the measures into groups, the following map for preventive actions is formed as it is depicted in *Figure XXXI.* There are four adaptation tipping points, which are the time ranges of 2036-2044, 2052-2068, 2068-2092, and 2084-2106.

The measures are taken, based on this map, to face same or different climate variables or climate change-related conditions. In dot points, these variables are briefly presented, without naming the actual intervention measures that deal with these variables, pointing out the associated to the map's tipping points as followed:

<u>Tipping Point</u>

<u>Present</u> → Measures for intervention works and social awareness for road tunnel defense against:

- CO_2 atmospheric concentration
- Hailstorm
- Intense rainfall
- Extreme Temperature
- Expected social changes in population density, electric mobility, and nuisance due to climate change

<u>2036-2044</u> → New measures are taken against:

- Hailstorm
- Intense rainfall
- Expected social changes in nuisance (maintenance works) due to climate change

<u>2052-2068</u> → New measures are taken against:

- CO_2 atmospheric concentration
- Hailstorm
- Intense rainfall
- Extreme Temperature

<u>2068-2092</u> → New measures are taken against:

- Expected social changes in electric mobility
- CO_2 atmospheric concentration
- Extreme shower

<u>2084-2106</u> → New measures are taken against:

- CO_2 atmospheric concentration
- Extreme shower
- Expected social changes in nuisance (maintenance works) due to climate change

At the beginning, the adaptation of the road tunnel on the effects of climate change starts by applying the independent measures, P.A.15.i., P.C.8.iii. and P.E.1.ii. and the Actions Sets of B, D, and F. At the adaptation tipping point of 2036-2044 an assessment of the current road tunnel condition associated with the effects of climate change and appraising the updates of climate change evolvements, new actions take place. These would be the Action Set A and G. The same process is executed for the next adaptation tipping points till the end of the due research analysis. In 2052-2068, the Action Set C and E are activated and the P.E.1.ii. is repeated. In 2068-2092, Action Set D is implemented again, and P.8.C.ii. takes on and in the last tipping point, 2084-2106, Action Set D and F should be applied again and the P.E.1.ii. be repeated to realize the road tunnel system's cause preventive adaptation on the climate changes. Beyond the latter tipping point, no analysis has taken place.

8.3.2. Map for Mitigative Actions

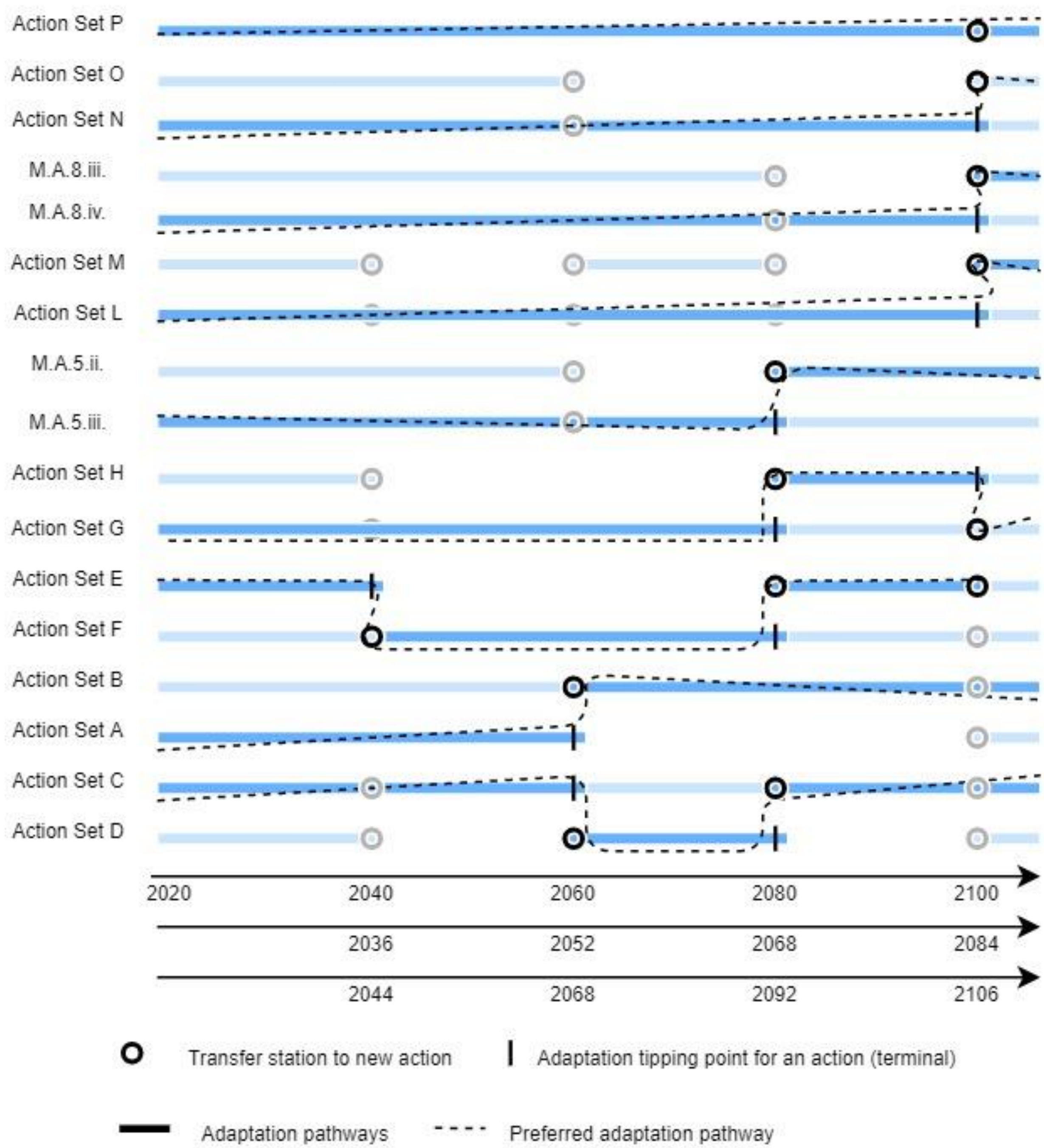


Figure XXXII: Strategic plan for adaptation - mitigative actions

At the same way as it was described in subchapter 8*.3.1.,* the map for mitigative actions is elaborated in this section (*Figure XXXII)*. The measures are taken, based on this map, to face same or different climate variables or climate change-related conditions. In dot points, these variables are briefly presented, without naming the actual impact mitigative measures that deal with these variables, pointing out the associated to the map's tipping points as followed:

Tipping Point

Present → Measures that can mitigate potential impact on road tunnel organization values and raise social awareness against:

- Groundwater effect and North Sea level change
- High Temperature and extreme hot days
- Low temperature and extreme ice days
- Long drought periods and then intense rainfalls
- Social changes in population density, electric mobility, nuisance, and tunnel safety due to climate change
- Hailstorm
- Extreme showers

2036-2044 → New measures are taken against:

- High Temperature and extreme hot days
- Social changes in nuisance (maintenance works) due to climate change

2052-2068 → New measures are taken against:

- Groundwater effect
- High Temperature and extreme hot days
- Low temperature and extreme ice days
- Long drought periods and then intense rainfalls
- Social changes in population density due to climate change
- CO_2 atmospheric concentration

2068-2092 → New measures are taken against:

- High Temperature and extreme hot days
- Low temperature and extreme ice days
- CO_2 atmospheric concentration
- Social changes in population density due to climate change

2084-2106 → New measures are taken against:

- Low temperature and extreme ice days
- Social changes in population density, electric mobility, nuisance (maintenance works), and tunnel safety due to climate change
- Groundwater effect
- Hailstorm and extreme weather

- High Temperature

At the beginning, the adaptation starts with the implementation of the measures, M.A.5.iii., and M.A.5.iv. and the Actions Sets of A, C, E, G, L, N and P. At the adaptation tipping point of 2036-2044, an assessment of the current road tunnel condition associated with the effects of climate change and appraising the updates of climate change evolvements, new actions take place. These would be the Action Set F. In the next adaptation tipping point of 2052-2068, the Action Sets B and D are applied, in 2068-2092, the independent measure M.A.5.ii., and the Action Sets D, E, and H take place. Finally, in the last tipping point, 2084-2106, the independent measure M.A.8.iii. starts together with the Action Sets G, M, and O, and Action Set P is repeated. The rest of measures continue to be applied besides the Actions Set E which stops, and no other measures are proposed beyond the last adaptation tipping point.

8.4. Conclusion

The modeling of adaptation strategies was conducted to create two strategic maps, a map which depicts the implementation order of the selected measures for road tunnel adaptation to prevent functional underperformance and a map which depicts the implementation order of the selected measures for road tunnel adaptation to mitigate the potential impact on its organization values in case of functional underperformance. In that way, the execution of the DAPP model fifth and sixth step, *5) Develop adaptation pathways and map,* and *6) Select preferred pathways* were completed.

The modeling starts with the formulation of sequential actions *(8.1.).* For every basic event, its proposed measures, either for cause prevention or impact mitigation, were prioritized based on implementation order preference to *develop adaptation pathways*. Not all proposed measures should have been used, but only the indicated ones. The recognition of the basic events that are faced by measures of the same chronological duration and the same chronological order allowed the grouping of those measures of every period into the same Action Set *(8.2.)* and subsequently, many sets of sequential actions were defined within the analysis timeframe. The visualization of those Action Sets into a map was the last part of this chapter and in that way, the main research goal of creating an adaptation pathways map with *selected pathways* was achieved *(8.3.).*

Chapter 8 replied to two out of three parts of the Sub Question 3: *''What are the potential dynamic pathways that model the life cycle adaptation strategies? and which ones are preferred to be followed''* and the third part, *''To what extent do these pathways result in decision-making information that policymakers might use?''* is going to be answered in *Chapter 9,* where the validation of research work will take place. The opinion of two experts on the developed methodology and my personal reflection will conclude to what extent these maps result in useful decision-making information.

9. Research results

In this chapter, the research results are summarized to discuss the DAPP decision-making model for road tunnel life cycle management and the opinion of two experts that were asked to validate the research work through interviewing.

- In *subchapter 9.1.,* the research results regarding the developed methodology, method's applicability and importance are discussed, and
- In *subchapter 9.2.* the research work validation takes place where the views of the interviewees on the structured methodology of DAPP model, the generalized implementation for LC decision-making and the interested parties are elaborated.

The outcome of this chapter replies to the third part of the Sub Question 3: *''To what extent do these pathways result in decision-making information that policymakers might use?''* It means that *Phase III* is completed and therefore, the due research.

9.1. DAPP for road tunnel life cycle management

The developed methodology

Climate change is widely known about the uncertainties that come up for the future of infrastructure assets. The focus of this research was the road tunnels that are located in the Dutch territory and its main concern was the development of a decision-making methodology for road tunnel adaptation on the new demands as these come up from the effects of the climate crisis. Long-term decision planning is not an easy task under a deeply uncertain climate future considering the dynamic and, sometimes, unknown evolvement of climate change over time. It makes the whole decision-making process even more complicated. However, the Dynamic Adaptive Policy Pathways seems to be a promising decision-making model in this direction.

The methodology that was structured based on the principles of the DAPP model had as first step the analysis of the climate variables projections based on the most intense climate scenario of the KNMI literature and then to narrow it down to the ones that are mostly associated with a road tunnel asset. One of the DAPP advantages is the fact that it does not seek robust asset's adaptation in any climate variable but adaptation to the only relevant with the asset ones. Moreover, it inspires, in a very early phase, the climate variables connection with the functional requirements of a road tunnel and not immediately with the road tunnel's structural components. Other decision-making practices focus on the main asset's structural components that are affected generally by climate change which could lead to the assessment of irrelevant components and climate variables, in DAPP this is avoided. Another benefit of the DAPP model is that such a decision-making process can deal with multiple similar assets at the same time. It focuses on an area in which its climate changes affect simultaneously lots of assets. The Netherlands is a small country, and climate change is expected to be the same in the whole territory. Therefore, each of the 16 identified road tunnels in the Dutch territory will face the same causes of issues and levels of consequences. This generalization is thought to be acceptable in this case, but it would not be in other potentially bigger regions such as the USA or Russia because those countries occupy enormously land, and much climatic differentiation could be observed among the regions. Consequently, this structured methodology would be beneficial mainly in small regions rather than bigger ones but its innovation as a process to result in one solution for many problems seems to make DAPP appealing compared to other approaches.

Moreover, in this approach, the executors must define the main functions of a road tunnel, identify the requiring systems and performance, and in such a way analyze the whole road tunnel system's function failure structure. The critical mindset of the executors is important to translate theoretical problems that have not occurred yet into concrete values referring to potential situations. Therefore, DAPP allows the executors to communicate as a group, combine their knowledge and consequently interpret the gained information of climate analysis, and relate it to the found failures. The quantification of failure into unavailability rate, and not into failure probability like in other approaches, eases the process and it is an alternative way to reflect the grade of a road tunnel system's failure. The qualitative analysis of the associated impact which is also required for the completion of this analysis part, makes this structured methodology to be completed. However, the sensitivity of the assumptions should be recognized and evaluated. In this methodology, sensitivity analysis is not included, and the reliability of the Phase I results could be doubted, even though the visualization of the results into charts and matrices could clarify the attention the decision-makers should pay. Lastly, this DAPP methodology would be time-demanding for the executors that are not familiar with this approach, mainly because Phase I asks for a thorough analysis, its outcomes are quite important for the next phases and it seems to occupy around 70% of the whole developed methodology.

The outcome of every task provides the needed information to further proceed the decision-making planning. Based on the expertise of the executors, adaptation actions are defined in Phase II to prevent events that lead to an unavailable road tunnel and, in case of such an event, adaptation actions are defined to mitigate the impact of the caused road tunnel unavailability on organization values. There are plenty of different impacts that are considered when implementing DAPP, which is not happening in other approaches that are mainly focusing on economic terms. The social environment, system's reputation, and asset's quality are some values the impact of climate crisis on them should not be underestimated. The executors define actions that subjectively are the most appropriate to face more than one problem relying on their analysis and visualize them in easy-to-comprehend BowTie diagrams. The setting of the sell-by-date of those adaptation actions allows the decision-maker to decide what to select and in which order to execute these options which means that DAPP provides flexibility of taking a decision. In this methodology, the criticality assessment of every proposed mitigative measure is achieving by scoring the measure's positive effect on these six organization values if it was to be applied. In that way, we prioritize the proposed mitigative measures and select the one that deal with the same problem but effectively and efficiently. On the other hand, the criticality assessment of every proposed preventive measure is achieving by deciding the desired measure's robustness that is seeking. The reassessment of vulnerabilities and opportunities was continuously considering when defining the actions to assure the positive contribution of those actions as solutions on the actual problems.

Finally, the modeling of an adaptation strategy in Phase III is the last analysis part of the developed methodology and summarizes the whole analysis into two adaptation maps as the DAPP model indicates. The adaptation pathways are the sequence of actions that the executors decide to include in the strategy, which means that not every proposed measure of Phase II is used. The DAPP model innovation is also recognized when the measures are grouping into action sets, to avoid the confusion coming from the plethora of measures and deliver compacted sets of measures that are implemented simultaneously within flexible timeline. The visualization of those action sets in a map as adaptation pathways and the definition of adaptation tipping points as implementation timing ranges emphasizes the flexibility of DAPP planning in long-term decision-making. It achieves concrete adaptation of a road tunnel to the new environment conditions in a dynamic rather than in a static way. On top of that, the ability of having plethora of alternative strategic options makes the decision-makers even more willing to use the DAPP model.

Method applicability

The DAPP model is designed for extended and long-term decision-making planning, mainly applied in water management, and based on this philosophy I recognized that this model could have prospects in other domains like the one of road infrastructure management. It is very important for someone to realize which assets can benefit most and which ones do not require to be considered in such a complex methodology.

Highways, bridges, and tunnels are the main road asset infrastructures, and they request different life cycle adaptation planning approaches. The lifespan of a highway is approximately 50 years and the road pavement which is the main component of a highway is less than 10 years. The short-term adaptation planning for new maintenance and operational procedures is the main concern for this kind of infrastructure. It means that any decision-making methodology of DAPP cannot be deployed and therefore, I would not suggest the implementation of the due structured methodology in highways decision-making, especially when the consideration of climate change evolvement is taken as a triggered factor. In most cases, we cannot observe severe climate changes within 10 years, the average lifespan of road pavements.

On the other hand, bridges are designed in such a way to last on average 100 years, double as much of highways. There could be an interest in the DAPP model consideration in this kind of road infrastructure because of the long lifespan. However, almost, in any case, the bridges’ structure is unique and customized solutions are needed. Although the climate projections and effects would be valid too in every bridge in the Netherlands, the uniqueness of a bridge structure would not allow the application of the structured methodology in this research in a generic way by supporting the same preventive and mitigative measures in every bridge in the Dutch territory. Every bridge has its own needs, no generalized adaptation demands exist like in the road tunnel case.

Importance

The organizations that own assets of a long lifespan require an extensive life-cycle investment plan to ensure the return on investment and the viability of their assets itself in the further future. The importance of the previous consideration was recognized and was the aim of my research to develop a decision-making methodology based on the DAPP model which fulfills the methodological gap by giving a different insight of a structured long-term decision-making planning procedure the moment that adaptation strategies are required due to external influences, in this case, of climate change, and to be dynamic rather than static.

The identification of the DAPP prospects on this domain of asset management made me understand that the first 6 of 10 steps of the model (*Figure I.*) should be of my main interest for exploration now. These steps clearly ask for tools/methods to execute their goals. It seems that until step 6, a structured methodology can be developed and be established as a format methodology for any other road tunnel cases in regions like in the Netherlands. Steps 7 to 10 include activities that policymakers, asset managers, or asset owners can subjectively make their own decisions without necessarily using a specific tool or method. However, further investigation of the steps 7-10 would be important too.

The interested parties of this DAPP methodology are road tunnel owners, infrastructure asset managers, and policymakers as the research are approached holistically for road tunnel systems in the Netherlands. Climate change is one of the top issues currently in any long-term decision-making planning for infrastructure and these parties would be potential favored by this innovative approach that integrates climate crisis into decision-making. It is innovative and feeds for the thought of the involved ones. Moreover, this methodology could, even more importantly, inspire people in this direction to develop alternative practices or upgrade the given methodology.

9.2. Research validation

In this chapter the validation of the research is attempted wondering whether the work result fulfills the initial goal of developing a structured methodology for long-term decision making for road tunnel adaptation on the effects of climate change.

Firstly, my personal reflection on research is presented in *subchapter 9.1.* where I particularly express my opinion regarding the developed methodology on road tunnels adaptation to the future environment conditions (*9.1.1.)* and the method applicability in general in other road infrastructure *(9.1.2.)* and how important is the existence of a methodology for long term adaptation decision-making considering the effects of climate change on significant road infrastructure *(9.1.3.)*. Secondly, the reflection of two more asset management practitioners on the developed methodology is discussed regarding its structure correlating it to the DAPP model *(9.2.),* their point of view on a generalized implementation of this methodology for infrastructure life-cycle decision-making not only for road tunnels but also for other kind of infrastructure *(9.3)* and finally, their reflection on the involved parties which may apply it *(9.4).*

The selection of experts who were invited to participate in the questionnaire for research validation was based on the following criteria:

- An expert that has deep interpretation of the Dynamic Adaptive Policy Pathways model characteristics and purpose for use, an expert who may also have experience on implementing DAPP in the same or different domain.

  ***Nikeh Booister** was invited to be the one of two participators in this validation process. She is currently working as a consultant in water safety, flood risk & climate adaptation in Sweco Netherlands. She works on topics related to policy, planning, strategy related projects in the Netherlands and internationally. Ms. Booister is familiar to applying DAPP in the domain of water management, a characteristic which played a decisive role on being invited to validate the developed methodology.*

- An expert that occupies in the management of road infrastructure assets and recognizes the importance of considering the products of climate change on the lifespan of the assets and the necessity of them being part of long-term decision-making planning to ensure asset's viability over time

  Peter Vermey *is an Infrastructure Asset Manager in Sweco Netherlands in the domain of road assets and he is dedicated to ensuring assets performance and securing the return on investment before and after financial close. He is aware that the climate crisis is one of the major enemies in attaining the viability of assets and believes that the challenge nowadays is the establishment of a decision-making process that not only takes into account climate change but also concludes in reliable results. Therefore, he recognizes the significance of developing such a methodology to support this process with minimal uncertainties.*

The structured methodology of DAPP model

Three questions were asked that are associate with the reflection on DAPP model. More precisely, the DAPP applicability on road tunnel assets, inabilities, capabilities, and comprehensibility of the developed structured methodology are discussed by elaborating and comparing the answers of the experts. These three questions were defined based on my primary consideration to be as more precise as possible about what I am inquiring into this phase to validate my research. By hearing the expert's opinion about integrating these methods/tools, I result in the recognition of methodology's strengths and weaknesses and the identification of potential improvements in the future. The recorded answers are elaborated in *Appendix – subchapter 9.2.*

<u>Question 1:</u> Do you reckon that by using the methods/tools (Hamburger model, Fault Tree Analysis, Criticality Assessment, BowTie Analysis) the steps of Figure I. can be sufficiently reflected to lead to the modelling of adaptation strategies?

> Nikeh Booister argued that although she is aware of the specific methods but not familiar with using them, she believes that the sequence of those steps would lead to the modelling of adaptation strategies. But she reckons that the proposed way would take much time to be executed, it might be a long way to conclude to the adaptation strategies. However, she advocates the selection of those methods whether she deems them necessary to be applied regardless of the long process that needs to be followed. Peter Vermey recognizes that the structured methodology can bring impressive results, mainly because it allows the executor to visualize the outcomes and comprehend them deeper and decide a proper adaptation strategy. Moreover, he believes that the methodology can provide concrete results by Phase I and II, but in Phase III the selected strategy is completely dependent on the subjective opinion of the executor and not mainly a strategy that the methodology concludes itself. Finally, regarding the added value by implementing the BowTie analysis, he reckons it is a good tool to visualize and play with strategies, and therefore acquire more understanding. For Peter Vermey, the most important result is the outputs of Phase I and II about the top risks of the climate crisis for all road tunnels in the Netherlands.

***<u>Question 2:</u>* Regarding the comprehensibility of this methodology, do you reckon that a person, which implements this methodology, could face difficulties in executing the phases?**

Nikeh Booister supports that the less steps are followed the more comprehensible a methodology can be for a person that is willing to execute it. Someone would pinpoint the complexity in executing the steps in each phase because based on her experience the DAPP model is implemented through workshops and sections, which methodology is thought simpler in her mind. However, she points out that the best methodology is the one that achieves better a specific goal. Therefore, she believes that in a different domain beyond the one of water management, another methodology, like this, could be the most appropriate and it would not be such a major issue for someone to understand how to implement these phases. On the other hand, Peter Vermey approaches the question in a different way by advocating that the Phase I and II include steps that someone can learn, execute and bring results but still requires from the executor to understand the sensitivity of their assumptions and in Phase III their creative way of thinking to define a proper adaptation strategy. Peter Vermey concludes that the most demanding aspect of this methodology is the recognition of those sensitive parameters that can change the analysis results in a great way.

***<u>Question 3:</u>* Do you see any prospect of improvement by adding or excluding something on the existing structured methodology of those three phases (in a phase or overall)?**

Nikeh Booister does not focus on proposing the add or exclusion of a method/tool but she reflects her answers on the methodology communication to the people. The visualization of the developed methodology is integral to be done in such a way which clearly shows the methodology steps and if necessary, to allow the reader to dive in more details with the minimal effort. On the other hands, Peter Vermey concentrated on the methodological tools that have been used in this research and points out the necessity of the sensitivity analysis establishment in Phase I and II. He believes that there are more other basic events that potentially cause road tunnel unavailability and the solidity of their frequency assumptions must be, somehow, tested. By adding sensitivity analysis, the methodology would become more trustful and people would be more certain about their adaptation decisions. Moreover, the cost benefit analysis of the proposed actions is quite important mainly because of the main interest in the investment resources that might be eventually required and he also supports the necessity of methodology's visualization by approving the depiction of the adaptation strategy into maps.

The answers on these three question conclude that the structured methodology is believed to be capable to model adaptation strategies, even though the experts pointed out that the process seems to be extensive by following this sequence of methods and tools and they remarked on the actual contribution of BowTie diagrams as neutral. However, the acceptance of this extensive methodology might be relied on the potentially promising resulting strategy in clear visualized way. Regarding the comprehensibility, both experts reckon that the executors would not face difficulties to handle the methodology and become easily familiar to using it. Finally, the weaknesses that were remarked are suggestions for improvement. Sensitivity analysis of the significant input parameters, the analysis of the link between costs and benefits by implementing the proposed strategic measures and the consideration about optimum people communication within the methodology execution are the suggested adding.

Generalized implementation for LC decision-making

Two questions were asked that are associate with the reflection on generalized implementation for LC decision-making. My primary consideration was also in this case to be as more precise as possible about what I am inquiring into this phase to validate my research. By hearing the expert's opinion about potentially generalized implementation of this developed structured methodology for Life Cycle decision-making of road tunnel infrastructure and for other kind of road infrastructure as well, I result in to assess the suitability of DAPP model in road infrastructure life cycle adaptation on the effects of climate crisis. The recorded answers are elaborated in *Appendix – subchapter 9.3.*

<u>Question 4:</u> DAPP is widely known in Water Management. What is your point of view regarding the use of DAPP for life cycle decision-making in road tunnel infrastructure management? What about when this use aims the asset's adaptation on the upcoming effects of climate change?

> Nikeh Booister advocates that the structured methodology based on the DAPP approach might be a useful tool for life cycle decision-making in road tunnel infrastructure adaptation in climate effects. It is important for her the road infrastructure being considered in long term horizon terms because the surrounding environment is changing in a long-term way. Moreover, she recognizes the scientific value of my research in the methodological decision-making theory taking into consideration the climate crisis in the Netherlands mainly due to the importance to involve the upcoming effects of climate change in every infrastructure management from now on. The same consideration is expressed by Peter Vermey too, who reckons that the research on DAPP model can give new perspective for life cycle decision-making in road tunnel asset management which is able to address the effects of climate change.

<u>Question 5:</u> Would you agree and why/why not that there would be a difference in implementing the DAPP model in road infrastructure management in general (e.g. bridges,* highways*)?

> Nikeh Booister reckons that there should not be a difference in implementing the DAPP model in other kinds of road infrastructure, because the decision-maker would be favored by using a common methodology for all kinds of road infrastructure, a methodology which can be future-proof. However, Peter Vermey supports that the DAPP is not suitable for every kind of road infrastructure. He does not recognize any value when implementing DAPP in highways comparing to road tunnels because of the short lifespan of the highways and the usability of DAPP for long-term decision-making processes. Moreover, road tunnels are more complex assets of more than 100 years' lifespan and they can accept many little changes over time, so decisive actions are required. Regarding bridges, DAPP needs to be implemented in a customized way, not in a generic one like that we are looking for, due to the peculiarities of every single bridge structure.

The conclusion of those two questions' responses lies on the fact that experts recognize the importance of implementing long-term adaptation planning for road infrastructure mainly because they are integrated into the urban environments that require long-term planning too. Both experts recognize the importance of integrating the climate changes effects in the road infrastructure domain too. However, they point out that this structured methodology would benefit mostly long-service life assets like tunnels and potentially bridges and not highways.

Interested parties

Only one question was intentionally defined to inquire into the interested parties by implementing this structured methodology. It is very important to know the grade of acceptance of the methodology by relevant parties. The experts called to recognize any incentive or discouragement for asset manager to use it.

<u>Question 6:</u> Do you recognize any incentive (or discouragement) for the asset managers to implement thoroughly this structured methodology of the DAPP model for road tunnel asset long-term adaptation planning on the effects of climate change and why?

> Nikeh Booister reckons that it is a discouragement for an asset manager to implement this DAPP structured methodology mainly because it is a new approach, something different which requires time to become familiar to it, and in general when someone starts working based on a new and different way of working, it is also costly. Even in case of willingness to implement it, organizations care mainly to save money, and therefore they must be convinced of the necessity of executing frequent adaptation works in the future. They prefer to complete any adaptation activities as sooner as possible because in most cases the political aspect plays a decisive role in the way a public-use road asset is adapted to the new demands, choosing the most economically advantageous options. On the other hand, the view of Peter Vermey in this question is slightly different. He believes that when something new is invented which solves the problems of existing methodologies, like an innovative decision-making methodology, then an asset manager would be willing to implement it. Otherwise, if he/she does not recognize the added value, then it is a discouragement for them to explore this new methodology mainly because of the same reasons as Nikeh Booister supported, it demands lots of time, requires money, and also the asset managers are called to convince the asset organization about the benefits the new approach is capable to give.

9.3. Conclusion

The research results were presented in this chapter by explaining the innovation on the road tunnel life cycle management process when Dynamic Adaptive Policy Pathways are implemented under the climate change uncertainty. A discussion on the developed methodology, method applicability, and its importance took place in *subchapter 9.1*. Moreover, the validation of the research work (*subchapter 9.2*.) by interviewing two decision-making experts was thought to be very important in this final phase. The developed methodology of the DAPP model is reflected as comprehensible and capable to model adaptation strategies, a potential generalized implementation of that methodology for life cycle decision-making of other road infrastructure would be suggested for the long-service life ones mainly and the interested parties would find this methodology appealing whether they are convinced about the necessity of taking regular adaptation actions and that existing problems can be apparently solved.

Therefore, associating the content of *9.1.* and *9.2.,* the third part of the *Sub Question 3: ''To what extent do these pathways result in decision-making information that policymakers might use?''* was replied and *Phase III* was completed. Moreover, it inspires the recommendations for further research (*10.2.)* and consequently, this graduation research is finalized.

10. Research conclusion

In this chapter, the conclusions from the research work are described. In *subchapter 10.1.* the answer to the main research question is given and as well as to the three sub-questions based on the outcomes of every phase of the methodology that is developed. Recommendations for further research are given in *subchapter 10.2.* on improving the developed methodology and conducting further methodological exploration of the rest DAPP model steps 7-10.

10.1. Answer to research question

This research aims to give an answer to the following main research question:

To what extent can Dynamic Adaptive Policy Pathways be deployed for the life cycle management of road tunnel infrastructure mitigating the long-term effects of climate change to result in useful decision-making information?

Nowadays, the life cycle management of road infrastructure is challenging especially for assets like road tunnels that their service life lasts more than a century and little changes in their structure can be imposed. The climate crisis is the enemy of road tunnels because it tends to affect their function performance endangering eventually their viability in the long-term horizon. It seems that developing a methodology based on the terms of the DAPP approach, an alternative long-term decision-making process for road tunnel adaptation to the effects on climate change can be achieved in a dynamic way rather than a static one. This structured methodology, which is developed and presented here, gives the flexibility the decision-makers require on the timing of their future adaptation actions. The adaptation maps of the DAPP model visualize a road tunnel adaptation strategy which mitigates the ongoing effects of climate change by indicating the tipping points for adaptation as period ranges and not as a specific future date. In that way, the decision-maker is getting aware of when to expect the proposed measures to be taken as this decision is dependent on the exact climate that will exist at that future moment. So, the decision-maker is capable to handle this uncertainty. Therefore, the research outcome concludes that this structured methodology based on DAPP would positively contribute to useful decision-making information because the research results seem more effective than the ones of the currently applied decision-making practices. The added value of the DAPP approach lies in its flexible character compared to the to date practices, which mainly define robust adaptation actions that deal with any extreme future and propose strict implementation times. By paying extra attention to the sensitivity of the assumptions and the feasibility of the proposed measures/actions, the decision-making methodology can be improved. The answers in the following sub-questions are given by having executed the phases of the proposed long-term decision-making process for road tunnel adaptation on the effects of climate change:

1. *Sub-question 1: What are the functions of a road tunnel and to what extent can future climate change impact the system's functional failure?*

Phase I deals with the execution of steps 1-2 of the DAPP approach (Figure I). The Functional Breakdown Structure analysis of a road tunnel was the initial step of the methodology. The functions of a road tunnel are characterized as Functional requirements and five main functions were identified: Assimilating traffic flow, Providing route flexibility, Connecting with the road network traffic management facilities, Facilitating communication, and Future-proofing system's prosperity. Further analysis of the functions through the execution of functional decomposition with the Hamburger model allowed me to develop the failure mode structure of these functions through a Fault Tree analysis. At that point, having executed a thorough analysis of the climate variables and having correlated them with the road tunnel system, based on the projections of the W_H climate scenario of KNMI'14 report in 2050 and 2085, I was able to define the basic events that cause road tunnel unavailability when a specific function cannot be fulfilled anymore. Therefore, the contribution of every basic event in the unavailability rate of a road tunnel from every function in four different time periods was aimed to be defined as well as the corresponding potential impact on the tunnel's organization values (safety, social environment, asset quality, finance, reputation, availability). This outcome indicates the extent of future climate change effects on the failure mode of the road tunnel system's functions and conclude to 40 out of 59 identified basic events that require preventive and/or mitigative measures.

2. *Sub-question 2: What actions could be taken to prevent functional failures and mitigate consequences?*

Phase II deals with the execution of steps 3-4 of the DAPP approach (Figure I). The actions are defined based on the outcome of Phase I about the basic events that are concluded as the ones which impose the definition of preventive and/or mitigative measures to deal with these potential functional failures and consequences respectively. For these basic events, adaptation measures for cause prevention and adaptation measures for impact mitigation were defined, up to 4 different measures, one for each analysis period, and were presented with BowTie diagrams to visualize the correlation of the basic events with the proposed adaptation measures and with the respective category of impact on organization values. Therefore, the outcome of this phase was the definition of 23 preventive and 61 mitigative measures. The selection of the ones which are to be included in the adaptation strategy is executed in Phase III which gives the answer to the following sub-question 3.

3. *Sub-question 3: What are the potential dynamic pathways that model the life cycle adaptation strategies? Which ones are preferred to be followed and to what extent do these pathways result in decision-making information that policymakers might use?*

In Phase III, I execute the steps 5-6 of the DAPP approach. I choose the preventive measures, which I had proposed in Phase II, that I am going to include in my life cycle adaptation strategy of the road tunnels, and I put them in implementation order based on my preference and belief that this is the correct way. I do the same in the case of mitigative measures as well. About the latter, firstly I must estimate their actual positive contribution to preserving the organization values by scoring them and then to choose the one with the higher score. I reckon that this is the optimum way to decide which of the available options for impact mitigation, which deal with the same problem, to choose. Subsequently, I group both the preventive and mitigative measures into respective action sets, which are going to be executed at the same time range in the future, and then I reflect them in preventive and mitigative adaptation maps. By presenting them as potential dynamic pathways, I model the potential life cycle adaptation strategies by choosing my preferred strategy and depicting the execution order of my selected action sets with black dotted lines. It is important to say that some action sets are executed in parallel during the period analysis. Finally, the answer to whether the pathways' outcome results in decision-making information that policymakers might use in practice derives from the validation process that I executed by interviewing two experts. They conclude that the developed methodology on DAPP can bring impressive results, mainly because it allows the executor to visualize the outcomes even though it might be a long way to conclude to the adaptation strategies. Therefore, these pathways can result in useful decision-making information whether the sensitive parameters that can change the analysis results in a great way are recognized and special attention is paid to them when formulating assumptions for them, for example the frequency assumption of a specific basic event.

10.2. Recommendation for further research

1. Current developed methodology
    - ❖ Phase I is the main body of the current methodology where the FBS of a road tunnel system is executed to correlate failure modes and climate variables. Moreover, this phase is characterized by a plethora of assumptions that decision-makers must do to define frequencies, potential time for recoveries if failure happens, and then quantify the unavailability rates which are valuable for further steps. Therefore, the execution of sensitivity analysis in this methodology part is integral. The executors must recognize how sensitive are the phase's results by defining specific basic events, they must be certain to cover as more as possible potential basic events and finally, they must be certain about their quantitative assumptions. Consequently, by conducting sensitivity analysis, more solid and robust the results of this phase will be.
    - ❖ Phase III includes, among others, the assessment of the proposed mitigative measures about the actual positive contribution on preserving the organization values of a road tunnel system. In the due methodology, it is executed by the decision-makers based on their experience and expertise to assess them. However, the execution of cost benefit analysis would add an extra value to the solidity of the finally selected mitigative measure to be included in the adaptation strategy. This kind of analysis could be also implemented in the preventive measures' selection process.

2. Continuation of DAPP steps
    - ❖ The DAPP model consists of 10 steps and this graduation research was conducted for the execution of the first 6 steps. I recommend that further research analysis should be continued to conclude whether a concrete methodology can execute the steps 7-10 or the realization of those steps is only an act of personal decision-making process without the use of a method or tool to support this process and consequently, to complete the methodology. Moreover, an attempt of finding out an alternative and less extensive structured methodology for long-term adaptation decision-making processes to deal with the effects of climate change would be recommended.

References

Auld, H., MacIver, D., & Klaassen, J. (2006). Adaptation Options for Infrastructure Under Changing Climate Conditions. *2006 IEEE EIC Climate Change Conference*, (pp. pp. 1-11). Ottawa, ON. doi:10.1109/EICCCC.2006.277248

Barnett, J., & O'Neill, S. (2010). Maladaptation. *Global Environmental Change 20*, 211-213.

Bles, T., van der Doef, M., van Buren, R., J.T. , B., R.J. , B., Venmans, A., & van Meerten, J. (2012). *Investigation of the blue spots in the Netherlands National Highway Network.* Delft: Deltares.

Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, 137-150. doi:https://doi.org/10.1016/j.polsoc.2016.05.002

Deltares. (2018). *Bijlagen bij het rapport: Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma. Een verkenning.* Delft: Deltares. doi:11202230-005-BGS-0002,

Espinet, X., Schweikert, A., & Chinowsky, P. (2015). Robust Prioritization Framework for Transport Infrastructure Adaptation Investments under Uncertainty of Climate Change. *American Society of Civil Engineers*. doi:10.1061/AJRUA6.0000852.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2012). Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Springer*, 411–423. doi:10.1007/s10584-012-0494-5

Gram, R. (2012). *RWS Landelijke Tunnelstandaard - Implementatie in nieuwe en bestaande tunnels.* Rijkswaterstaat.

Grendstad, G. (2013). Adaptation to climate change - Project Group on Climate Change – task 16 . *Conference of European Directors of Roads* (p. 42). Oslo: CEDR's Secretariat General .

Groves, D. G., Molina-Perez, E., Bloom, E., & Fischbach, J. R. (2019). Robust Decision Making (RDM): Application toWater Planning and Climate Policy. In V. A. Marchau, W. E. Walker, P. J. Bloemen, & S. W. Popper, *Decision Making under Deep Uncertainty, from theory to practice* (pp. 135-163). Cham, Switzerland: Springer. doi:https://doi.org/10.1007/978-3-030-05252-2

Haasnoot, M., Kwakkel, J., Walker, W., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change 23*, 485-498.

IAM. (2015). *Asset Management - An Anatomy Version 3.* Bristol,UK: Institute of Asset Management.

Kenny, S., Dupré, K., & McEvoy, A. (2018). Climate change considerations within the asset management of core infrastructure for rural Ontario Municipalities - an initial assessment. *Building Tomorrow's Society,*.

Kind, J. M., Baayen, J. H., & Wouter Botzen, W. (2018). Benefits and limitations of real options analysis for the practice of river flood risk management. *Water Resources Research, 54*(4), 3018 - 3036.

KNMI. (2014). *KNMI'14: Climate Change scenarios for the 21st Century - A Netherlands perspective.* De Bilt: Koninklijk Nederlands Meteorologisch Instituut. Retrieved from www.climatescenarios.nl

KNMI. (2015). *KNMI'14 climate scenarios for the Netherlands - A guide for professionals in climate adaptation.* De Bilt, Netherlands: KNMI.

Kwakkel, J., Haasnoot, M., & Walker, W. (2016). Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software 86*, 168-183.

Ligtvoet, W., van Minnen, J., & Franken, R. (2013, March 18). *The effects of Climate Change in the Netherlands: 2012.* Retrieved from PBL Netherlands Environmental Assessment Agency: https://www.pbl.nl/en/publications/the-effects-of-climate-change-in-the-netherlands-2012

Lindsey , R., & Dahlman, L. (2020, January 16). *Climate Change: Global Temperature*. Retrieved from Climate.gov: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Lindsey, R. (2020). *Climate Change: Atmospheric Carbon Dioxide*. Retrieved from www.climate.gov: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Marijke , V., Bouwman, A., van Dorland, R., & Eerens, H. (2015). *Worldwide climate effects Risks and opportunities for the Netherlands.* The Hague: PBL Netherlands Environmental Assessment Agency.

Mater, J. (2016). Carbonation in Concrete Infrastructure in the Context of Global Climate Change: Model Refinement and Representative Concentration Pathway Scenario Evaluation. *Journal of Materials in Civil Engineering, 28*(4).

Meyer, M. D., Amekudzi, A., & O'Har, J. (2010). Transportation Asset Management Systems and Climate Change, Adaptive Systems Management Approach. *Journal of the Transportation Research Board, No. 2160*, 12-20. doi:DOI: 10.3141/2160-02

Ministry of Transport and Water Management. (2013). *Regeling aanvullende regels veiligheid wegtunnels*. Retrieved from www.wetten.overheid.nl: https://wetten.overheid.nl/BWBR0019806/2013-07-01#Artikel2

Mondoro, A., Frangopol, D. M., & Liu, L. (2017). Bridge Adaptation and Management under Climate Change Uncertainties: A Review. *American Society of Civil Engineers*. doi:10.1061/(ASCE)NH.1527-6996.0000270.

Mueller, K., & Straatmann, T. (2014). Organizational Values. (A. Michalos, Ed.) *Encyclopedia of Quality of Life and Well-Being Research, Springer*.

NAMS. (2011). *International Infrastructure Management Manual. (International ed., 4th ed) Institute of Public Works Engineering Australia.* Wellington, National Asset Management Steering NAMS Group.

Nicholas, J., & Steyn, H. (2017). Project Management for Engineering 5th edition. In G. K. Chesterton, *Chapter 10: Project Risk Management* (p. 747). New York: Routledge.

Pakkala , T., Köliö , A., Lahdensivu , J., & Pentti , M. (2015). The Effect of Climate Change on Freeze-Thaw Cycles in Nordic Climate. (G. J. Andrade C., Ed.) *Durability of Reinforced Concrete from Composition to Protection*.

Pereboom, D., van Muiswinkel, K., & Bles, T. (2016). Risk Assessment of Highway Flooding in the Netherlands. In J.-M. Torrenti, & F. La Torre, *Materials and Infrastructure 2 Volume 5B* (pp. 177-192). London, UK: ISTE Ltd.

RAND.org. (2020). *Robust Decision Making*. Retrieved from https://www.rand.org/topics/robust-decision-making.html

Ranger, N., Reeder, T., & Lowe, J. (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO J Decis Process*, 233-262. doi:DOI 10.1007/s40070-013-0014-5

Rijkswaterstaat. (2016). *Systeemspecificatie RWS Tunnelsysteem.* RWS.

RWS. (2020). *Landelijke Tunnelstandaard*. Retrieved from www.rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/zakelijk/werken-aan-infrastructuur/bouwrichtlijnen-infrastructuur/aanleg-tunnels/landelijke-tunnelstandaard/index.aspx

Sayers, P. B., Galloway, G. E., & Hall, J. W. (2012). Robust decision making under uncertainty - Towards adaptive and resilient flood risk management infrastructure. In P. B. Sayers, G. E. Galloway, & J. W. Hall, *Flood Risk* (pp. 281-302). London: ICE Publishing. doi:http://dx.doi.org/10.1680/fr.41561.281

Stewart, M. G., Wang, X., & Nguyen, M. N. (2011). Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structures 33*, 1326–1337.

Sutton, I. (2010). Consequence and likelihood analysis. In *Process Risk and Reliability Management: Operational Integrity Management* (pp. 191-276). Oxford,UK: William Andrew.

van den Boomen, M. (2020). *Replacement optimisation for public infrastructure assets: Quantitative optimisation modelling taking typical public infrastructure related features into account.* Delft: Delft University of Technology. doi:10.4233/uuid:3cef9da8-d432-4d6a-8805-4c094440bd56

van den Boomen, M., Spaan, M., Shang, Y., & Wolfert, R. (2020). Infrastructure maintenance and replacement optimization under multiple uncertainties and managerial flexibility. *Construction Management and Economics, 38*(1), 91-107. doi:10.1080/01446193.2019.1674450

Vesely, W., Dugan, J., Fragole, J., Minarick, J., & Railsback, J. (2002). Fault tree handbook with aerospace applications. *NASA Office of Safety and Mission Assurance*.

Walker W.E., W., Lempert R.J., R., & Kwakkel, J. (2013). Deep Uncertainty. *In: Gass S.I., Fu M.C. (eds) Encyclopedia of Operations Research and Management Science. Springer*.

Walker, W., Haasnoot, M., & Kwakkel, J. (2013). Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability*, 955-979. doi:10.3390/su5030955

World Bank Group. (2017). *Integrating Climate Change into Road Asset Management.* Washington, DC 20433, USA: World Bank Publications.

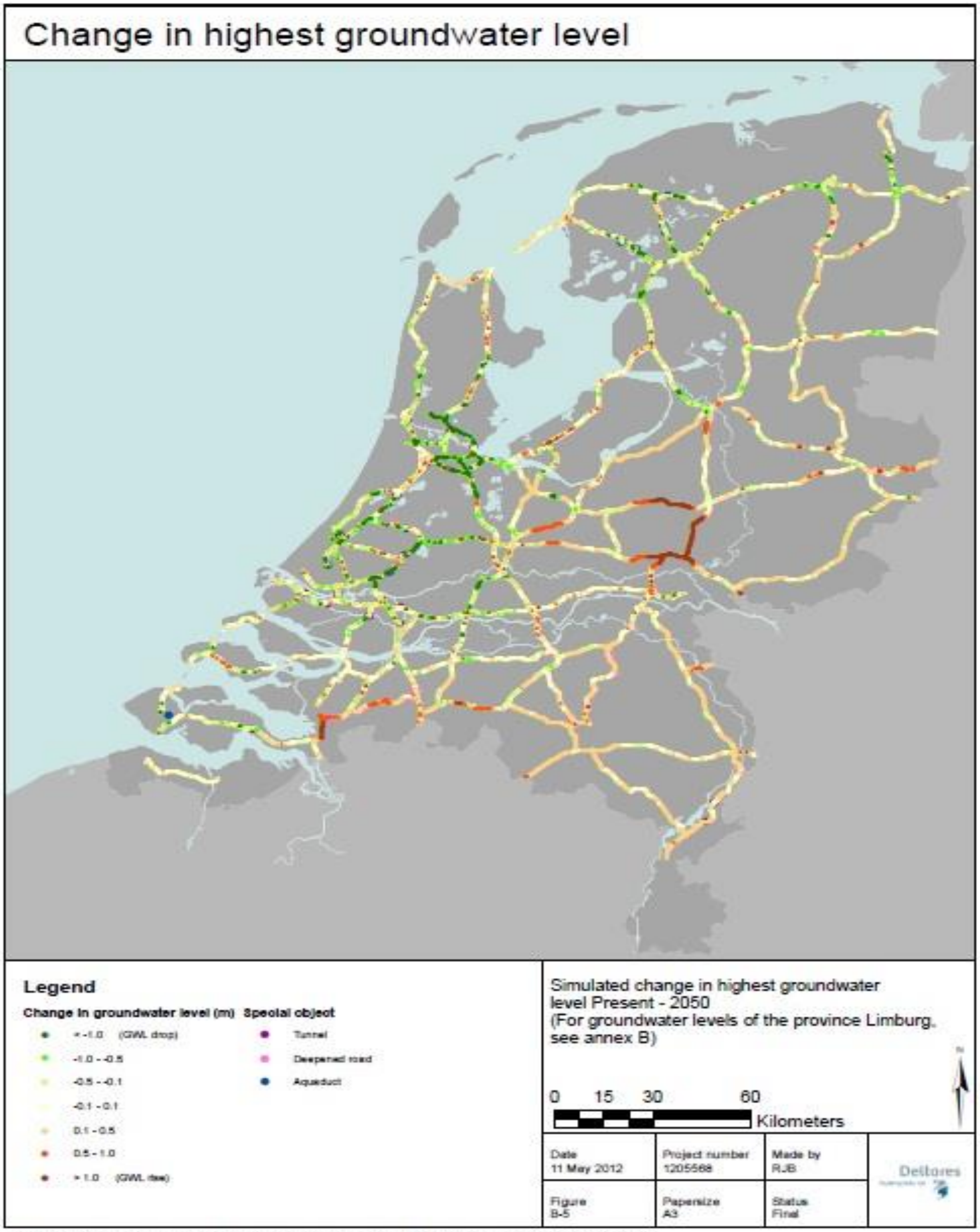
Xie, H.-B., Wang, Y.-F., Gong, J., Liu, M.-H., & Yang, X.-Y. (2018). Effect of Global Warming on Chloride Ion Erosion Risks for Offshore RC Bridges in China. *KSCE Journal of Civil Engineering, 22*(9), 3600-3606. doi:DOI 10.1007/s12205-018-1547-8

Yaning , Q., Medina, R., Myers McCarthy, L., Mallick, R., & Daniel, J. (2017). Decision Tree for Postflooding Roadway Operations. *Transportation Research Record: Journal of the Transportation Research Board No2604*, 120-130. doi:https://doi.org/10.3141/2604-15

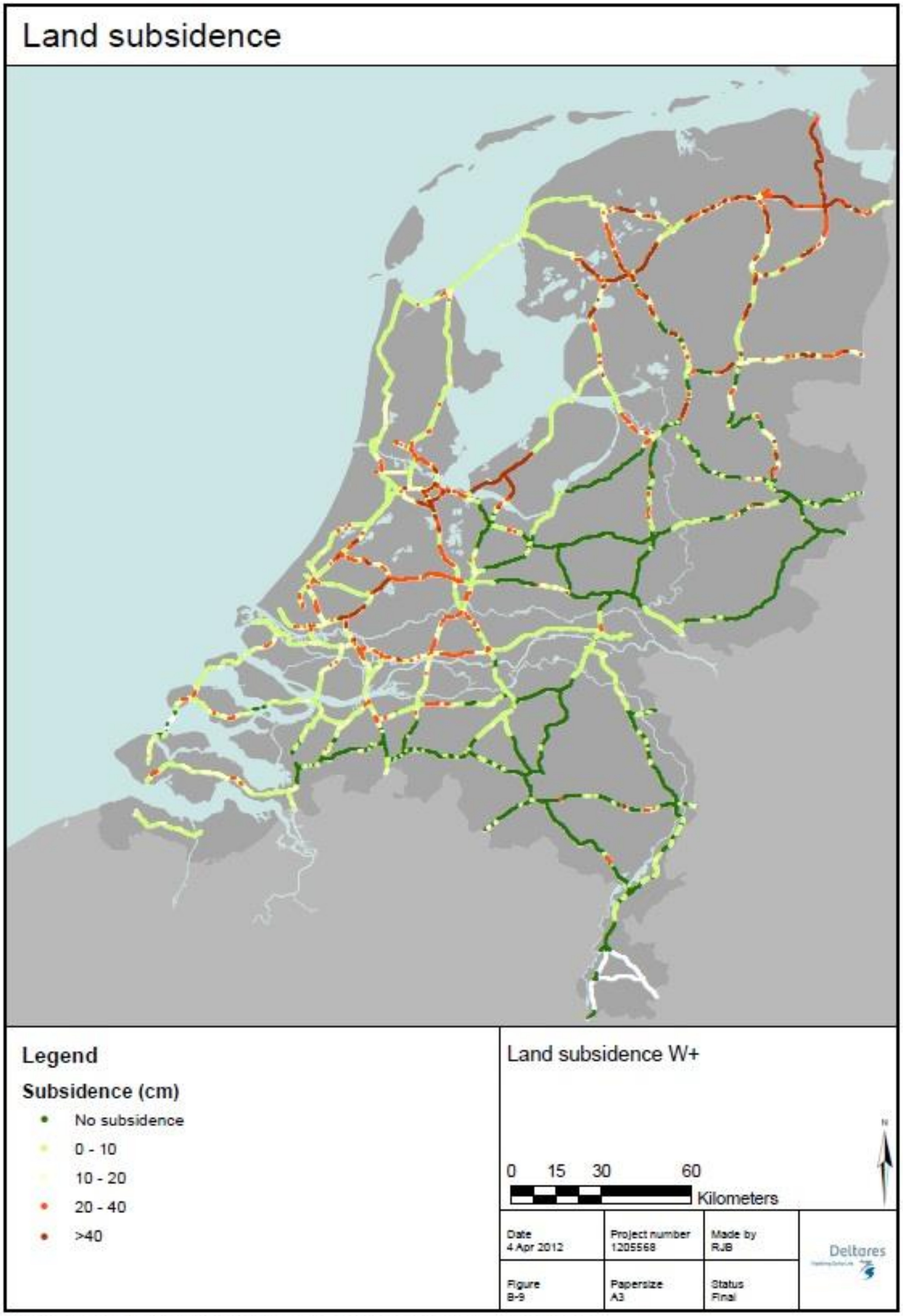
Zaal, T. M. (2009). *Integrated design and engineering: as a business improvement process.* Maj Engineering Publishing.

Appendix

Appendix – subchapter 3.4.



Report 'Investigation of the blue spots in the Netherlands National Highway Network', 1205568-000-GEO-0007, version 2, May 2012
Client: Rijkswaterstaat - Centre for Transport and Navigation



Report 'Investigation of the blue spots in the Netherlands National Highway Network', 1205568-000-GEO-0007, version 2, May 2012
Client: Rijkswaterstaat - Centre for Transport and Navigation

Appendix – subchapter 4.1.

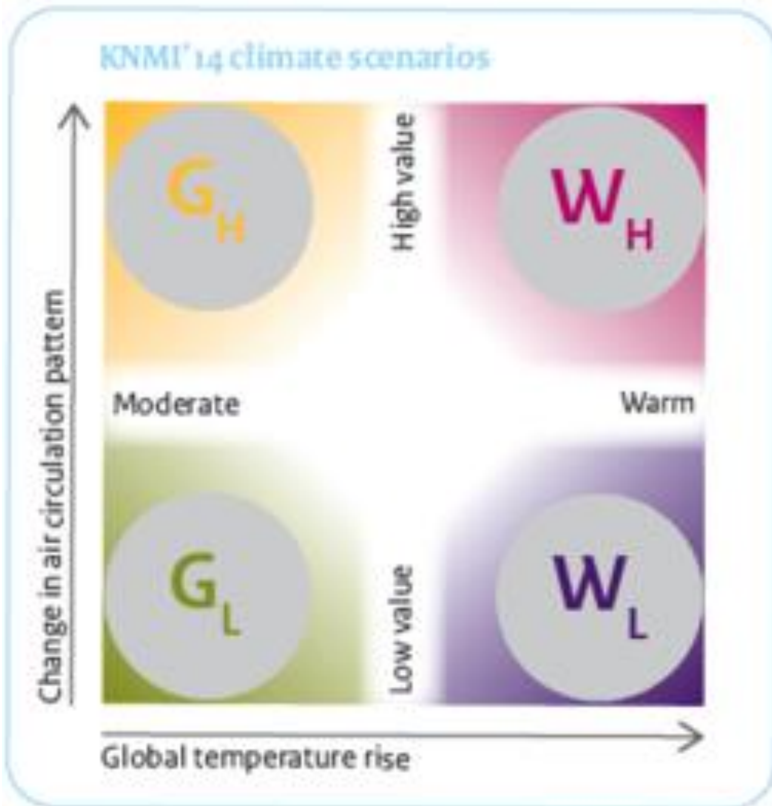


Fig 1 Climate scenarios of KNMI

The IPCC scenarios for the future greenhouse gases emissions and pollutants (RCP 8,5: high emissions, RCP4,6: emissions stabilization) allow KNMI to estimate the future temperature increase, in G case by about 1^{o}C in 2050 and 1,5^{o}C in 2085 relative to the 1981-2010 period. On the other hand, in W case, the temperature rise will be 2^{o}C in 2050 and 3,5^{o}C in 2085.

Several observation stations are used in the Netherlands by KNMI to determine the climate normal and the natural variability for each climate variable in 30-year time scale. Sea level is the only climate variable that KNMI does not possesses its own observations but relies on data collected by PSMSL. 6 stations along the Dutch coastal line tracks a record for the sea level since 1901. Moreover, 5 different stations are been using for mist observations since 1956. One single observation station in De Bilt is used for temperature, precipitation, solar radiation, evaporation, and drought and one in Den Helder for wind records with a different observation starting point for all of them. More precisely, the temperature values cover the period 1901-2013, includes daily average, minimum and maximum and is thought the longest record has been made by KNMI, the precipitation intensity and wind direction recorded values refer to the time period between 1906-2013 and wind speed since 1981, the solar radiation and evaporation observations start many years later and cover the period 1958-2013, the same for precipitation deficit (drought) by starting in 1951 and mist in 1956. However, mist observations end in 2002.

The 30-year period of KNMI'14 report presents climate normal for ''1951-1980'' and ''1981-2010'' periods which are not necessarily correspond timely with the recorded values of some variables. The solar radiation and evaporation normal for ''1951-1980'' are calculated for their measured period ''1958-1980''. Similarly, the mist normal is calculated for the years ''1956-1980'' but refers to the years ''1951-1980''. Finally, the mist normal of the ''1981-2010'' period is actually calculated for ''1981-2002'' because 2002 is the year when the value measuring stops.

Appendix – subchapter 4.2.

Impacts on climate variables

Temperature

Since 1901, KNMI has been keeping track of the temperature variations in the region of De Bilt in Utrecht, and valuable information has arisen regarding temperature trends up until the year 2013. The record shows an average increase of 1.8°C, exact double as the average global warming-up which was witnessed between 1880-2012 over the land and sea surface. There is worth mentioning how great the temperature changes in the country are the moment that the last 15 years of that period, the global gradual temperature rise was relatively slow. *Figure XXXIII* depicts the non-linear temperature variation and development over the aforementioned time frame. A LOESS is presented by a bold line to point out the trend. The major rise was observed after the second half of the 20th century (since 1951) consisting the 1.4°C of the total average. Generally, the land warms up faster than the sea. During the winter months in the Dutch territory, the temperature has been milder as a result of more frequent western winds, and on the other hand during the summer period, the temperature has been elevated because of solar radiation rise (KNMI, 2014).

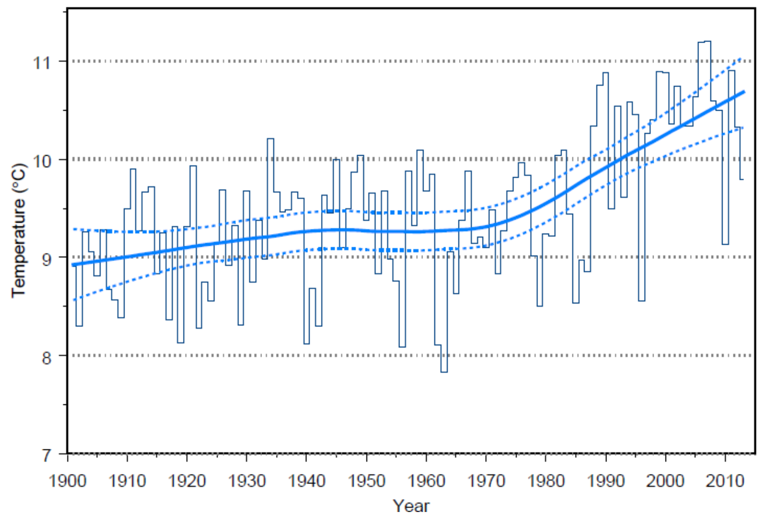


Figure XXXIII: Annual mean temperature in De Bilt 1901-2013 and a LOESS bold line (KNMI, 2014)

Temperature projections has been forecasted by KNMI based on the data of temperature evolution during the previous century and the development of these four climate scenarios. *Figure XXXIV* visualizes the, almost 100-year, temperature observations into three 30-year averages in blue line plus the forecasted average temperatures resulted from the four climate scenarios of 2050 and 2085 in the winter and summer season within their range of temperature variation. In KNMI'14 report, the reference time is the period 1981-2010 and two more scenario time horizons are defined. The period 2050 refers to 2036-2065 and estimates a Global Mean Temperature Response (GMTR) of 1-2°C and period 2085 to the years 2081-2100 and forecasts GMTR of 1.5-2°C. In both 2050 and 2085 projections, the lower limit of temperature range is about the ''G'' group scenario and the upper one about the ''W'' group scenario (KNMI, 2014).

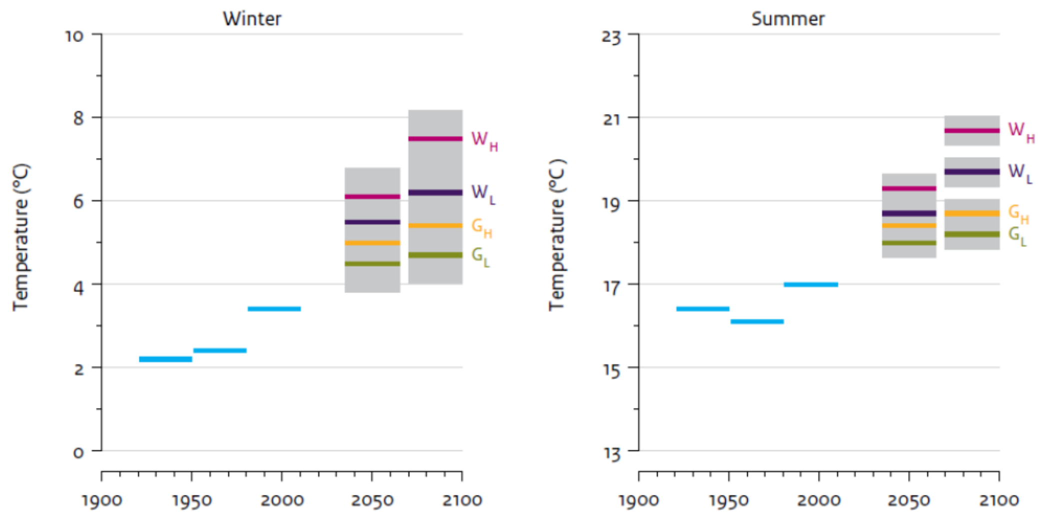


Figure XXXIV: Winter and summer average temperatures of 1901-2013 observations into three 30-year periods and average temperatures of the four KNMI'14 climate scenarios of 2050 and 2085 projections within their range of temperature variation (grey) in De Bilt, Netherlands (KNMI, 2014)

In the Netherlands, the temperature will continue its upward trend for all four KNMI’14 scenarios (G_L, G_H, W_L, W_H) showing a slightly higher increased valued during the winter months compared with the other seasons. The summer season will also experience more frequent and hotter days. The KNMI’14 scenarios of wetter winters and drier summers (G_H and W_H) estimate that the global warming average will be considerably smaller than the one of the Netherlands. As a result, the Dutch winters will have fewer ice days where the minimum temperature is below zero and even fewer ice days of maximum zero Celsius temperature degrees. Moreover, the temperature differences between the upcoming winters will have been gradually declining because of the minimization of ice days. Concerning the summers, the differences will have been increasing as the summers are getting warmer. KNMI points out the occurrence of extreme temperatures during summers similar of tropical ones (KNMI, 2015).

The Dutch territory will experience regional temperature differentiation. The unprecedented differences in summer temperatures in the northern and southern parts will be the most intense in the extreme KNMI’14 scenario of W_H, with the southern part is getting warmer. Therefore, the temperature of inland is getting warmer than the coastal one. However, the winters are warming up more in the eastern than in the western which consequently means that the existing regional differentiation in temperature is declining (KNMI, 2015).

Precipitation

The precipitation volume has also shown an extreme increase since 1901. The planet warming up contributes to more quantity of water to vapor, especially since the 1970's, all over the world. The annual amount of precipitation has been increased rapidly by 14% in the Netherlands since the 1950's reaching a total rise of 26% since the start of the 20th century. Consequently, all the seasons except summer have become wetter since the days with more than 10mm and 20mm of precipitation in winter and summer respectively have increased.

Figure XXXV depicts the chronological development of precipitation volumes and a LOESS linear regression fit underlines this trend during the years. The total average increase is found 178.6mm between the time threshold values. The coastal areas in the Netherlands seem to experience higher changes rather than in the inland territory. It has been observed that the precipitation rise is causing mainly because of an increasing trend of exceeding the moderate precipitation thresholds of a year. The precipitation development arouses lots of interest because the hourly intensity of the most extreme rainfalls rises by about 12% per degree of temperature. Precipitation and temperature are found out mutually dependent.

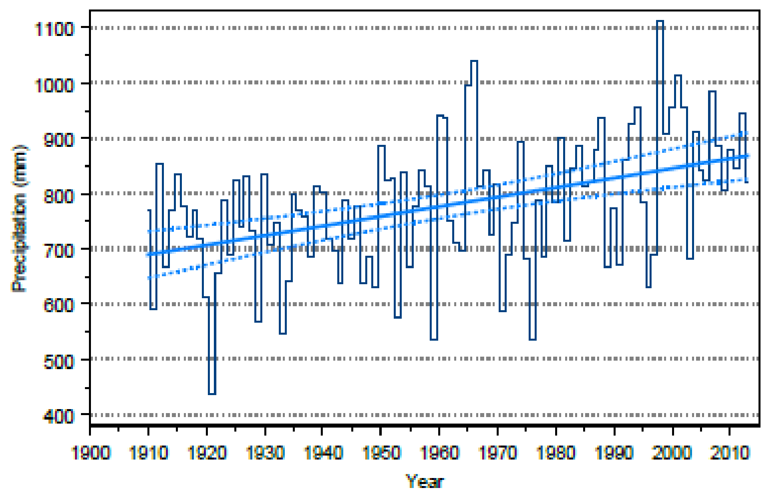


Figure XXXV: Annual mean precipitation in De Bilt 1901-2013 and a LOESS bold line (KNMI, 2014)

The future is forecasted quite complex regarding the precipitation evolvement. Although in all seasons there is an increase, in summer the conditions are unclear. Two of the scenarios (G_L and W_L) anticipate a small increase and on the other hand, the other two (G_H and W_H) show the exact opposite. KNMI indicates the airflow pattern and soil drying out as main determinants for that variation.

Between the scenarios of 2050 and 2085, precipitation of the climate projection W_H points out major volume differentiation both in winter and summer (*Figure XXXVI).* Moreover, during the summer days, extreme showers of more than 20mm may either decrease or increase, although the occurrence of heavy rainfalls is shown to increase in all scenarios. However, a subtle difference in precipitation is noticed between coast and inland which is estimated by about 10%. Therefore, the focus on the most extreme W_H is justified by the aforementioned differentiations and variations.

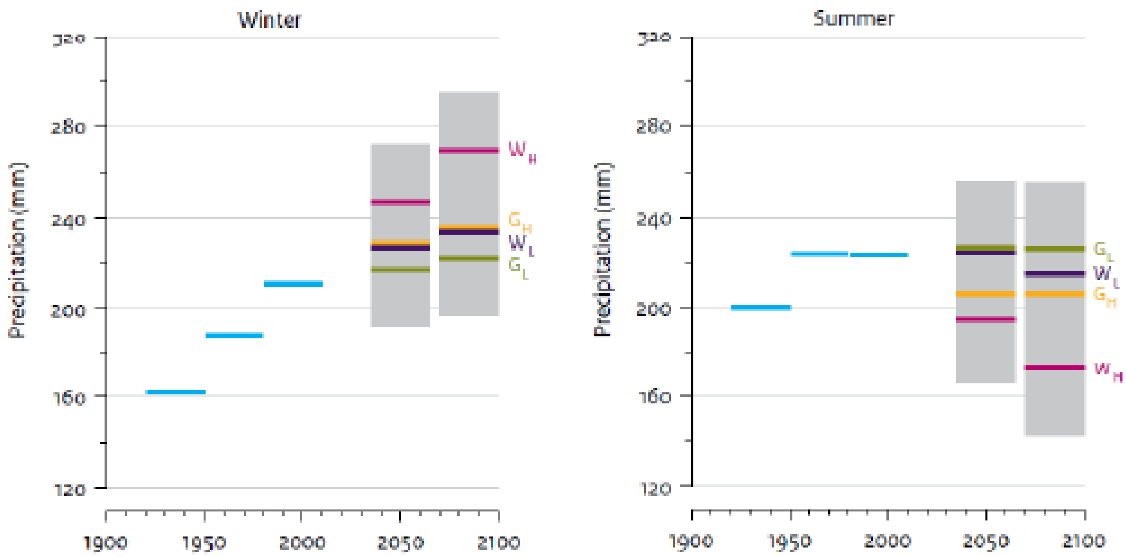


Figure XXXVI: Winter and summer average precipitation of 1901-2013 observations into three 30-year periods and average precipitation of the four KNMI'14 climate scenarios of 2050 and 2085 projections within their range of precipitation variation (grey) in De Bilt, Netherlands (KNMI, 2014)

Wind

Wind speed observations over the last 140 years have shown no visible and comprehensive tendency regarding storminess (high winds) and windiness (mean winds) development in the Southern North Sea. Non-direct long-term observation scarcity and unavailability of measurements over the open sea are some issues which can be proved prone to errors. However, through consistent and precise air pressure measuring, an upward trend of the annual average wind speed was observed after the middle of 20th century, reaching the peaks noticeably at the end of 19th and 20th century as it is depicted in *Figure XXXVII.* It worth of mentioning that the strength of westerly winds rose in moderate latitudes of the Northern Hemisphere.

The same observations have made on the number of storms per year. In the middle century and since 2000, there is a decrease of storm incidents above the North Sea. The peak of storm frequency happens at the beginning and end of the previous century (*Figure XXXVII*.). Regarding the inland wind observations between early 1960's and 2000's the surface winds have been shown a downward trend in the Northern Hemisphere and consequently in the Netherlands. Experts support that the increasing building development has changed the land surface roughness and consequently has contributed to the calming

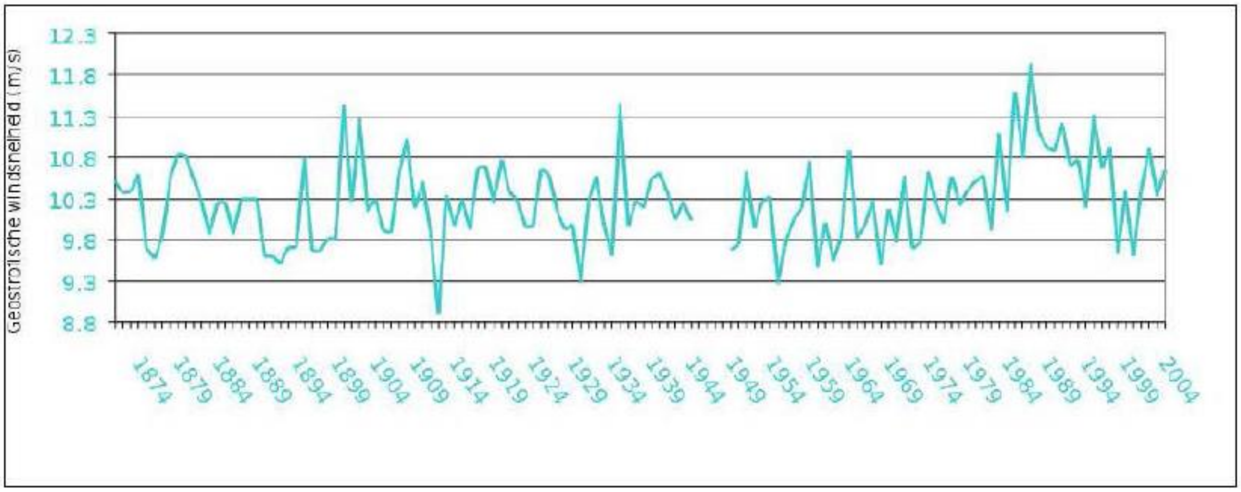


Figure XXXVII: Measure of windiness speed which covers the whole southern North Sea (KNMI, 2014)

of wind flows. Moreover, the incident of storms could also be affected by the same. After 2000's the number of storms is getting more and more declined above the North Sea, as it is presented in *Figure XXXVIII*, something that could be concluded for the inland as well.

The future evolution of wind speed and frequency is difficult to be estimated. The uncertainties are great and other parameters contribute to that, not only for the Netherlands but for the whole Europe. The wind speed can change a little mainly because of human intervention as it has been mentioned earlier but the frequency may not be affected at all. Besides, these changes could also be interpreted as natural variability. The wind direction, however, seems to differentiate among the climate scenarios. The currently common west-south air flow remains dominant in the G_H and W_H scenarios during winter and less in G_L and W_L for the same season. During summer, there is a unanimous decrease of that airflow pattern, more intensely in the scenarios of wetter winters and drier summers (H).

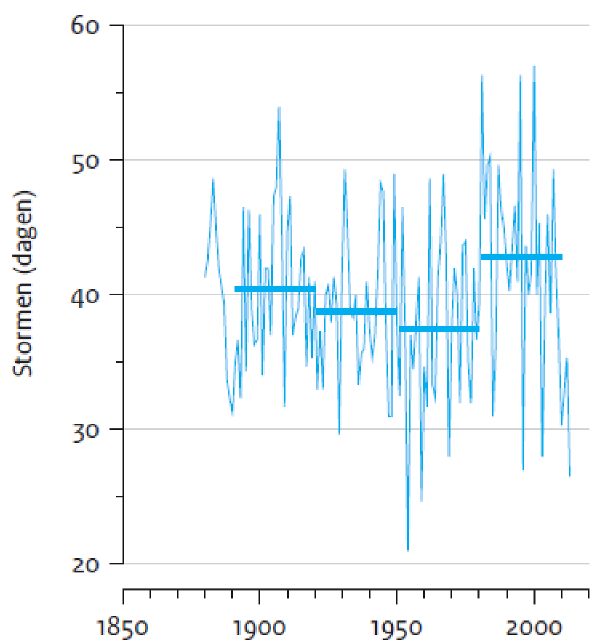


Figure XXXVIII: Number of storms per year above the North Sea (KNMI, 2014)

It is obvious that the wind patterns in the Netherlands will either change a bit or not change at all over the next decades. There is not a considerable connection between climate change and wind patterns, therefore the research cannot include wind an influenced variable which impact the road tunnel infrastructures.

Sight, mist, hailstorm & thunderstorm

In the report of 2014, KNMI makes a reference about the sight and mist phenomena in the Netherlands. It states that the sight has been improved the recent years and the reduction of mist is considerably pronounced. The main factor which contributes to this downward trend is the decrease in air pollution. In 1956, the annual mean fog was about 500 hours and gradually reached to about 200 hours in 2002 (*Figure XXXIX).* In 2014, KNMI estimated on average even 60 hours of less fog in the coastal side comparing with the inland.

The forecasts for the future indicate further reduction of those days per year but not in a rapid way as it was observed in the previous century. In 2050, the mean foggy hours will be about 190 per year. This prediction is referred to all of four climate scenarios. The climate change is not related with this phenomenon. The air pollution plays the integral factor for the sight conditions. Although reduced visibility projection is an important parameter to take into consideration in a road network, lack of correlation with the climate change indicates the due research to not include sight on the effects on road tunnel infrastructure.

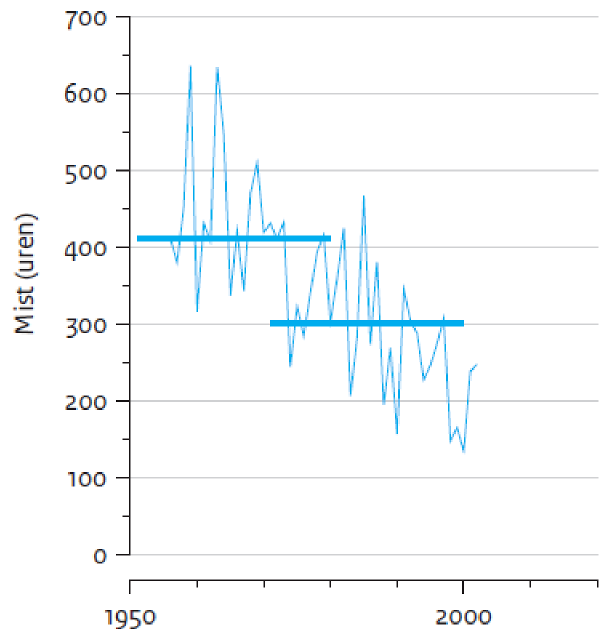


Figure XXXIX: Annual mist hours in the Netherlands with sight less than 1km (KNMI, 2015)

The IPCC says that statements about hailstorms and thunderstorms in frequency and intensity are difficult to be done mainly because of lack of measurements and scientific research in global level. As it was presented previously regarding the future temperature and precipitation phenomena, the increase of water vaporing will consequently increase the frequency and intensity of hailstorms in the Netherlands. More water vaporing means more condensation heat and consequently the strength of vertical movements in clouds is increasing and the hailstone size as well. Till 2050, in the extreme climate scenarios of warmer climate (W_L, W_H), hailstorm will occur twice as it occurred between 1981-2010 (KNMI, 2015). It seems that the functions of a road tunnel infrastructure can be affected by the more frequent incidents of hailstorms.

Similarly, thunderstorms are expected to rise as well. Their increase is attributed to climate change and have effects on the road infrastructure. Thunderstorms can distract the functions of a road tunnel system and therefore risks related to thunders are recognized and considered later in the research.

Clouds and solar radiation

Cloudiness observations in the Netherlands have shown little difference since the decade of 1950s. It seems that the clouds have become more transparent, increasing the overall brightness. The reduction of air pollution is attributed to this observation. At the same time, there is also a rise of solar radiation since the start of its measurement, which became available in the Netherlands in 1958. The increase of solar radiation contributes to the overall temperature increase of about 1°C in the Netherlands between 1981-2013 by about 1/5. The noticeable difference between the periods 1958-1980 and 1981-2013 indicates the climate change in the recent decades (*Figure XIII*). Despite this, the differences can possibly be a result of natural variability of the 30-year time scale, not necessarily because of human-causes. Forecasts show that in the climate projections of G_H and W_H, cloudiness is going to decrease intensively as drier summers occur. Reversely, solar radiation is going to rise during summertime in the same climate projections.

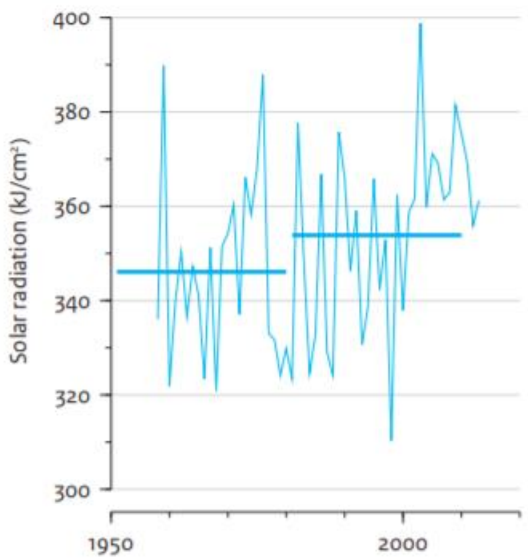


Figure XIII: Annual solar radiation observations on the ground surface in De Bilt and means in 30-year time span (KNMI, 2015)

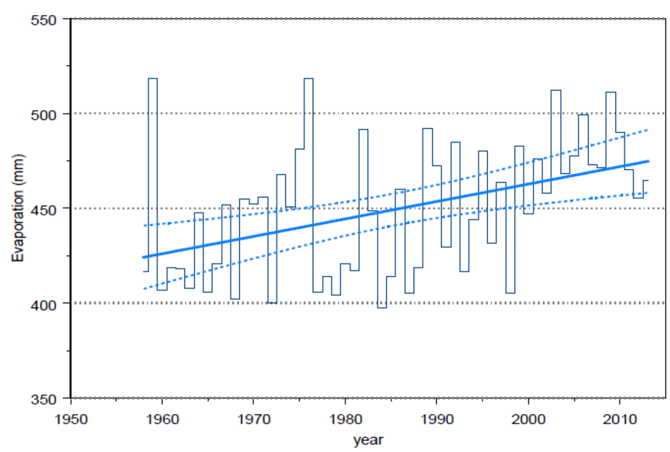


Figure XIV: Observation of potential evaporation in the growing season (1 April-1 September) in the De Bilt, Netherlands. The bold line represents a linear regression fit (KNMI, 2014)

Therefore, solar radiation is included on the list with the climate variables that may have a potential effect on the road tunnel infrastructure as it is not clear yet if it is caused by the human or naturally.

Evaporation and drought

There is no direct way to measure evaporation but only through daily solar radiation and daily temperature. The widely known Makkink formula is used by KNMI to calculate the potential evaporation in the Netherlands since 1987. The potential evaporation has increased by about 12% between 1958 and 2013 in De Bilt during the growing season in the summer. This upward trend is caused due to the observed temperature and solar radiation rise at the same period as it has been already mentioned earlier (KNMI, 2014). *Figure XIV* visualizes the annual evaporation measures in millimeters accompanying with a linear regression fit.

The same formula is used to calculate evaporation changes in future conditions. It seems that the potential evaporation is increasing proportionally with the solar radiation and by about 2% for every degree of temperature increase (KNMI, 2015). Climate change affects evaporation which could have a potential impact on road tunnel infrastructure. At this point it worth of mentioning the difference between the actual and potential evaporation which is referred to the actual soil concentration in water. Evaporation projections may differ quite a lot comparing the ones of temperature and solar radiation.

Drought observations is even more complex and difficult to assess its changes since the start of measuring in the middle of 20th century based on IPCC. In the Netherlands has been noticed more and more drought periods for the same period and it is likely that these phenomena will increase further in the future. The precipitation deficit is an indicator of drought and is projected higher during summertime in scenarios G_H and W_H, therefore, longer and more intense drought periods are estimated (KNMI, 2014). Precipitation and temperature define evaporation variables and consequently overall drought conditions.

Drought could also have a potential effect on a road tunnel especially on the tunnel banking in the entrances which could lose some of its strength from the grass that covers the banking if it withers.

Sea level

Between 1901 and 2010 observations of sea level shown an average rate of 1,7mm increase per year and a total of 19cm sea level rise. In the North-East Atlantic Ocean, the rise in sea level was almost the same as the global average and specifically in the Dutch North Sea coast this increase was calculated about 1,8mm/year. IPCC points out that the increasing trend of sea level in the North Sea basin is depending on natural variations related to the wind which are much larger than the ones for the world average sea level (KNMI, 2015).

The rate of sea level rise will be higher than the one has already observed since 1901 and potentially will exceed 2,0mm/year along the Dutch coast. There are many physical contributors to the global and regional sea level rise. The ocean expansion due to temperature and salinity changes and mass loss of glaciers and ice sheets I Greenland and Antarctic play an important role on the level rise. Moreover, atmospheric pressure and land water changes attribute to that as well (KNMI, 2014). The ranges of sea level rise in the Dutch coastline are projected for 2050 and 2085 scenarios. Greenland and Antarctic ice sheets contribution is included in the calculations for the values estimation. The North Sea expansion has been included as well. *Figure XL* illustrates the observed values for the period 1901-2010 and the projected values of both future periods 2050 and 2085 including the four different scenarios.

The ranges of values are plotted in an area, in green for G scenarios and blue for W scenarios, to cover all potential realities in the future. Beyond 2100, scientists support that the sea level will continue to gradually increase even if the greenhouse gases concentrations are to stabilize because it takes many years for the oceans, ice sheets and glaciers to respond to the global warming. However, projections for the sea level contentions in 22nd century and afterwards is hardly to make mainly because of lack of sufficient and reliable data (KNMI, 2014).

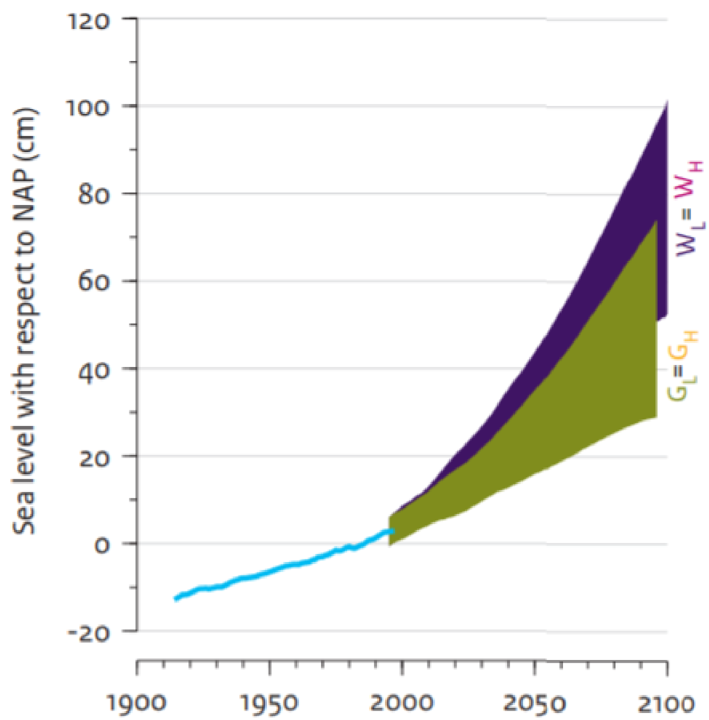


Figure XL: Observed sea level rise since 1901 till 2010 at the Dutch North Sea coast and the projections in the KNMI'14 scenarios (KNMI, 2015)

Increase of the North Sea level can affect the Dutch road tunnel infrastructure. The inland water level can either become lower or higher in some areas increasing uncertainty for the emerging risks. The structural integrity and operationality of a tunnel, which is a structure laid underneath the ground and potentially intervenes the water horizon, could be affected by groundwater level fluctuation. Therefore, sea level rise is taken into consideration in the risk analysis of its products to a road tunnel asset.

Atmospheric CO_2 concentration

The concentration of CO_2 in the atmosphere has significantly been affected by the ongoing and enormous growth of CO_2 emissions worldwide since the era of the industrial revolution. It has increased rapidly since the 18th century after a stable level of 270-285 parts per million (ppm) until then. Looking in even longer-term more than 800,000 years ago and comparing the values, the CO_2 concentration in Earth's atmosphere, nowadays, has noted the highest value that has ever been recorded (*Figure XLII*). The cycle peaks in CO_2 concentration of the warmer interglacial (higher CO_2) which were less than 300ppm seem much less than the current one that is well over 400ppm.

The forecasts for the future CO_2 concentration in the atmosphere are ominous because it is expected to increase further. Even though the CO_2 emissions were stabilized or significantly decreased, this would not mean the same for the concentration as well. The time which is required for the emitted CO_2 to be removed naturally from the atmosphere can vary on other parameters like land vegetation and ocean contribution. Therefore, even though the human CO_2 emissions stopped right, the concentration would not be reduced soon.

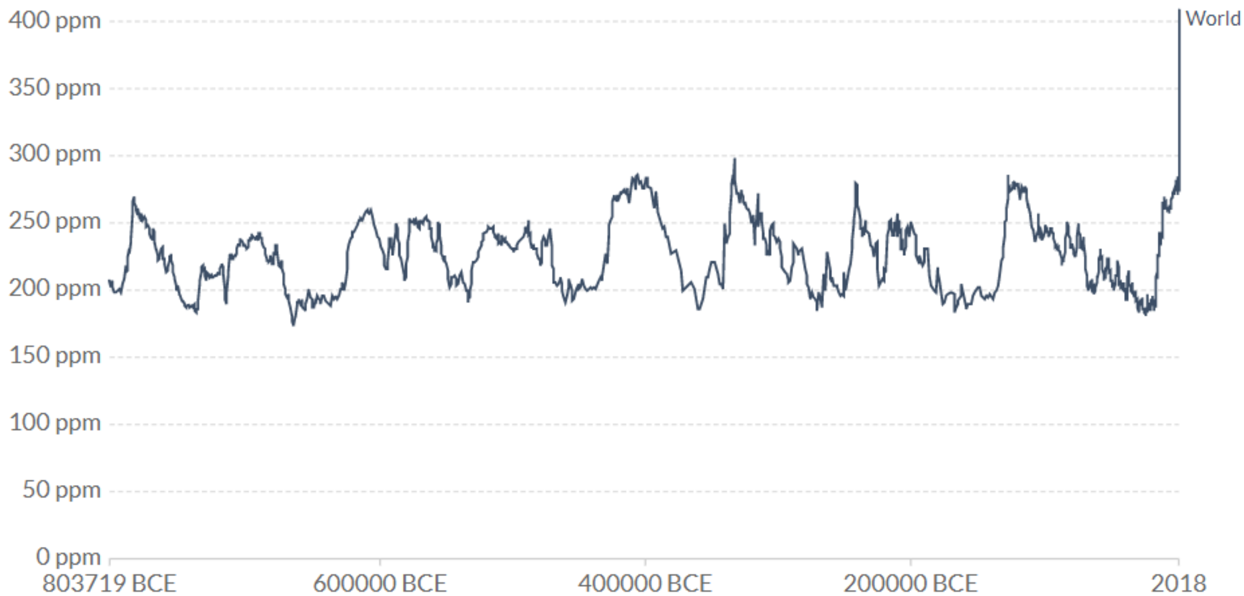


Figure XLII: Atmospheric CO_2 concentration, 803719 BCE to 2018 (Lindsey, 2020)

Stewart, Wang, & Nguyen (2010) carried out a research study regarding the atmospheric content of CO_2 within the 21st century and lead to some predictions using three carbon emission scenarios. In the A1FI carbon emission scenario is assumed very rapid economic growth, a population which peaks in the middle of century and then decreases, more efficient and effective technologies and intensive consumption of fossil energy. The next one, A1B, has similar characteristics with A1FI with a difference in the fossil energy use which is assumed balanced or even zero. Finally, the scenario of CO_2 stabilization at 550ppm by the year 2050 is considered because of policy intervention. The *Figure XLIII* illustrates the atmospheric CO_2 content over the 21st century of high emissions, medium emissions, and emissions under policy interventions for the scenarios respectively. CO_2 projection modeling errors are depicted as well as low and upper bounds for each case. In this research, the A1B scenario is taken into consideration because the W_H KNMI's climate scenario matches in high carbon dioxide emissions conditions in the future (RCP8.5, Representative Concentration Pathways) (KNMI, 2015) but not in such a level as in the A1FI scenario.

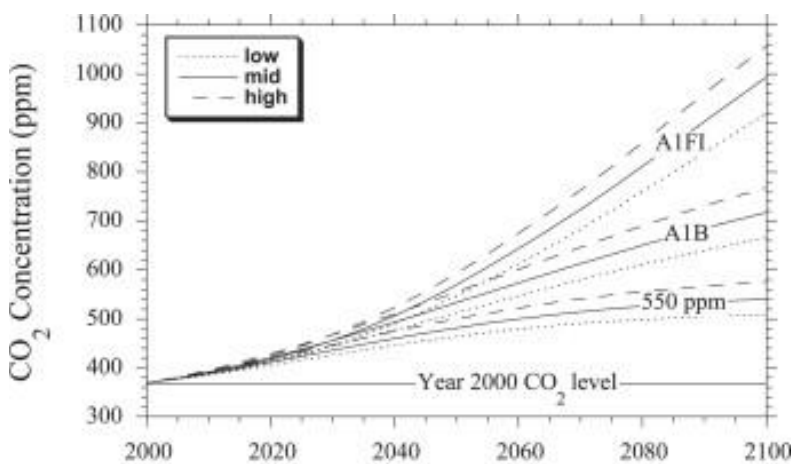


Figure XLIII: Estimations of atmospheric CO_2 concentration based on three carbon emission scenarios (Stewart, Wang, & Nguyen, 2011)

Appendix – subchapter 5.3.

5.3.1.: Function A

TopA: Failing to assimilate traffic flow

The top event ''TopA'' can be a result of 'OR Gate' and caused by the intermediate events INTER1. or INTER2. or both simultaneously which is mathematically expressed as:

TopA = 1-(1-INTERA1.) * (1-INTERA2.)

INTERA1.: Failure in carrying capacity

The INTERA1. event can be a result of ''OR Gate'' and caused by the INTERA1.1. or INTERA1.2. or INTERA1.3. or a combination of them which is mathematically expressed as:

INTERA1. =1-(1-INTERA1.1.) * (1-INTERA1.2.) * (1-INTERA1.3.)

INTERA1.1.: Civil Structural design failure

The INTERA1.1. event can be a result of ''OR Gate'' and caused by the INTERA1.1.1 or INTERA1.1.2. or INTERA1.1.3. or a combination of them which is mathematically expressed as:

INTERA1.1. =1-(1-INTERA1.1.1.) * (1-INTERA1.1.2.) * (1-INTERA1.1.3.)

INTERA1.1.1.: Excessive mechanical stress

The INTERA1.1.1. event can be caused when A1. happens.

A1.: Hydrostatic pressure

The hydrostatic pressure on the tunnel's civil structure which is imposed by the groundwater table is a variable that is included in the structural design of the reinforced concrete elements against shear, compressive and flexural failure. (Bles, et al., 2012) investigates the changes of the groundwater level (GWL) that are going to be happen on the Dutch Highway Network in the most adverse climate scenario of W_H of the KNMI'06 report. At this point, it worth of mentioning that few differentiations are presented between the KNMI'06 and KNMI'14 climate projections with the latter one to be slightly stricter on its postulation (KNMI, 2014). This means that any assumption that can emerge from the content of the report (Bles, et al., 2012) should be expected slightly more robust than the ones in the report of KNMI'06.

Map of the National Highway Network depict the simulated change in groundwater level in 2050 with a reference period the year of report publication (Appendix A1). The spots of 16 road tunnels are included in this map and at the same time, the GWL change is colored to indicate the range of expected change. Any positive GWL change contributes to increasing hydrostatic pressure on the civil structure of the tunnel infrastructure. In this way, the occurrence of positive GWL change reflects the increasing hydrostatic pressure.

INTERA1.1.2.: Deformation of tunnel foundation structure

The INTERA1.1.2. event can be a result of ‘’OR Gate’’ and caused by the A2. or A3. or a combination of them which is mathematically expressed as:

INTERA1.1.2. =1-(1-A.2) * (1-A3.)

A2.: Soil subsidence >10cm

Events of soil subsidence can be harmful for the tunnel foundation system. (Bles, et al., 2012) presents maps of the National Highway Network depicting the simulated soil subsidence in 2050 for the adverse climate scenario of W_H (Appendix A2). Any subsidence that is more than 10cm can be the reason for severe damages and the gradual development of any such an event over time in the vicinity of those 16 road tunnels, it is proposed as the frequency of that basic event and reflects the unavailability of the road tunnel system.

A3.: Groundwater effect

The particular basic event is discussed in the report of (Bles, et al., 2012) and mentioned in the description of A1. regarding the quantitative projection of groundwater level in the Dutch territory the next decades. The increasing precipitation volumes and rise of North Sea level, which have been mentioned in Chapter 2, affect the water horizon and result in higher water table. Consequently, such conditions apply pressure to the tunnel’s foundation and cause a dampness problem. This can make the foundation to be stressed and deformed. Water level increase more than 10cm is taken into consideration to define the number of tunnels that should expect such an experience in 2050. The quotient resulting from the number of those tunnels divided by the total number of road tunnel assets is assumed to be the potential effect of increased GWL more than 10cm. For the year 2100 is assumed that the cases will be as such doubled.

INTERA1.1.3.: Reinforced concrete degradation

The INTERA1.1.3. event can be a result of ‘’OR Gate’’ and caused by the A4. or A5. or A6. or a combination of them which is mathematically expressed as:

INTERA1.1.3. =1-(1-A4.) * (1-A5.) * (1-A6.)

A4.: Carbonation/CO_2-induced penetration

The atmospheric carbon dioxide concentration is one of the contributors for the corrosion of a concrete structure. CO_2 penetrates gradually the concrete mass, decreases the alkalinity (pH) level, erodes the steel bars and the products of the erosion crack the concrete mass which in turn weakens the concrete’s durability and strength. The phenomenon of concrete carbonation seems to relate to the global climate change and the more and more increasing CO_2 concentration is going to affect the progression of that sort of corrosion in concrete infrastructure (Mater, 2016). The study of (Mater, 2016) confirms previous studies that the carbonation depths will increase over the life span of a reinforced concrete structure while its progression is speeded up, especially in areas where the climate will be warmer with moderate humidity levels (like the one of W_H). Regarding the 5th assessment report of IPCC (2014), the data analysis indicates that in the worst-case scenario the carbonation depth will increase in the range of 15-20% until 2100. Therefore, considering that the experimental study was executed in ideal laboratory concrete samples, in practice the detriment is expected to be even higher. The quality of concrete produced in site is lower than of that in a laboratory even though rigorous compliance with the code specifications is followed which potentially could attenuate the early start of concrete mass corrosion (Mater, 2016).

Consequently, a road tunnel structure will also experience the effects of early carbonation corrosion during its lifespan. The exposure in high CO_2 concentration and at the same time in higher temperature conditions can deteriorate the cover of reinforced concrete elements sooner than it was expected. Cover deterioration of concrete elements and possible exposure of their reinforcing steel bars are undoubtedly unacceptable in any infrastructure. The reinforced concrete degradation is increasing, more rapidly than it may be expected, over the next decades because of the faster evolvement of concrete mass carbonation.

A5.: Chloride ions-induced penetration

The chloride ion concentration on the atmosphere is another contributor to the corrosion of a concrete structure. The presence of high groundwater in the location of a civil structure which is characterized by high levels of humidity and often wet weather conditions creates an unfavorable environment which decreases the concretes resistance in deterioration. The chloride ions tend to penetrate the concrete mass and erode the reinforcing steel bars. The variability of penetration depth can be high because of the variability of environmental and material properties and general uncertainty (Stewart, Wang, & Nguyen, 2011).

Recent study supports that the global warming will speed up the process of chloride ion penetration and consequently the concrete deterioration (Xie, Wang, Gong, Liu, & Yang, 2018). It is found out that the amount of chloride ion on the surface of reinforcing steel bars is going to be 6% to 15% higher in 2100 comparing to current observations. These projections are based on the climate scenario RCP8.5 of the 5th assessment report of IPCC in 2014 which is the one that in the KNMI'14 report is referred to $W_{H.}$ However, the authors conclude that the climate change will little affect the initiation of corrosion by chloride ions of the reinforced concrete structures.

A6.: Freeze-thaw cracking

Frequent and extreme fluctuations of weather temperatures within a range of positive and negative temperature values can also cause to some extent concrete degradation. The phenomenon of freeze-thaw cracking is usual in locations where very low (below zero) temperatures and high ones are observed within the same day. The water principles penetrate through the porosity of the concrete to its mass, the water is freezing under the low temperature, the ice cracks the mass because of the volumetric expansion of water and finally the concrete mass is getting more vulnerable after the melting of ice. In the next freeze-thaw cycles, the length of those cracks is getting bigger and bigger (Pakkala , Köliö , Lahdensivu , & Pentti , 2015).

In the Dutch environment, the incidents of freeze-thaw are not few but not minimal. The KNMI'14 report expects an overall decrease of ice days over the next decades, an increase in the number of warm days per year and the days where the temperature will fluctuate extremely between positive and negative values within a day are going to be fewer and fewer. However, the wet days are slightly decreasing over the next decades which works unfavorably for freeze-thaw cracking to happen.

INTERA1.2.: Soil cohesion lost

The INTERA1.2. event can be a result of ''AND Gate'' and caused by the A7. and A3. at the same time which is mathematically expressed as:

INTERA1.2. =A7. * A3.

A7.: Soil deformation

The compressed soil structure underneath the tunnel foundation can lose its resistance whether in some areas of that soil layer there is possibly dissimilar ground settlement. This basic event can logically be expected to happen in conditions where ground subsidence has been noticed in nearby area of the road tunnel location. However, it does not mean that whenever ground subsidence happens at the same time soil deformation will be resulted. In the first case the whole ground section is moving vertically and not dissimilarly as in the case. The frequency of such an event will be assumed as a small percentage of the one in A2.

A3.: Groundwater effect

The same description as it has been given earlier is applied to this case. The same considerations are considered for that particular intermediate event INTERA1.2.

INTERA1.3.: Insufficient tunnel pavement design

The INTERA1.3. event can be a result of ''OR Gate'' and caused by the A8. or A9. or INTERA1.3.1. or a combination of them which is mathematically expressed as:

INTERA1.3. =1-(1-A8.) * (1-A9.) * (1-INTERA1.3.1.)

A8.: New demands for public transportation

Overall climate change can potentially affect the population density of some regions in the Dutch territory. Extreme weather conditions in some parts of the country may force the population to relocate its residence. Such an increase will change the regional commuting needs and simultaneously the demands for public transportation.

The design of public infrastructures includes parameters such as the number of users that will be able to use the infrastructure every day. In case that the traffic load that a road tunnel is designed to serve everyday increases, some additions that increase the traffic load capacity are needed. The establishment of bus lanes which enhances public transportation and a greener way of commuting is reasonably anticipated. Changes in speed limits and/or travel times should also be in mind. This basic event could contribute implicitly to making a tunnel pavement design gradually insufficient.

A9.: Pavement deformation

The road pavement outside of a road tunnel seems to be vulnerable in deformation in the future. The anticipated days of extremely high temperatures (heat waves) could affect the flatness of the asphalt and deform the road surface bringing about considerable damages. Moreover, ground subsidence could also cause deformation of the road pavement in different spots resulting in the same level of damages. Undoubtedly, this sort of events would be unacceptable to happen and for that reason, the frequency of that basic event is assessed by combining the frequency of the previously mentioned causes (temperature, ground subsidence) in the future.

INTERA1.3.1.: Traffic bottleneck

The INTERA1.3.1. event can be a result of ''OR Gate'' and caused by the A10. or A11. or A12. or a combination of them which is mathematically expressed as:

INTERA1.3.1. =1-(1-A10.) * (1-A11.) * (1-A12.)

A10.: Conversion of neighboring roads into low traffic

Climate change will force regional and local public organizations to propose green solutions to face the increasing tendency of traffic bottlenecks. Many people use their own vehicles to commute every day which is about to change the following years aiming for the development of environmental conscience. One way of creating this mindset is the minimization of CO_2 emissions. Conversion of roads into pedestrians' areas or roads of low traffic is expected as measures. The use of some sort of road sections such as a tunnel may be reasonably increased as the number of alternative routes decreases. The requiring performance level of speed limits, travel times, lanes' dimensions, and other regulatory requirements would not be able to be achieved. A potential event like this one should not be neglected.

A11.: Malfunction of a nearby movable bridge

The functionality of a tunnel can also be degraded by other nearby infrastructure assets, for instance a movable bridge. This kind of bridge constitutes by electromechanical equipment that allow the bridge to operate. Some weather conditions can deteriorate the reliability and availability of those structures. Days with heat waves can block the mechanical equipment that opens and closes a movable bridge as some components or devices can be easily overheated. Then an unavailable bridge can immediately affect the traffic load of neighboring road sections. In a tunnel, such an event could hinder the smooth passing through the tunnel by creating traffic congestion.

A12.: Cautious driving

The drivers tend to be cautious especially during rainfall, hailstorm, or thunderstorm events. The road users feel subconsciously the need to protect themselves. Moreover, during the cold days of winter, road users consider also that a thin layer of ice on the road surface could potentially bring about a car accident. All the aforementioned climate variables are evolved differently over time. The precipitation volume increases although the number of ice days decreases. Therefore, it worth mentioning that frequently vehicle drivers will be cautious if the weather extremes are growing.

INTERA2: Ineffectual traffic flow safety

The INTERA2. event can be a result of ''OR Gate'' and caused by the INTERA2.1. or INTERA2.2. or INTERA2.3. or a combination of them which is mathematically expressed as:

INTERA2. =1-(1-INTERA2.1.) * (1-INTERA2.2.) * (1-INTERA2.3.)

INTERA2.1.: Obstructed passage

The INTERA2.1. event can be a result of ''OR Gate'' and caused by the A13. or INTERA2.1.1. or a combination of them which is mathematically expressed as:

INTERA2.1. =1-(1-A13.) * (1-INTERA2.1.1.)

A13.: Clear height lowering

In the future, the clearance of a road tunnel will potentially face the danger of declining. The increasing daily users not only of the ones that drive cars but also the ones of special transport vehicles may change the needs of ventilating the tunnel. The levels of nitrogen dioxide (NO_2) in a tunnel should be ranged within acceptable values. In the worst-case scenario of installing bigger ventilation systems to achieve the minimum requirements for air quality as the last option to address this issue, the regulatory clear height of a tunnel may be unable to be preserved. Such an event could be assessed in correlation with future transportation demands which may be observed and this would be a widespread estimation from a transport expert.

INTERA2.1.1.: Tunnel flooding

The INTERA2.1.1. event can be a result of ''OR Gate'' and caused by the A14. or A15. or a combination of them which is mathematically expressed as:

INTERA2.1.1. =1-(1-A14.) * (1-A15.)

A14.: Extreme rainfall

The climate scenario W_H is expecting more frequent and intense showers until 2100. The volume of water a road tunnel must be drained within i.e. an hour will be increased. The drainage system could potentially become inadequate to perform well if fail to withdraw the water from the road's surface resulting in tunnel flooding. Subsequently, the tunnel would have become unsafe for cars and transport vehicles of goods. The frequency of such an event is related to the overall precipitation evolvement in the Dutch territory.

A15.: Hailstorm

Hailstorms are expected to be twice as much in 2050 and so on in 2100. This is a result of long periods of high temperatures and low showers. It is a phenomenon that happens mainly during the summer and early autumn. Moreover, the size of hailstones is projected bigger as well. Such conditions could affect the drainage system like in case A14. The system could potentially be not capable to deal with the size and intensity of a hailstorm and its products. The road surface outside the tunnel is going to be less friendly to the road users by increasing the chances of car accidents when going in and out of it. The frequency assumptions of that event can be based on generalized opinion because of unavailability of hailstorm data records the previous years.

INTERA2.2: Limited entrance visibility

The INTERA2.2. event can be a result of ''OR Gate'' and caused by the A16. or A17. or a combination of them which is mathematically expressed as:

INTERA2.2. =1-(1-A16.) * (1-A17.)

A16.: Thunderstorm

Thunderstorms are expected to be twice as much in 2050 and 2100. This event is considered in the same way such as in A15. Increasing mean precipitation over the years increases the frequency of thunderstorms as well. The road visibility can be diminished in an event of extreme thunderstorm. The road users may not have a clear view of the tunnel when driving towards it. This phenomenon is quite uncertain regarding its frequency. There is a lack of data records for thunderstorms. Therefore, making assumptions for the future can rely on the overall mean precipitation which is expected in the W_H scenario in the future and expert judgment.

A17.: Extreme hailstorm

Extreme hailstorm degrades the visibility of drivers when going in and out of the tunnel. Moreover, the light intensity of the pavement in the entrances of the tunnel may be insufficient because the light can reflect on the hail and distract the driver. The frequency of such an event is assumed as a small percentage of the one in A15. event.

INTERA2.3.: Unstable soil banking system

The INTERA2.3. event can be a result of ''AND Gate'' and caused by the A7. and INTERA2.3.1. at the same time which is mathematically expressed as:

INTERA2.3. =A7. * INTERA2.3.1.

A7.: Soil deformation

The same description for Soil deformation is applied here like in INTERA1.2.

INTERA2.3.1.: Landslide

The INTERA2.3.1. event can be a result of ''AND Gate'' and caused by the A18. and A19. and A20. at the same time which is mathematically expressed as:

INTERA2.3.1. =A18. * A19. * A20.

A18.: Extreme high temperature

The days with temperatures higher than 25^{o}C are increasing the next decades on the climate scenario W_H. KNMI assumes generally that the warm days will be more in the future than nowadays and whenever extremes will be observed it will last for many days. The frequency of those extremes emerges from the number of days that are indicated in *Table II.*

A19.: Extreme rainfall after a long period of drought

After a long warm period of low or no events of light raining, extreme rainfalls are expected. It is a weather pattern that has been well observed. Although, there will be a slight increase on the amount of yearly mean precipitation, KNMI expects more extended drought periods. The precipitation deficit is getting bigger (*Table II*).

A20.: Grass withering

Watering the grass is wide known as necessary to keep the grass alive. Some deepening tunnels have soil slopes in both sides of the road part which reaches to the tunnel entrances. These slopes are covered with grass to keep the mass cohesive. Grass withering could be vulnerable for the soil structure. The temperature and drought expectations for the future are considered for the evaluation of the frequency of A20.

5.3.2.: Function B

TopB: Failing to provide route flexibility

The top event ''TopB'' can be a result of 'OR Gate' and caused by the intermediate events INTERB1 or INTERB2 or INTERB3 or a combination of them which is mathematically expressed as:

TopB = 1-(1-INTERB1.) * (1-INTERB2.) * (1-INTERB3.)

INTERB1.: Adverse road pavement

The INTERB1. event can be a result of ''OR Gate'' and caused by the B1. or INTERB1.1. or INTERB1.2. or a combination of them which is mathematically expressed as:

INTERB1. =1-(1-B1) * (1-INTERB1.1.) * (1-INTERB1.2.)

B1: Water on road surface

Water is a major road hazard because either in liquid form or ice it can cause considerable car accidents. Road networks in areas like the Netherlands which are vulnerable to the water attacks, it goes without saying that it raises concerns regarding the frequency a road section will experience surficial water on its pavement. The North Sea level and GWL rise which are postulated in the W_H scenario could potentially make a road tunnel unavailable for operation and so could also do the excessive precipitation volumes.

INTERB1.1.: Unclear marking

The INTERB1.1. event can be a result of ''OR Gate'' and caused by the B1. or B2. or both which is mathematically expressed as:

INTERB1.1. =1-(1-B2.) * (1-B3.)

B2.: Solar radiation

Solar radiation is a climate variable that is expected to slightly increase in the W_H climate scenario until 2100. Solar radiation causes color fading of any surface that receives direct sunlight for long time during a day. Frequent unclear marking could be caused by this basic event.

B3.: Extreme hailstorm

The outcome of a hailstorm event results from the intensity of the storm itself. In case of an intense hailstorm, the road pavement is totally covered with hailstones. The time that is needed a road to be cleaned up physically or technically from the hail can be varied. The road part that leads to a road tunnel can be such a case. It will be difficult for the road users to distinguish the pavement's marking if that is covered totally with hailstones. As it is said, hailstorms are expected at least doubled until 2100.

INTERB1.2.: Insufficient road pavement design

The INTERB1.2. event can be a result of ''OR Gate'' and caused by the B4. or B5. or both which is mathematically expressed as:

INTERB1.2. =1-(1-B4.) * (1-B5.)

B4.: Bumps or holes on road pavement

High temperature affects the upper layer of asphalt mass. The asphalt is overheated and subsequently the thermal expansion occurs. When this phenomenon happens in rush hours, where also heavy vehicles pass though, holes and bumps can be created in the weaker spots of the road pavement.

B5.: Surface cracking

It is created also by the phenomenon of thermal expansion and contraction which occurs within a short period of time (i.e. few hours, a day). Weather conditions with considerable temperature differences within a day make the road surface to expand and contract, a fact that weakens the road surface from the cracks that are created.

INTERB2.: Poor traffic direction management

The INTERB2. event can be a result of ''OR Gate'' and caused by the B6. or INTERB2.1. or B10. or INTERB2.2. or a combination of them which is mathematically expressed as:

INTERB2. =1-(1-B6.) * (1-INTERB2.1.) * (1-B10.) * (1-INTERB2.2.)

B6.: Insufficient alternative routes

Conversion of roads into pedestrians’ areas or roads of low traffic is expected as a measure to deal with the minimization of CO_2 emissions. The road tunnel will potentially be on a route that will be drivers’ only option to follow to reach their destination. Therefore, the use of this asset will increase not only in rush hours but also in general and traffic direction management will be more difficult to be proceeded smoothly whenever adjacent road network is needed.

INTERB2.1.: Disruption of traffic setting

The INTERB2.1. event can be a result of ‘’OR Gate’’ and caused by the B7. or B8. or B9. or a combination of them which is mathematically expressed as:

INTERB2.1. = 1-(1-B7.) * (1-B8.) * (1-B9.)

B7.: VRI error

The traffic signal system fails to adjust rapidly under intense weather conditions when it's required. The system’s sensors may not operate properly or even totally fail. The frequency of the system's unavailability is increased if the system’s vulnerability is enhancing by the general impact of climate changes.

B8. Traffic measurement error

The traffic measurement system can potentially fail to perform as it is required because of its sensors' vulnerability. The reasoning is exactly the same as the one of the basic events B7.

B9. Tunnel non-response in traffic alternation

Although a successful traffic setting could be achieved, a partial flooding event of one of the tubes of a road tunnel would not allow a traffic alternation to be accomplished. Climate change brings about a rise in the yearly mean precipitation and an increase of the days with extremely high precipitation volumes. The frequency of a flooding event is increasing and so does for the unavailability rate of a tunnel system to operate by alternating the traffic flow within the tunnel tubes.

B10.: Execution of maintenance works

The intense impact of climate change on the road tunnel infrastructure can be such a great one that may require more frequent short-term maintenance works and sooner extended maintenance interventions. Routine maintenance sooner than it was expected ventilation and drainage system optimization, and/or earlier reinforced concrete elements reinforcements or reparation.

INTERB2.2.: Failing to provide information on boards

The INTERB2.2. event can be a result of ‘’OR Gate’’ and caused by the B11. or B12. or both of them which is mathematically expressed as:

INTERB2.2. = 1-(1-B11.) * (1-B12.)

B11: Short circuit/malfunction

The presence of moisture in electronic devices and equipment can increase the current in the circuit within a short time which then causes a short circuit as the fuse is blown. In this case of fuse missing, the wires of the electronic device heat up and it is very likely a fire to start. Although the number of wet days slightly decrease until 2100, the yearly mean precipitation is increasing considerably in every event of rainfall which in turn raise the moisture presence in an electronic device and consequently the occurrence of any malfunction.

B12.: Partially or entirely external damage

The electronic devices/equipment which are exposed to the weather conditions are prone to rapid deterioration and damages. Damage on a digital information board can happen in an event of a hailstorm. The hailstones can potentially break partially or entirely parts of such equipment (i.e. board panel cover glass) causing something costly unavailability and reparation. The intensity and frequency of hailstorm events are dramatically growing, and such incidents of damages are more likely to happen.

INTERB3.: Traffic management failure

The INTERB3. event can be a result of ‘’OR Gate’’ and caused by the B13. or INTERB3.1. or both which is mathematically expressed as:

INTERB3. =1-(1-B13.) * (1-INTERB3.1.)

B13: Congestion control scenarios failure

These scenarios have been developed based on observations of congestion events and strategies that deal with such events. Traffic congestion derives among others also from bad weather conditions. The drivers tend to be more cautious which affects the overall traffic flow speed and travel time. The congestion control scenarios are used to adjust the traffic lighting to keep a smooth flow. However, these scenarios may be not capable enough to face the short impact the weather conditions may have in any case on the road network. Climate extremes are expected which must be dealt with those control scenarios adequately.

INTERB3.1.: Failure of safety control scenarios

The INTERB3.1. event can be a result of ‘’OR Gate’’ and caused by the B14. or B15. or both which is mathematically expressed as:

INTERB3.1. = 1-(1-B14.) * (1-B15.)

B14.: Emergency services/vehicle disruption

The emergency services are disturbed by the other road users and generally from events of traffic bottleneck. Moreover, the disturbance may come from the alternation of available traffic routes that such services can use to reach their destination. Flooding events of a road section like a road tunnel would change the route an ambulance or firetruck could follow. Also considering the chaos such an event could cause in the traffic flow, the response time of those emergency services increases considerably and reflects a failure of safety control to be achieved.

B15.: Blackout

Thunderstorms can be quite intense sometimes that blackout events may be resulted in. Any tunnel installation that requires electricity cannot operate which affects the safety requirements on the road tunnel. If there is not an energy generator during a blackout to light up and keep on the electronic systems, the safety control scenarios are going to fail.

5.3.3.: Function C

TopC: Failed connection with the road network traffic management facilities

The top event ''TopC'' can be a result of 'OR Gate' and caused by the intermediate events INTERC1. or INTERC2. or both which is mathematically expressed as:

TopC = 1-(1-INTERC1.) * (1-INTERC2.)

INTERC1.: System's error

The INTERC1. event can be a result of ''OR Gate'' and caused by the C1. or C2. or both which is mathematically expressed as:

INTERC1. =1-(1-C1.) * (1-C2.)

C1.: Delay in communicating traffic changes

Unexpected weather conditions can cause some disturbing events (i.e. flooding) and any delay in communicating traffic changes could cause frustration on the road users. Frustration can come from an instant feeling of insecurity or in a worst-case scenario from an event of human casualties. The climate scenario W_H expects a rise in the number of weather phenomena that are unexpected to happen to the season they occur. Therefore, the tunnel asset organization may be found unprepared sometimes within the year.

C2.: Wrong provision of information

The provision of information to the road users for every road section of the network especially for those sections which are close to each other should be in sync. Any visual or audio messaging must be given in such a way to allow a smooth passing of the users from one road section to the other. A road tunnel when recognizing effects from climate events should react under the consideration not to create congestion and insecurity. The system’s failure to assess the weather conditions sufficiently would make the road tunnel unavailable for the provision of correct information and alert messaging to the road users would result in failing to achieve coordinated action with the rest road network.

The INTERC2. event can be a result of ‘’OR Gate’’ and caused by the INTERC2.1. or INTERC2.2. or INTERC2.3. or a combination of them which is mathematically expressed as:

INTERC2. =1-(1-INTERC2.1.) * (1-INTERC2.2.) * (1-INTERC2.3.)

INTERC2.1.: Insufficient drainage system on demand

The INTERC2.1. event can be a result of ‘’OR Gate’’ and caused by the C3. or C4. or both which is mathematically expressed as:

INTERC2.1. = 1-(1-C3.) * (1-C4.)

C3.: Hailstorm

The drainage system is designed based on the requirements of road tunnel regulations, protocols, and general directives. The system consists of other subsystems such as the sewage system, the pumping system, and the cellars where the water is collected. The minimum requirements emerge from the precipitation volumes that must be addressed in any case and by the size of the due road tunnel asset. Hailstones of bigger mean size than it was expected and used in the drainage design can make the subsystems to underperform and therefore the drainage system insufficient and failed and the road tunnel unavailable for use.

C4.: Extreme shower

The same consideration with C3. but this time in liquid form of precipitation. Above an amount of water, the drainage system may potentially be incapable to achieve the needed drainage times.

INTERC2.2.: Underperformance of sensors

The INTERC2.2. event can be a result of ‘’OR Gate’’ and caused by the C5. or C6. or both which is mathematically expressed as:

INTERC2.2. = 1-(1-C5.) * (1-C6.)

C5.: Extreme temperature

The sensors that are used to assess the current weather conditions are designed to a specific level of reliability. The reliability is also dependent on the conditions where the sensors are maintained. The sensors are wearing out faster when they are exposed to extreme weather conditions which change rapidly, so the movement detection that is normally executed by sensors could be faulty whether the sensors' reliability changes over time.

C6.: High precipitation volume

Frequent humid weather could also contribute to the wearing out of the sensors that are used for the lighting adjustment to the external environment. The sensors fail to perform well deviating from the protocols standards and subsequently failing to achieve unity of tunnel's and road network's traffic management system. The light intensity inside the tunnel may be different than the lighting of the rest road network.

INTERC2.3.: Underperformance of ventilation system

The INTERC2.3. event can be a result of ''OR Gate'' and caused by the C7. or C8. or both which is mathematically expressed as:

INTERC2.3. = 1-(1-C7.) * (1-C8.)

C7.: Exceedance of vehicle capacity

Climate change can also change the population density of some areas in the Netherlands. It can also increase the number of vehicles that use the road network in such areas. A road tunnel may experience an exceedance of the upper limit of vehicles that can use the asset per day. After that limit traffic bottleneck is caused. Tunnel installations such as the ventilation system are designed to serve specific capacity. When this is violated, then these systems are incapable to deal with the new demands.

C8: Fire by an electric car crash

In the following years, an evolutionary dominance of electric vehicles is expected. More and more people are selecting environmentally friendly means of commuting and electric mobility is thought one of the ways to minimize carbon dioxide emissions globally by using vehicles that do not emit CO_2 at all. Therefore, in a car crash event, the frequency of an electric car being involved is increasing. So is the size and consequences of a fire event that comes from battery liquids would be enormous. The ventilation system is very likely to be inadequate to deal with such a cloud of smoke and tunnel air clearance.

5.3.4.: Function D

TopD: Blocking communication

The top event ''TopD'' can be a result of 'OR Gate' and caused by the intermediate events INTERD1 or INTERD2 or by both which is mathematically expressed as:

TopD = 1-(1-INTERD1.) * (1-INTERD2.)

INTERD1.: Incapability to provide information to the road users

The INTERD1. event can be a result of ''OR Gate'' and caused by the INTERD1.1. or INTERD1.2. or by both which is mathematically expressed as:

INTERD1. =1-(1-INTERD1.1.) * (1-D5.)

INTERD1.1.: Insufficient visual guidance

The INTERD1.1. event can be a result of ''OR Gate'' and caused by the D1. or INTERD1.1.1. or both of them which is mathematically expressed as:

INTERD1.1. = 1-(1-D1.) * (1-INTERD1.1.1.)

D1.: Damage in digital installations

External damages in the digital displays that are used to communicate messages to the road users outside of the tunnel can occur in an event of a hailstorm. The climate variable of precipitation as far as hailstorms are concerned is expected to evolve considerably the following decades based on the climate scenario W_H. The intensity of the storm and/or the size of the hailstones can cause severe damages. Therefore, this could even lead to an unavailable road tunnel for damage reparation purposes.

INTERD1.1.1.: Technical malfunction/sensors failure

The INTERD1.1.1. event can be a result of ''OR Gate'' and caused by the D2. or D3. or D4. or in a combination of them which is mathematically expressed as:

INTERD1.1.1. = 1-(1-D2.) * (1-D3.) * (1-D4.)

D2.: Intense raining

Even though the yearly mean number of wet days is slightly decreasing over the next years, the overall mean precipitation is increasing gradually. This means that more and more rainfalls will characterize as intense. So, the risk of any electromechanical equipment to fail is rising if the environment in which they operate become more adverse. Moreover, the visibility distance may be reduced if the intense rain decline the clarity of the display and weaken the light intensity. Consequently, technical malfunctions could be caused by such events leading even to an unavailable road tunnel.

D3.: Hot day

Table II indicates a rise of heat days in 2050 reaching out twice as much in 2100. Heat days means extremely high temperatures for the Dutch environment as it is used to having. Technical malfunctions such as sensor failure can be caused just because the reliability of some equipment is declining when its functional limits are exceeded like in this case. The communication of information to the road users could not be achieved, making the road tunnel unavailable for operation to fix such issues.

D4.: Ice day

The exact opposite of D3. basic event happens in this case. The ice days are gradually decreasing reaching out almost four times less until 2100. Technical malfunctions can also happen in this case. It is the exact opposite case of D3. Again, digital messaging cannot be communicated to the road users and some road tunnel downtime would be required to repair the damages and resolve the issue.

D5.: Insufficient audio guidance

This basic event can be caused by many reasons. Thunderstorms like hailstorms are expected to double until 2100. Short circuit events easily result from thunderstorms. Moreover, the noise nuisance increases when a road tunnel is full of vehicles, and such incidents seem to be more frequent in the future. Therefore, any audio guidance to the users could potentially make the provision of information impossible whether such events occur. Consequently, the Function D of the road tunnel could not be fulfilled and lead to an unavailable road tunnel in order that this functional requirement of facilitating communication to be restored.

INTERD2.: Insufficient telephone communication

The INTERD2. event can be a result of ‘’OR Gate’’ and caused by the D6. or INTERD2.1. or by both which is mathematically expressed as:

INTERD2. =1-(1-D6.) * (1-INTERD2.1.)

D6.: Weak mobile signal

In any event of a thunderstorm, the mobile signal inside the road tunnel will be potentially weakened. Thunders affect the mobile signal in general. This means that for a specific period of time the mobile signal is lost, and the use of mobile phones is unable. The downtime and the time between such events define the unavailability of the road tunnel which among others should not hamper telephone communication.

INTERD2.1.: Few installations of emergency telephones

The INTERD2.1. event can be a result of ‘’AND Gate’’ and caused by the D7. and D8 which is mathematically expressed as:

INTERD2.1. = D7. * D8.

D7.: Exceedance of vehicle capacity

As it was said, more and more road users are going to use a road tunnel. A road tunnel may experience an exceedance of the upper limit of vehicles that can use the asset per day. This could hamper the easy access of the users to emergency telephones if it's needed and the number of those telephones becomes inadequate to serve potentially more demand. The road tunnel will become unavailable to allow its users to communicate with the emergency services.

D8.: Essential tunnel evacuation

When flooding or a fire event is burst or in any other incident inside the tunnel, the tunnel evacuation is essential. The use of emergency telephones increases in such cases. The discussion on the climate change evolvement over time in Chapter 2 and later indicates that more emergency telephone installations would be required soon as the occurrence of such events are going to increase. Therefore, the road tunnel can become unavailable to allow its users to communicate with the emergency services just like in D7.

5.3.5.: Function E

TopE: Failing to future-proof system's prosperity

The top event ''TopE'' can be a result of 'OR Gate' and caused by the intermediate events INTERE1. or INTERE2. or INTERE3. or by a combination of them which is mathematically expressed as:

TopE = 1-(1-INTERE1.) * (1-INTERE2.) * (1-INTERE3.)

INTERE1.: Public condemnation

The INTERE1. event can be a result of ''OR Gate'' and caused by the E1. or E2. or by both which is mathematically expressed as:

INTERE1. =1-(1-E1.) * (1-E2.)

E1.: Tunnel design for nuisance prevention

The increasing commuting through the road tunnel, which would be caused by the overall climate change and potential increase of population density in the vicinity of the asset, would rise the noise and visual nuisance level coming from the vehicles and consequently, the nearby inhabitants would be disturbed. This matter would make the road tunnel unavailable to allow the execution of the required interventions which fix the issue. Any disregard for nuisance restoration would affect the future of the road tunnel and its prosperity.

E2.: Maintenance works

Frequent maintenance works make the road tunnel frequently unavailable. These works, as we have already described in the previous section, are going to increase as the impact of the environment on the asset is getting bigger. Road users would not be attracted to the idea to commute occasionally in longer alternative routes to reach their destination. The frequency of traveling in longer routes is considerable for the users especially when the unavailability of the tunnel lasts weeks or even months. The economic damage for some of the road users (i.e. logistic services) would be an enormous resource loss (and not only that). Intense and substantial public condemnation is expected in such a case.

INTERE2.: Tunnel structure design failure

The INTERE2. event can be a result of ''OR Gate'' and caused by the INTERE2.1. or E5. or E6. or by both which is mathematically expressed as:

INTERE2. =1-(1-INTERE2.1.) * (1-E5.) * (1-E6.)

INTERE2.1.: Uncontrollable deterioration

The INTERE2.1. event can be a result of ''OR Gate'' and caused by the E3. or E4. or by both. The unavailability of INTERE2.1. is dependent on the unavailability of each component and is mathematically expressed as:

INTERE2.1. = 1-(1-E3.) * (1-E4.)

E3.: CO_2-induced penetration/Carbonation

The expected enormous increase in carbon dioxide atmospheric concentration in the next decades would increase the pace of concrete mass deterioration. The lack of knowing the extent of deterioration and the time of it makes it uncontrollable. The road tunnel, therefore, is in danger to complete its life cycle faster than it was expected which in turn is translated as unavailability of the tunnel to its users.

E4.: Chloride ions-induced penetration

The same sort of tunnel unavailability can be caused by the chloride ions-induced penetration on the concrete mass as it has been discussed already in the previous section. It is expected to degrade the concrete to lesser extent than carbon dioxide impact because the concentration of chloride ions is slightly increasing compared to the carbon dioxide one which increases rapidly.

E5.: Inadequate architectural design

The overall climate change will create new needs and consequently new demands to incorporate in the road tunnel system. These changes could be on the architectural design of the asset. Any disregard for tunnel structure design restoration would hamper the system's prosperity in the future. Therefore, such interventions to rehab the impact would make the road tunnel unavailable for operation.

E6. Unstable land

The fluctuation of the groundwater level in the road tunnel location affects the soil condition on that location. The land load capability can potentially be weakened so the technical soil design that was made on the tunnel construction is going to fail. The result would be an unstable land table and an unavailable road tunnel for use so that the restoration works take place.

INTERE3.: Lack of sufficient surrounding space for construction adding

The INTERE3. event can be a result of ''OR Gate'' and caused by the E7. or E8. or by both which is mathematically expressed as:

INTERE3. =1- (1-E7.) * (1-E8.)

E7.: Urban recreation

The urban recreation around the road tunnel will be necessary whether population growth and housing y is happening because of overall climate change. The road tunnel is therefore expected to stop its operation in order that such interventions to take place. The downtime can vary from few weeks even months if only adjacent social facilities are required to be developed.

E8.: Excessive strain on the existent structure

This event can be caused by many minor things that all together could impose excessive strain on the tunnel structure. The land subsidence, groundwater table, and higher traffic loads are some examples that contribute to putting extra stress on the road tunnel structure. Therefore, the system is expected to stop its operation in order that relevant interventions be taken place. In case that more construction space is needed, and it is not feasible such sufficient space to be found, then the road tunnel prosperity during and beyond its service life is endangered.

Appendix – subchapter 6.3.

6.3.1.: Function A

Basic Event: A1: Hydrostatic pressure

Any positive groundwater level (GWL) change that (Bles, et al., 2012) expects in tunnel locations is considered for the assessment of the unavailability. Six out sixteen tunnels (37,5%) will experience positive GWL change until 2050. The next fifty years it is assumed double as many cases. The step is 7.5% for every 10 years. The following are going to be used as enhancing factors on the base failure rate.

2020-2039: 0.30

2040-2059: 0.45

2060-2079: 0.60

2080-2100: 0.75

It is assumed that positive GWL change will occur once per 20 years, so considering that the number of tunnels that will experience it is increasing, the final failure rate is increasing proportionally for each time period. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 70 days, the unavailability of fulfilling the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,3 -> λ: 0,015

MTBF= 1/λ, MTBF: 24,333.33 days

NA=70/(MTBF+70), NA=0.00286

2040-2059: λ: 0,0225

MTBF= 1/λ, MTBF: 16,222.22 days

NA=70/(MTBF+70), NA=0.0043

2060-2079: λ: 0,03

MTBF= 1/λ, MTBF: 12.166,66 days

NA=70/(MTBF+70), NA=0.0057

2080-2100: λ: 0,0375

MTBF= 1/λ, MTBF: 9.733,33 days

NA=70/(MTBF+70), NA=0.0071

Impact on organizational values

The impact is assessed to be *Critical* because of the severity of the effects on organization values as they are described in *Table III.*

Basic Event: A2: Soil subsidence

On the map of Deltares (Bles, et al., 2012) has been found that six of the total sixteen road tunnels (37.5%) will experience ground subsidence more than 10cm by 2050. In 2100, the author assumes that the cases will be double and the probability in any moment will be calculated in proportion of that knowledge, which means 7.5% change every 10 years. Therefore, the following work as enhancing factors on the base failure rate for the calculation of the frequency of that basic event for every time period:

2020-2039: 0.3

2040-2059: 0.45

2060-2079: 0.60

2080-2100: 0.75

It is assumed that ground subsidence more than 10cm will occur once per 20 years, so considering that the number of tunnels that will experience it is increasing, the final failure rate is increasing proportionally for each time period. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 60 days, the unavailability of function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,3 -> λ: 0,015

MTBF= 1/λ, MTBF: 24,333.33 days

NA=60/(MTBF+60), NA=0.00246

2040-2059: λ: 0,0225

MTBF= 1/λ, MTBF: 16.222,22 days

NA=60/(MTBF+60), NA=0.00368

2060-2079: λ: 0,03

MTBF= 1/λ, MTBF: 12.166,66 days

NA=60/(MTBF+60), NA=0.004907

2080-2100: λ: 0,0375

MTBF= 1/λ, MTBF: 9.733,33 days

NA=60/(MTBF+60), NA=0.006127

Impact on organizational values

The impact is assessed to be *Critical* as it is described in *Table III.*

Basic Event: A3: Groundwater effect

Under the same consideration with B1, five of sixteen road tunnels (31.25%) will experience groundwater table increase more than 10cm. It is also assuming that in 2100 there will be double as many cases under this condition. The step is 6.25%. The following are going to be used as enhancing factors on the base failure rate:

2020-2039: 0.25

2040-2059: 0.375

2060-2079: 0.50

2080-2100: 0.625

It is assumed that GWL increase more than 10cm will occur once per 20 years, so considering that the number of tunnels that will experience it is increasing, the final failure rate is increasing proportionally for each time period. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 90 days, the unavailability of the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,25 -> λ: 0,0125

MTBF= 1/λ, MTBF: 29,200 days

NA=90/(MTBF+90), NA=0.0031

2040-2059: λ: 0,01875

MTBF= 1/λ, MTBF: 19,466.67 days

NA=90/(MTBF+90), NA=0.0046

2060-2079: λ: 0,025

MTBF= 1/λ, MTBF: 14,600 days

NA=90/(MTBF+90), NA=0.0061

2080-2100: λ: 0,03125

MTBF= 1/λ, MTBF: 11,680 days

NA=90/(MTBF+90), NA=0.00765

Impact on organizational values

The impact is assessed to be *Critical as well.*

Basic Event: A4: Carbonation/CO_2-induced penetration

(Mater, 2016) confirms IPCC report of 5th assessment that the carbonation depth will increase by 20% until 2100. In this research, it is assumed more rapidly concrete erosion by 20% for every time period. The following values are going to be used as enhancing factors.

2020-2039: 0.2

2040-2059: 0.2

2060-2079: 0.2

2080-2100: 0.2

It is assumed that carbonation depth enough to make a road tunnel unavailable for operation as a result of function underperformance will occur once per 20 years. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 50 days, the unavailability of the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 1,2 -> λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2040-2059: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2060-2079: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2080-2100: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

Impact on organizational values

The impact is assessed to be *Critical* as any caused damages will be financially and practically painful for the organization and the surrounding area.

Basic Event A5: Chloride ions-induced penetration

The atmospheric concentration in chloride ions is expected to increase slightly. Therefore, the probability of chloride ion-induced penetration in a concrete mass is unlikely to change over the next years. This means less than 6% is increasing, reaching to 15% in 2080 and later. The following values are going to be used as enhancing factors:

2020-2039: 0.06

2040-2059: 0.06

2060-2079: 0.15

2080-2100: 0.15

It is assumed that chloride ions depth enough to make a road tunnel unavailable for operation because of function underperformance will occur once per 30 years. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 50 days, the unavailability of the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/30) * 1,06 -> λ: 0,0353

MTBF= 1/λ, MTBF: 10,330.19 days

NA=50/(MTBF+50), NA=0.0048

2040-2059: λ: (1/30) * 1,06 -> λ: 0,0353

MTBF= 1/λ, MTBF: 10,330.19 days

NA=50/(MTBF+50), NA=0.0048

2060-2079: λ: (1/30) * 1,15 -> λ: 0,0383

MTBF= 1/λ, MTBF: 9,521.74 days

NA=50/(MTBF+50), NA=0.0052

2080-2100: λ: (1/30) * 1,15 -> λ: 0,0383

MTBF= 1/λ, MTBF: 9,521.74 days

NA=50/(MTBF+50), NA=0.0052

Impact on organizational values

The impact is assessed to be *Critical* for the exact reason as in basic event A5.

Basic Event A6: Freeze-thaw cracking

The climate scenario W_H will be warmer with more hot days and fewer ice days. Therefore, incidents like this are getting fewer and fewer. It is assumed 61% until 2050 and 80% until 2100 decrease on the number of ice days in *Table II*. The following values are going to be used as enhancing factors:

2020-2039: 0.39

2040-2059: 0.39

2060-2079: 0.20

2080-2100: 0.20

It is assumed that the freeze-thaw cracking enough to make a road tunnel unavailable for operation because of function underperformance will occur once per 50 years. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 50 days, the unavailability of the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/50) * 0,39 -> λ: 0,0078

MTBF= 1/λ, MTBF: 46,794.87days

NA=50/(MTBF+50), NA=0.00106

2040-2059: λ: (1/50) * 0,39 -> λ: 0,0078

MTBF= 1/λ, MTBF: 46,794.87days

NA=50/(MTBF+50), NA=0.00106

2060-2079: λ: (1/50) * 0,2 -> λ: 0,004

MTBF= 1/λ, MTBF: 91,250 days

NA=50/(MTBF+50), NA=0.000547

2080-2100: λ: (1/50) * 0,2 -> λ: 0,004

MTBF= 1/λ, MTBF: 91,250 days

NA=50/(MTBF+50), NA=0.000547

Impact on organizational values

The same justification with the previous basic events A4 and A5, *Critical.*

Basic Event A7: Soil deformation

It is assumed that the probabilities of soil deformation to occur is 30% of the occurrence of ground subsidence. This means that there is 30% chance soil deformation to happen when ground subsidence occurs in the location of the road tunnel.

2020-2039: 0.09

2040-2059: 0.135

2060-2079: 0.18

2080-2100: 0.225

It is assumed that soil deformation will occur on the 30% of the tunnels which are experiencing ground subsidence more than 10cm once per 20 years. Considering that the number of tunnels that will experience it is increasing, the final failure rate is increasing proportionally for each time period. Then, the mean time between failure is calculated as inversely proportional of failure rate expressed in days. Finally, having firstly assumed the needed mean time to repair this issue, which is 60 days in this case too, the unavailability of fulfilling the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,09-> λ: 0,0045

MTBF= 1/λ, MTBF: 81,111.11 days

NA=60/(MTBF+60), NA=0.00074

2040-2059: λ: (1/20) * 0,135 -> λ: 0,00675

MTBF= 1/λ, MTBF: 54,074.07 days

NA=60/(MTBF+60), NA=0.00111

2060-2079: λ: 0,009

MTBF= 1/λ, MTBF: 40,555.55 days

NA=60/(MTBF+60), NA=0.00147

2080-2100: λ: 0,01125

MTBF= 1/λ, MTBF: 32,444.44 days

NA=60/(MTBF+60), NA=0.00185

Impact on organizational values

The impact is assessed to be *Critical* because of the severe damages on technical and social environment.

Basic Event A8: New demands for public transportation

Making assumptions for that event is challenging. Policies of municipalities and provinces for the following years regarding the goals the society aims to achieve would help in assessing probabilities. Here, it is assumed a 30% chance to occur such a change the first time period and 20% fewer chances of the previous period value for every next time period. The following enhancing factors are defined to be used in failure rate estimation:

2020-2039: 0.70

2040-2059: 0.56

2060-2079: 0.448

2080-2100: 0.3584

It is assumed that this would occur once per 20 years. The mean time between these changes is calculated as inversely proportional of failure rate expressed in days. Having firstly assumed the needed mean time to respond to this issue, which is 90 days in this case too, the unavailability of fulfilling the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,7-> λ: 0,035

MTBF= 1/λ, MTBF: 10,428.57 days

NA=90/(MTBF+90), NA=0.00855

2040-2059: λ: (1/20) * 0,56 -> λ: 0,028

MTBF= 1/λ, MTBF: 13,035.71 days

NA=90/(MTBF+90), NA=0.00685

2060-2079: λ: 0,0224

MTBF= 1/λ, MTBF: 16,294.64 days

NA=90/(MTBF+90), NA=0.0055

2080-2100: λ: 0,01792

MTBF= 1/λ, MTBF: 20,368.3 days

NA=90/(MTBF+90), NA=0.0044

Impact on organizational values

The impact is assessed to be *Critical* because if this happens, the raised problems will be difficult to be dealt with, especially regarding the social environment, safety, and financial terms.

Basic Event A9: Pavement deformation

Deformation of the road pavement can reasonably happen as it was described in subchapter 5.3.1. It is assumed to happen by 20% less frequent only in case of ground subsidence during the first time period. Subsequently, the technological advancement of asphalt materials expects to improve the ability of those materials to absorb deformations causing from weather conditions. Therefore, a declined possibility is postulated for the next time periods until 2100 declined each time by 20% of the previous year value.

2020-2039: 0.24

2040-2059: 0.192

2060-2079: 0.1536

2080-2100: 0.123

As It is assumed that ground subsidence more than 10cm will occur once per 20 years, so is for the pavement deformation. The consideration for the rest remains the same. Having firstly assumed the needed mean time to repair this issue, which is 7 days, the unavailability of fulfilling the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,24 -> λ: 0,012

MTBF= 1/λ, MTBF: 30,416.67 days

NA=7/(MTBF+7), NA=0.00023

2040-2059: λ: 0,0096

MTBF= 1/λ, MTBF: 38,020.83 days

NA=7/(MTBF+7), NA=0.000184

2060-2079: λ: 0.00768

MTBF= 1/λ, MTBF: 47,526.04 days

NA=7/(MTBF+7), NA=0.000147

2080-2100: λ: 0,00615

MTBF= 1/λ, MTBF: 59,349.59 days

NA=7/(MTBF+7), NA=0.000118

Impact on organizational values

The impact is assessed to be *Limited* as it is described in *Table III.*

Basic Event A10: Conversion of neighboring roads into low traffic

Making assumptions for that event is also challenging to be done. Any assumption can emerge from the general political and social direction of local authorities. Current climate worries and issues seek solutions in the future which are in line with the social interest. In the due analysis, it is considered that current European policies and plans for urban infrastructure and green developments would affect this event to occur by 30% of the corresponding values of the event A8 of each time period until 2100. The following reduction factors are defined to be used in the failure rate estimation:

2020-2039: 0.21

2040-2059: 0.168

2060-2079: 0.1344

2080-2100: 0.1075

It is assumed that this basic event will lead to tunnel's unavailability once per 20 years. The mean time between these changes is calculated as inversely proportional of failure rate expressed in days. Having firstly assumed the needed mean time to respond to this issue, which is 90 days in this case too, the unavailability of fulfilling the relevant function and therefore tunnel's operation is calculated by the following expression.

2020-2039: λ: (1/20) * 0,21> λ: 0,0105

MTBF= 1/λ, MTBF: 37,761.90 days

NA=90/(MTBF+90), NA=0.00258

2040-2059: λ: (1/20) * 0,168 -> λ: 0,0084

MTBF= 1/λ, MTBF: 43,452.38 days

NA=90/(MTBF+90), NA=0.00206

2060-2079: λ: 0,00672

MTBF= 1/λ, MTBF: 54.315.47days

NA=90/(MTBF+90), NA=0.00165

2080-2100: λ: 0,005375

MTBF= 1/λ, MTBF: 67,906.97 days

NA=90/(MTBF+90), NA=0.00132

Impact on organizational values

The impact is assessed to be *Critical.*

Basic Event A11: Malfunction of nearby movable bridge

Unavailability of a system that can be resulted from extreme weather conditions is not impossible to happen, such as the blocking of a movable bridge to operate. However, this possibility will be low, stable for every time period and dependent on the frequency of maintenance works of that particular asset. It is assumed to be 2 per 100 years and so is the frequency when the functional failure of a road tunnel could occur and therefore tunnel's unavailability if the movable bridge is nearby and part of the same road section. The mean time to repair this issue is assumed 2 hours.

2020-2039: λ:0.02

MTBF= 1/λ, MTBF: 18,250 days

NA=0.0833/(MTBF+0.0833), NA=4.566*10^{-6}

2040-2059 λ:0.02

MTBF= 1/λ, MTBF: 18,250 days

NA=0.0833/(MTBF+0.0833), NA=4.566*10^{-6}

2060-2079: λ:0.02

MTBF= 1/λ, MTBF: 18,250 days

NA=0.0833/(MTBF+0.0833), NA=4.566*10^{-6}

2080-2100: λ:0.02

MTBF= 1/λ, MTBF: 18,250 days

NA=0.0833/(MTBF+0.0833), NA=4.566*10^{-6}

Impact on organizational values

The impact is assessed to be *Negligible.*

Basic Event A12: Cautious driving

In extreme weather, most drivers tend to be more cautious and reduce travel speed. If more weather extremes are happening, more frequently the road users will feel discomfort and cautiousness in the way of their driving. Over time, cautious driving is expected to be more frequent but stable after a while in the future. This conclusion is made on the consideration of the anticipated climate extremes on those periods. It is assumed that 4% of the days per year, the drivers will be cautious during extreme phenomena for the first time period and then 8% of the days. Finally, it is assumed 1 hour for response on this issue.

2020-2039: λ:0.04

MTBF= 1/λ, MTBF: 25 days

NA=0.0416/(MTBF+0.0416), NA=0.00166

2040-2059: λ:0.08

MTBF= 1/λ, MTBF: 12.5 days

NA=0.0416/(MTBF+0.0416), NA=0.00332

2060-2079: λ:0.08

MTBF= 1/λ, MTBF: 12.5 days

NA=0.0416/(MTBF+0.0416), NA=0.00332

2080-2100: λ:0.08

MTBF= 1/λ, MTBF: 12.5 days

NA=0.0416/(MTBF+0.0416), NA=0.00332

Impact on organizational values

The impact is assessed to be *Negligible.*

Basic Event A13: Clear height lowering

Potential increase of traffic load would raise the question whether the requiring level of safety is preserved. New or bigger installations should be integrated as for instance the ventilation system. The clear height could be affected of such an intervention. Besides that, the frequent presence of special vehicles in the road tunnel may impose enhancing safety measures which demand for extra space (including height) and in turn frequent interventions for height adjustments on demand. This could happen once per 20 years for the first two time slots and once per 15 for the other two time periods and the requiring time for adjustments is postulated 40 days.

2020-2039: λ: 1/20=0.05

MTBF:1/λ, MTBF=7300 days

NA:40/(MTBF+40), NA=0.00545

2040-2059: λ: 1/20=0.05

MTBF:1/λ, MTBF=7300 days

NA:40/(MTBF+40), NA=0.00545

2060-2079: λ: 1/15=0.066

MTBF:1/λ, MTBF=5475 days

NA:40/(MTBF+40), NA=0.00725

2080-2100: λ: 1/15=0.066

MTBF:1/λ, MTBF=5475 days

NA:40/(MTBF+40), NA=0.00725

Impact on organizational values

The impact is assessed to be *Critical.*

Basic Event A14: Extreme rainfall

Based on the KNMI'14, the number of wet days, the days which precipitation is more than 10mm, are going to slightly increase. In the period of 2050, approximately 9 days per year will be extremely rainy and, in the period of 2100, the days will be approximately 11. These values can be converted into percentage and be 2,5% and 3,0% respectively. Therefore, in the time periods 2020-2039 and 2040-2059 the frequency is 2,5% and in 2060-2079 and 2080-2100, this become 3,0%. The mean time to withdraw the surficial water would at least 4 hours or 0.166 days.

2020-2039: λ:0.025

MTBF:1/λ, MTBF=40 days

NA:0.166/(MTBF+0.166), NA=0.00413

2040-2059: λ:0.025

MTBF:1/λ, MTBF=40 days

NA:0.166/(MTBF+0.166), NA=0.00413

2060-2079: λ:0.03

MTBF:1/λ, MTBF=33.33 days

NA:0.166/(MTBF+0.166), NA=0.00495

2080-2100: λ:0.03

MTBF:1/λ, MTBF=33.33 days

NA:0.166/(MTBF+0.166), NA=0.00495

Impact on organizational values

The impact is assessed to be *Negligible.*

Basic Event A15: Hailstorm

The lack of database for hailstorm observations makes KNMI to empirically support that the incidents of hailstorm will be double until 2100. So, this is reflected to the assumptions that are made for the frequency of this weather phenomenon. The fact that hailstorms tend to occur mostly during the warm period of summer and early autumn indicates the author to propose seven incidents per year for the first two time periods, eleven incidents per year during the third one and fourteen during the period 2080-2100. Moreover, less than 1 day is assumed as downtime for the road tunnel to become available for operation again.

2020-2039: λ:0.019

MTBF:1/λ, MTBF=52.14 days

NA:1/(MTBF+1), NA=0.0188

2040-2059: λ:0.019

MTBF:1/λ, MTBF=52.14 days

NA:1/(MTBF+1), NA=0.0188

2060-2079: λ:0.03

MTBF:1/λ, MTBF=33.18 days

NA:1/(MTBF+1), NA=0.029

2080-2100: λ:0.038

MTBF:1/λ, MTBF=26.07 days

NA:1/(MTBF+1), NA=0.037

Impact on organizational values

The impact is assessed to be *Minor.*

Basic Event A16: Thunderstorm

The same mindset regarding the assumptions of hailstorm events is followed for that event as well. The frequency of thunderstorms in every time period is proposed as 1.9%, 1.9%, 3% and 3.8% respectively and at the same way the unavailability rate of the road tunnel system is calculates. Moreover, four hours are assumed as mean time to repair for the road tunnel to become available for operation again.

2020-2039: λ:0.019

MTBF:1/λ, MTBF=52.14 days

NA:0.166/(MTBF+0.166), NA=0.00317

2040-2059: λ:0.019

MTBF:1/λ, MTBF=52.14 days

NA:0.166/(MTBF+0.166), NA=0.00317

2060-2079: λ:0.03

MTBF:1/λ, MTBF=33.18 days

NA:0.166/(MTBF+0.166), NA=0.00498

2080-2100: λ:0.038

MTBF:1/λ, MTBF=26.07 days

NA:0.166/(MTBF+0.166), NA=0.00633

Impact on organizational values

The impact is assessed to be *Negligible.*

Basic Event A17: Extreme hailstorm

Extreme hailstorms are assumed to be 50% of the total hailstorm events. The frequencies are calculated by multiplying the corresponding frequencies of the basic event A15 by 0,5. Moreover, less than 1 day are assumed as downtime for the road tunnel to become available for operation again.

2020-2039: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:1/(MTBF+1), NA=0.0095

2040-2059: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:1/(MTBF+1), NA=0.0095

2060-2079: λ:0.015

MTBF:1/λ, MTBF=66.36 days

NA:1/(MTBF+1), NA=0.0148

2080-2100: λ:0.0192

MTBF:1/λ, MTBF=52.14 days

NA:1/(MTBF+1), NA=0.0188

Impact on organizational values

The impact is assessed to be *Minor*

Basic Event A18: Extreme high temperature

In 2050, thirty-six days per year will be extremely hot showing temperatures more than 25°C and in 2100 the number will rise to forty-eight per year. The frequency of extreme heat temperature events is 10% for the period 2020-2039 and 2040-2059 and 13% for the period 2060-2079 and 2080-2100. However, the temperatures that could contribute to a landslide event are more extreme and could be 1% of those heat days. Therefore, it is assumed a 1% frequency rate for this basic event, which means 3.65 times per year this event together with A19 and A20 result in an unavailable for use road tunnel because the landslide imposed the closing of the tunnel. The frequency for the second set of time periods is 1,3%. The mean time to repair is assumed 1 week. The unavailability of the road tunnel is calculated with the same expression.

2020-2039: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2040-2059: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2060-2079: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

2080-2100: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

Impact on organizational values

The impact is assessed to be *Limited.*

Basic Event A19: Extreme rainfall after a long period of drought

Although there is a slight increase in the amount of mean precipitation per year, there are periods where low or zero precipitation is expected. Extreme rainfall after a long period of drought can reasonably be anticipated. In some cases, the nature of the assumptions is quite subjective, and this is applied in this event as well. The same consideration as in A18 is followed in this basic event as well.

2020-2039: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2040-2059: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2060-2079: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

2080-2100: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

Impact on organizational values

The impact is assessed to be *Limited.*

Basic Event A20: Grass withering

The withering of grass relates to long periods of low precipitation and high temperature. The grass cannot be sustained and dies. There are lots of other reasons under which circumstances the grass withers, but it is not a matter for discussion. For this reason, it is assumed as the frequency of that event's occurring, 1% for the period 2020-2039 and 2040-2059, and 1,3% for the period 2060-2079 and 2080-2100. The mean time to repair the damages of a landslide is assumed 1 week. The unavailability of the road tunnel is calculated with the same expression.

2020-2039: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2040-2059: λ:0.01

MTBF:1/λ, MTBF= 100 days

NA:7/(MTBF+7), NA=0.065

2060-2079: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

2080-2100: λ:0.013

MTBF:1/λ, MTBF= 76.92 days

NA:7/(MTBF+7), NA=0.0834

Impact on organizational values

The impact is assessed to be *Limited.*

Table V: Synopsis of the values of unavailability rate of each basic event for every time period and qualitative characterization of the associated impact referring to Function A

Basic events		2040	2060	2080	2100	Impact
Hydrostatic pressure	A1	3.76%	5.35%	5.53%	6.06%	Critical
Soil subsidence >10cm	A2	3.19%	4.57%	4.76%	5.23%	Critical
Groundwater effect	A3	4.03%	5.73%	5.93%	6.56%	Critical
Carbonation/CO_2-induced penetration	A4	10.64%	10.17%	7.93%	6.97%	Critical
Chloride ions-induced penetration	A5	6.24%	5.97%	5.04%	4.43%	Critical
Freeze-thaw cracking	A6	1.37%	1.31%	0.53%	0.46%	Critical
Soil deformation	A7	0.00%	0.01%	0.01%	0.03%	Critical
New demands for puublic transportation	A8	11.16%	8.54%	5.34%	1.57%	Critical
Pavement deformation	A9	0.30%	0.23%	0.14%	0.10%	Limited
Conversion of neighboring roads into low traffic	A10	3.35%	2.56%	1.59%	1.12%	Critical
Malfunction of nearby movable bridge	A11	0.01%	0.01%	0.00%	0.00%	Negligible
Cautious Driving	A12	2.15%	4.12%	3.21%	2.82%	Negligible
Lowering clear height	A13	7.09%	6.78%	7.05%	6.19%	Critical
Extreme rainfall	A14	5.37%	5.13%	4.80%	4.22%	Negligible
Hailstorm	A15	24.80%	23.72%	28.81%	32.57%	Minor
Thunderstorm	A16	4.12%	3.94%	4.83%	5.40%	Negligible
Extreme hailstorm	A17	12.41%	11.87%	14.49%	16.24%	Minor
Extreme high temperatures	A18	0.00%	0.00%	0.00%	0.00%	Limited
Extreme rainfall after a long period of drought	A19	0.00%	0.00%	0.00%	0.00%	Limited
Grass withering	A20	0.00%	0.00%	0.00%	0.00%	Limited

6.3.2.: Function B

Basic Event: B1: Water on road surface

Although the North Sea level and GWL rise generally in the Netherlands based on the KNMI'14 W_H scenario, the effects on a road tunnel will be little. (Bles, et al., 2012) expects that the sea level rise in highway tunnel locations till 2050 is inconsiderable because the risk of a rise of aquifer hydraulic heads due to climate change is low. This means that a well-maintained road tunnel will not be susceptible to surficial flooding from incoming water underneath the tunnel as the structures are already designed for such pressure. Water on road surface could mainly happen from excessive precipitation volumes. Therefore, in the period of 2050, approximately 9 days per year will be extremely rainy and, in the period of 2100, the days will be approximately 11. These values can be converted into percentage and be 2,5% and 3,0% respectively. Regarding hailstorm events, in the period of 2050, seven hail days per year are proposed (1,9%) and, in the period of 2100, eleven as much (3,0%). The mean time to withdraw the surficial water would be less than a day.

2020-2039: λ:0.044

MTBF:1/λ, MTBF=22.81 days

NA:1/(MTBF+1), NA=0.042

2040-2059: λ:0.044

MTBF:1/λ, MTBF=22.81 days

NA:1/(MTBF+1), NA=0.042

2060-2079: λ:0.06

MTBF:1/λ, MTBF=16.59 days

NA:1/(MTBF+1), NA=0.057

2080-2100: λ:0.06

MTBF:1/λ, MTBF=16.59 days

NA:1/(MTBF+1), NA=0.057

Impact on organizational values

The impact is assessed to be *Minor* because the caused unavailability is less than 1 day, the financial damages will be less than €100k, the impact on the asset quality will be minor and the safety, social environment and reputation will be affected little.

Basic event B2: Solar radiation

The mean solar radiation in the periods 2020-2039 and 2040-2059 is expected 358kJ/cm^2 and slightly increase by 1 kJ/cm^2 the next two periods (*Table II*), this means that solar radiation will be stable in the Netherlands until 2100. It is assumed that the frequency of the moment that the road pavement marking will be unclear to the road users will be once per year. Moreover, the MTTR would be 1 day as well. So, for each time period:

λ:0.0027

MTBF:1/λ, MTBF=365 days

NA:1/(MTBF+1), NA=0.00274

Impact on organizational values

The impact on the organization values, in this case, will be *Minor* based on the description of *Table III* for this impact category.

Basic event B3: Extreme hailstorm

The justification is exact the same with basic event A17.

2020-2039: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:1/(MTBF+1), NA=0.0095

2040-2059: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:1/(MTBF+1), NA=0.0095

2060-2079: λ:0.015

MTBF:1/λ, MTBF=66.36 days

NA:1/(MTBF+1), NA=0.0148

2080-2100: λ:0.0192

MTBF:1/λ, MTBF=52.14 days

NA:1/(MTBF+1), NA=0.0188

Impact on organizational values

The impact will be *Minor* because the incident will make some users to feel uncomfortable, few complaints will arise, the rehabilitation cost will be small and the effect on asset's quality will be minor and so be in organization's reputation.

Basic event B4: Bumps or holes on road pavement

As it is shown in *Table II, i*n 2050 era, thirty-six days per year will be extremely hot showing temperatures more than 25°C and in 2100 the number will rise to forty-eight per year. It means that once per 10 and once per 8 days respectively, extreme hot days will occur in the Netherlands. Therefore, it is assumed that once per 5 years and once per 4 years bumps or holes will be created on the road pavement for the periods 2020-2059 and 2060-2100 respectively. Finally, the mean time to repair is assumed 1 week. The unavailability of the road tunnel is calculated with the same expression.

2020-2039: λ:0.00055

MTBF:1/λ, MTBF=1825 days

NA:7/(MTBF+7), NA=0.000382

2040-2059: λ:0.00055

MTBF:1/λ, MTBF=1825 days

NA:7/(MTBF+7), NA=0.000382

2060-2079: λ:0.000685

MTBF:1/λ, MTBF=66.36 days

NA:7/(MTBF+7), NA=0.00477

2080-2100: λ:0.000685

MTBF:1/λ, MTBF=66.36 days

NA:7/(MTBF+7), NA=0.00477

Impact on organizational values

The impact, in this case, will be *Limited* because it could affect the safety of the road users with light injuries, the local users would be disturbed, the asset would temporarily not comply with service level agreements and constitute unavailable for a week, the reparation costs will be considerable and critical questions by the local press could arise as a result of the aforementioned.

Basic event B5: Surface cracking

The climate scenario W_H will be generally warmer than the other ones with more hot days and fewer ice days. It means that big temperature fluctuations within a day will be minimal. In *Table II* is assumed 61% until 2050 and 80% until 2100 decrease on the number of ice days. The following values are going to be used as enhancing factors:

2020-2039: 0.39

2040-2059: 0.39

2060-2079: 0.20

2080-2100: 0.20

It is assumed that the road surface cracks would make a road tunnel unavailable for operation once per 10 years. Finally, the MTTR would be less than a week of reparation works. Therefore,

2020-2039: λ: (1/10) * 0,39 -> λ: 0,039

MTBF= 1/λ, MTBF: 9,358.97days

NA=7/(MTBF+7), NA=0.000747

2040-2059: λ: (1/10) * 0,39 -> λ: 0,039

MTBF= 1/λ, MTBF: 9,358.97days

NA=7/(MTBF+7), NA=0.000747

2060-2079: λ: (1/10) * 0,2 -> λ: 0,02

MTBF= 1/λ, MTBF: 18,250 days

NA=7/(MTBF+7), NA=0.000383

2080-2100: λ: (1/10) * 0,2 -> -> λ: 0,02

MTBF= 1/λ, MTBF: 18,250 days

NA=7/(MTBF+7), NA=0.000383

Impact on organizational values

The impact will be *Limited* based on the descriptions of *Table III.*

Basic event B6: Insufficient alternative routes

The same assumptions as in the basic event A10 are done in basic event B6. The following reduction factors are defined to be used in the failure rate estimation:

2020-2039: 0.21

2040-2059: 0.168

2060-2079: 0.1344

2080-2100: 0.1075

It is assumed that this basic event will lead to tunnel's unavailability once per 20 years and the MTTR is estimated as 90 days in this case too. At least three months would be needed to improve the traffic direction management sufficiently.

2020-2039: λ: (1/20) * 0,21> λ: 0,0105

MTBF= 1/λ, MTBF: 37,761.90 days

NA=90/(MTBF+90), NA=0.00258

2040-2059: λ: (1/20) * 0,168 -> λ: 0,0084

MTBF= 1/λ, MTBF: 43,452.38 days

NA=90/(MTBF+90), NA=0.00206

2060-2079: λ: 0,00672

MTBF= 1/λ, MTBF: 54.315.47days

NA=90/(MTBF+90), NA=0.00165

2080-2100: λ: 0,005375

MTBF= 1/λ, MTBF: 67,906.97 days

NA=90/(MTBF+90), NA=0.00132

Impact on organizational values

The impact is assessed to be *Critical* for the organization values. Any deviation from this direction could cause very serious injuries, even death, to the road tunnel users the moment that an increase on the number of the vehicles will be noted and consequently the probability for car accident is risen. The legal reequipments of asset's performance would not meet, the national press would criticize the emerging problems and the damages would be excessive both in case of a fatal incident and for the problem's restoration.

Basic event B7: VRI error

The intense weather conditions caused by the climate change seem to affect the VRI system of a road tunnel. In the period of 2050, approximately 9 days per year (2.5%) will be extremely rainy and, in the period of 2100, the days will be approximately 11 (3.0%). Moreover, extreme hailstorms, as it is elaborated in A17 and B3 could disrupt the traffic setting if the traffic signal system cannot adjust rapidly under extreme weather. Therefore, in all time periods, the frequency of that basic event will be the sum of the weather conditions of intense rainfall and hailstorm. The mean time to withdraw the surficial water would at least 4 hours or 0.166 days to 1 day.

2020-2039: λ:0.03459

MTBF:1/λ, MTBF=28.91 days

NA:1/(MTBF+1), NA=0.0334

2040-2059: λ:0.03459

MTBF:1/λ, MTBF=28.91 days

NA:1/(MTBF+1), NA=0.0334

2060-2079: λ:0.045

MTBF:1/λ, MTBF=22.22 days

NA:1/(MTBF+1), NA=0.0431

2080-2100: λ:0.0492

MTBF:1/λ, MTBF=22.22 days

NA:1/(MTBF+1), NA=0.0431

Impact on organizational values

The impact will be *Minor* in this case by supporting exactly the impact descriptions of the five organization values of *Table III.*

Basic event B8: Traffic measurement error

As it is described in *subchapter 5.3.2.*, the justification of the unavailability values is the same with the ones of basic event B7.

2020-2039: λ:0.03459

MTBF:1/λ, MTBF=28.91 days

NA:1/(MTBF+1), NA=0.0334

2040-2059: λ:0.03459

MTBF:1/λ, MTBF=28.91 days

NA:1/(MTBF+1), NA=0.0334

2060-2079: λ:0.045

MTBF:1/λ, MTBF=22.22 days

NA:1/(MTBF+1), NA=0.0431

2080-2100: λ:0.0492

MTBF:1/λ, MTBF=22.22 days

NA:1/(MTBF+1), NA=0.0431

Impact on organizational values

The impact will be *Minor* in this case too.

Basic event B9: Tunnel non-response in traffic alternation

Based on the KNMI’14 report, the days with precipitation volumes more than 10mm are increasing over time. In the period of 2050, the frequency rate will be 2.5% and in 2100, 3.0%. Moreover, the assumptions for the hailstorm evolution in the future in the basic event A15 are embraced in this basic event too. The frequency rate of basic event B9 for every time period will be the sum of the respective frequency rates of extreme rainfall and hailstorm event. Finally, the MTTR is estimated to be four hours.

2020-2039: λ:0.044

MTBF:1/λ, MTBF=22.72 days

NA:0.166/(MTBF+0.166), NA=0.00725

2040-2059: λ:0.044

MTBF:1/λ, MTBF=18.18 days

NA:0.166/(MTBF+0.166), NA=0.00725

2060-2079: λ:0.055

MTBF:1/λ, MTBF=33.33 days

NA:0.166/(MTBF+0.166), NA=0.00905

2080-2100: λ:0.055

MTBF:1/λ, MTBF=33.33 days

NA:0.166/(MTBF+0.166), NA=0.00905

Impact on organizational values

The impact in this case is noted as *Negligible* because of the possible immediate response in such an incident.

Basic event B10: Execution of maintenance works

It is accompted that, in average, once per twenty years major maintenance works will be required because of climate change on a road tunnel asset. The MTTR will be also considerable and is proposed as one month, in average. Therefore, regarding the time periods, the unavailability rate is estimated:

λ:0.05

MTBF:1/λ, MTBF=7300 days

NA:30/(MTBF+30), NA=0.00409

Impact on organizational values

Whenever maintenance works of such a scale will be executed, the impact on organization values is expected to be *Serious.* The costs will be major but less than €1 million, the regional press will criticize the asset's issues causing a damage on organization's reputation, the asset quality will be degraded but still the effects will be recoverable, the social environment will be extensively disturbed if considering one month of tunnel unavailability for maintenance works and finally, the parameter of safety is affected as well with potential serious injuries during such works.

Basic event B11: Short circuit/malfunction

The yearly mean precipitation in the 2050 era is expected 5.05% increase compared with the reference period and in the 2100 era, 7.05%. Moreover, it is assumed that the failure rate of an electronic device due to the presence of moisture is once per 2000 of a wet day. In this way, the failure rate for each time period is estimated based on this failure rate assumption correlated with the yearly mean precipitation increase. Finally, 1 day is defined as MTTR.

2020-2039: λ: (1/2000) *1.0505= 0.000525

MTBF:1/λ, MTBF=1,903.85 days

NA:1/(MTBF+1), NA=0.000525

2040-2059: λ: (1/2000) *1.0505= 0.000525

MTBF:1/λ, MTBF=1,903.85 days

NA:1/(MTBF+1), NA=0.000525

2060-2079: λ: (1/2000) * 1.0705= 0.000535

MTBF:1/λ, MTBF=1,868.29 days

NA:1/(MTBF+1), NA=0.000535

2080-2100: λ: (1/2000) * 1.0705= 0.000535

MTBF:1/λ, MTBF=1,868.29 days

NA:1/(MTBF+1), NA=0.000535

Impact on organizational values

The impact is indicated as *Minor* in this case based on the exact descriptions in *Table III.*

Basic event B12: Partially or entirely external damage

The justification is exact the same with basic event A17 but the MTTR is indicated as more than a day but less than a week which reflects the tunnel's unavailability for operation. In this case, seven days are taken as worst-case scenario.

2020-2039: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:7/(MTBF+7), NA=0.0629

2040-2059: λ:0.00959

MTBF:1/λ, MTBF=104.28 days

NA:7/(MTBF+7), NA=0.0629

2060-2079: λ:0.015

MTBF:1/λ, MTBF=66.66 days

NA:7/(MTBF+7), NA=0.095

2080-2100: λ:0.0192

MTBF:1/λ, MTBF=52.14 days

NA:7/(MTBF+7), NA=0.11836

Impact on organizational values

This basic event could cause *Limited* impact on the organization's values as they are exactly presented in the table.

Basic event B13: Congestion control scenarios failure

In the basic event A12, regarding the cautious driving during a day of extreme bad weather conditions, an assumption was made that drivers will be cautious approximately 4% of the year's days for the time period 2020-2039 and 8% for the rest time periods based on the analysis of the precipitation data on KNMI'14 report. There is a connection between cautious driving and congestion control scenarios failure. The drivers' behavior can change instantly, a fact that these scenarios may not recognize as fast as it should. Therefore, it is assumed that the frequency rate of this basic event is 1% of the cases where the drivers drive cautious under bad weather. Finally, the MTTR of the failure is estimated to a day.

2020-2039: λ:0.0004

MTBF:1/λ, MTBF=2500 days

NA:1/(MTBF+1), NA=0.0004

2040-2059: λ:0.0008

MTBF:1/λ, MTBF=1250 days

NA:1/(MTBF+1), NA=0.0008

2060-2079: λ:0.0008

MTBF:1/λ, MTBF=1250 days

NA:1/(MTBF+1), NA=0.0008

2080-2100: λ:0.0008

MTBF:1/λ, MTBF=1250 days

NA:1/(MTBF+1), NA=0.0008

Impact on organizational values

This basic event could cause *Minor* impact on the organization's values, as the safety will be affected by discomfort to the road users without necessarily complaints from the social environment, the cost will be small, less than €100k and the asset quality and reputation will slightly or even not be affected.

Basic event B14: Emergency services/vehicle disruption

The conversion of some routes, that at the same time could be available as emergency routes, into low traffic ones for sustainability purposes, would affect the emergency services. At this point, the assumptions of basic event A10 could be used but by decreasing the failure rates by a factor of 40%. The same initial failure rate of once per 20 years is applied of such a disruption and a MTTR of 90 days as well because a thorough expert's study should be needed to solve such an issue.

2020-2039: λ:0.0045*0.4 -> λ: 0.0018

MTBF:1/λ, MTBF=202,777.77 days

NA:90/(MTBF+90), NA=0.000444

2040-2059: λ: 0.0036*0.4 -> λ: 0.00144

MTBF:1/λ, MTBF=253,472.22 days

NA:90/(MTBF+90), NA=0.000355

2060-2079: λ: 0.00285*0.4 -> λ: 0.00114

MTBF:1/λ, MTBF=320,175.44 days

NA:90/(MTBF+90), NA=0.000281

2080-2100: λ: 0.00225*0.4 -> λ: 0.0009

MTBF:1/λ, MTBF=405,555.55 days

NA:90/(MTBF+90), NA=0.000222

Impact on organizational values

The impact would be quite considerable in this basic event and would be characterized as *Critical*. The national press would discuss the issue and governmental authorities should express their opinion, inefficient emergency services could cause the death of many people, the road user's would be disturbed in a high level, the asset quality would be thought as degraded because of potential unrecoverable effects excessing the legal requirements of asset's performance and finally, the excessive cost for restoration would impact the financial statement of the asset.

Basic event B15: Blackout

Thunderstorms can be quite intense sometimes causing blackout and therefore unavailability of safety control scenarios to operate as it has been designed. Taken into account the relevant assumptions for the basic event A16 regarding the frequency of thunderstorms per year, which are proposed as 1.9%, 1.9%, 3% and 3% for each time period starting from 2020 till 2100 respectively, it is also assumed that in 5% of the intense thunderstorm cases, a blackout event can happen. Moreover, 4 hours for reparation are given as MTTR.

2020-2039: λ:0.019*0.05 -> λ: 0.00095

MTBF:1/λ, MTBF=1,052.63 days

NA:0.166/(MTBF+0.166), NA=0.000158

2040-2059: λ:0.019*0.05 -> λ: 0.00095

MTBF:1/λ, MTBF=1,052.63 days

NA:0.166/(MTBF+0.166), NA=0.000158

2060-2079: λ: 0.03*0.05 -> λ: 0.0015

MTBF:1/λ, MTBF=666.666 days

NA:0.166/(MTBF+0.166), NA=0.00025

2080-2100: λ: 0.03*0.05 -> λ: 0.0015

MTBF:1/λ, MTBF=666.666 days

NA:0.166/(MTBF+0.166), NA=0.00025

Impact on organizational values

Such an event would cause little economic damage that could be thought as *Negligible.* The safety requirements, however, could not be met in an incident of a blackout but still could be considered as negligible. The asset quality and reputation would slightly be affected mainly because of the nature of the basic event.

Table VI: Synopsis of the values of unavailability rate of each basic event for every time period and qualitative characterization of the associated impact referring to Function B

Basic events		2040	2060	2080	2100	Impact
Water on road surface	B1	20.97%	20.99%	20.48%	18.65%	Minor
Solar radiation	B2	1.31%	1.32%	0.93%	0.85%	Minor
Extreme hailstorm	B3	4.59%	4.59%	5.09%	4.64%	Minor
Bumps or holes on road pavement	B4	0.18%	0.18%	1.62%	1.48%	Limited
Surface cracking	B5	0.36%	0.36%	0.13%	0.12%	Limited
Insufficient alternative routes	B6	1.24%	0.99%	0.56%	0.41%	Critical
VRI error	B7	16.53%	16.54%	15.26%	13.90%	Minor
Traffic measurement error	B8	16.53%	16.54%	15.26%	13.90%	Minor
Tunnel tube non response in traffic alternation order	B9	3.49%	3.50%	3.09%	2.82%	Negligible
Execution of maintenance works	B10	1.96%	1.97%	1.39%	1.27%	Serious
Short circuit/malfunction	B11	0.25%	0.25%	0.18%	0.17%	Minor
Partially or entirely external damage	B12	32.11%	32.14%	35.56%	41.42%	Limited
Congestion control scenarios failure	B13	0.19%	0.38%	0.27%	0.25%	Minor
Emergency service/ Vehicle disruption	B14	0.21%	0.17%	0.10%	0.07%	Critical
Blackout	B15	0.08%	0.08%	0.08%	0.08%	Negligible

6.3.3: Function C

Basic event C1: Delay in communicating traffic changes

Assessing the values of *Table III* regarding the precipitation variables, it is estimated that approximately 5% of the days per year unexpected weather conditions will happen in 2050 era and 8% in 2100 era. Some of them can be the reason for causing events related to traffic communication that could frustrate the road tunnel users. One third of those days could be the case of creating the feeling of insecurity, which in unacceptable, because the road tunnel is unprepared to connect with the road network traffic management facilities which is reflected as unavailability. If the MTTR is concerned, any work for restoration could even take a day.

2020-2039: λ: (0.05 * 365 * (1/3))/365 -> λ: 0.0166

MTBF:1/λ, MTBF=60 days

NA:1/(MTBF+1), NA=0.0164

2040-2059: λ: (0.05 * 365 * (1/3))/365 -> λ: 0.0166

MTBF:1/λ, MTBF=60 days

NA:1/(MTBF+1), NA=0.0164

2060-2079: λ: (0.08 * 365 * (1/3))/365 -> λ: 0.0266

MTBF:1/λ, MTBF=37.5 days

NA:1/(MTBF+1), NA=0.026

2080-2100: λ: (0.08 * 365 * (1/3))/365 -> λ: 0.0266

MTBF:1/λ, MTBF=37.5 days

NA:1/(MTBF+1), NA=0.026

Impact on organizational values

It is characterized as *Minor* impact on the six organization values based on the descriptions of *Table III.*

Basic event C2: Wrong provision of information

The meaning of this basic event is broader than the C1, it can happen under the same conditions but rarely. Therefore, it is assumed, one fourth of those days, wrong provision of information could be done. Finally, any work for restoration of the problem could be minimal, like 4 hours.

2020-2039: λ: (0.05 * 365 * (1/4))/365 -> λ: 0.0125

MTBF:1/λ, MTBF=80 days

NA:0.166/(MTBF+0.166), NA=0.00208

2040-2059: λ: (0.05 * 365 * (1/4))/365 -> λ: 0.0125

MTBF:1/λ, MTBF=80 days

NA:0.166/(MTBF+0.166), NA=0.00208

2060-2079: λ: (0.08 * 365 * (1/4))/365 -> λ: 0.02

MTBF:1/λ, MTBF=50 days

NA:0.166/(MTBF+0.166), NA=0.00331

2080-2100: λ: (0.08 * 365 * (1/4))/365 -> λ: 0.02

MTBF:1/λ, MTBF=50 days

NA:0.166/(MTBF+0.166), NA=0.00331

Impact on organizational values

It is characterized as *Minor* impact on the six organization values based on the descriptions of *Table III.*

Basic event C3: Hailstorm

The figures of basic event A15 regarding the expected hailstorms in the future are considered. However, a factor is needed to assess the frequency rate for each period because not every hailstorm event would result in an insufficient drainage system to handle such a storm. Considering that the amount of hailstorm is increasing over time and so does the size of the hailstones, it is assumed that one fifth of the hailstorm incidents could lead to a road tunnel unavailability for operation. Moreover, less than 1 day is assumed as downtime for the road tunnel to become available for operation again.

2020-2039: λ:0.019 * (1/5) -> λ: 0.0038

MTBF:1/λ, MTBF=263.16 days

NA:1/(MTBF+1), NA=0.00378

2040-2059: λ:0.019 * (1/5) -> λ: 0.0038

MTBF:1/λ, MTBF=263.16 days

NA:1/(MTBF+1), NA=0.00378

2060-2079: λ:0.03 * (1/5) -> λ: 0.006

MTBF:1/λ, MTBF=166.67 days

NA:1/(MTBF+1), NA=0.00596

2080-2100: λ:0.038 * (1/5) -> λ: 0.0076

MTBF:1/λ, MTBF=131.58 days

NA:1/(MTBF+1), NA=0.00754

Impact on organizational values

The impact is assessed to be *Minor* based on the exact descriptions of *Table III.*

Basic event C4: Extreme shower

In the period of 2050, 9 days per year will be extremely rainy and this increases by 3 more days (11) in 2100 (*Table III*). Therefore, the frequency rate for the time periods 2020-2039, 2040-2059 is formed as 2.5% and for the time periods 2060-2079 and 2080-2100 as 3%. At the same time, the mean time to repair and restore the drainage system could be at least 1 day of works in the road tunnel's field.

2020-2039: λ:0.025

MTBF:1/λ, MTBF=40.55 days

NA:1/(MTBF+1), NA=0.024

2040-2059: λ:0.025

MTBF:1/λ, MTBF=40.55 days

NA:1/(MTBF+1), NA=0.024

2060-2079: λ:0.03

MTBF:1/λ, MTBF=33.18 days

NA:1/(MTBF+1), NA=0.029

2080-2100: λ:0.03

MTBF:1/λ, MTBF=33.18 days

NA:1/(MTBF+1), NA=0.029

Impact on organizational values

The impact is assessed to be *Limited* because in case of an event of extreme shower where the drainage system becomes insufficient to perform on demand, some light injuries on the road users could be the result of the presence of surficial waters. Subsequently, the social environment would clearly be affected by this disturbance, the local press would discuss intensely about the incident reflecting that on the asset's organization reputation and asset's quality regarding its performance capabilities. Finally, the damages level would characterize as moderate exceeding €100k but not more than €500k.

Basic event C5: Extreme temperature

In basic event A18, the expected frequency rates of extreme temperature are elaborated for the era 2050 (10%) and 2100 (13%) which are used as well in this case. The sensors are supposed to fail to perform well once per 50 days of extreme high temperature for the era of 2050 and once per 35 for the era of 2100. The MTTR is approximately 4 days.

2020-2039: λ:0.1 * (1/50) -> λ:0.002

MTBF:1/λ, MTBF= 500 days

NA:4/(MTBF+4), NA=0.00794

2040-2059: λ:0.002

MTBF:1/λ, MTBF= 500 days

NA:4/(MTBF+4), NA=0.00794

2060-2079: λ:0.13 * (1/35) -> λ: 0.00371

MTBF:1/λ, MTBF= 269.23 days

NA:4/(MTBF+4), NA=0.0148

2080-2100: λ: 0.00371

MTBF:1/λ, MTBF= 269.23 days

NA:4/(MTBF+4), NA=0.0148

Impact on organizational values

The impact could be *Limited* as exactly it is stated in *Table III.*

Basic event C6: High precipitation volume

The values of basic event C4 are used in this case for every time period by multiplying the frequency rate a sensor to fail to perform well during a high precipitation event. Once per 50 incidents and once per 35 incidents are the factors for the era 2050 and 2100, respectively. The MTTR is assigned to be 4 days.

2020-2039: λ:0.025 * (1/50) -> λ: 0.0005

MTBF:1/λ, MTBF=2000 days

NA:4/(MTBF+4), NA=0.002

2040-2059: λ: 0.0005

MTBF:1/λ, MTBF=2000 days

NA:4/(MTBF+4), NA=0.002

2060-2079: λ:0.03 * (1/35) -> λ: 0.00086

MTBF:1/λ, MTBF=1,166.67 days

NA:4/(MTBF+4), NA=0.00341

2080-2100: λ: 0.00086

MTBF:1/λ, MTBF=1,166.67 days

NA:4/(MTBF+4), NA=0.00341

Impact on organizational values

The impact could be *Limited* as exactly it is stated in *Table III.*

Basic event C7: Exceedance of vehicle capacity

In the basic event A8, it was assumed that there is 30% chance for new demands for public transportation in the time period 2020-2039 and 80% for the other three periods. Therefore, at the same time, there will be an increase generally in the number of commuters by any kind of vehicle. The exceedance of the vehicle capacity is, however, another story which could affect the ventilation system. It is assumed that there is 20% to be happened for the time periods 2020-2039 and 2040-2059 and 30% for 2060-2079 and 2080-2100. As frequency of such an issue is proposed, once per 20 years and MTTR, 60 days.

2020-2039: λ:(1/20) * (0.2) -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2040-2059: -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2060-2079: λ:(1/20) * (0.3) -> λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

2080-2100: λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

Impact on organizational values

It will be *Critical* because an effect on the ventilation system of the road tunnel, the organization values would be affected intensely, especially the parameter of safety, asset quality, finance, and reputation.

Basic event C8: Fire by an electric car crash

Until 2050 half of the vehicles will be electric and until 2100 this could be even more than 80% of the vehicles globally. Half of the car crashes, electric vehicles would be involved. The design of ventilation system would need upgrade regarding the density and volume of smoke is capable to proceed in an event of a car crash fire. It is assumed that three car crash incidents, including an electric car, per ten years will initiate a fire that will be hardly dealt with the existent ventilation year for the time period 2020-2039, four incidents for the time period 2040-2059 and five incidents for the time period 2060-2079 and 2080-2100. The MTTR of ventilation system would be 40 days.

2020-2039: λ:0.3

MTBF:1/λ, MTBF=1,216.67 days

NA:40/(MTBF+40), NA=0.0318

2040-2059: λ: 0.4

MTBF:1/λ, MTBF=912.5 days

NA:40/(MTBF+40), NA=0.042

2060-2079: λ:0.5

MTBF:1/λ, MTBF=730 days

NA:40/(MTBF+40), NA=0.052

2080-2100: λ:0.5

MTBF:1/λ, MTBF=730 days

NA:40/(MTBF+40), NA=0.052

Impact on organizational values

It is indicated as *Critical* because of the severe consequences that this basic event could bring about on the organization values as it is described in *Table III.*

Table VII: Synopsis of the values of unavailability rate of each basic event for every time period and qualitative characterization of the associated impact referring to Function C

Basic events		2040	2060	2080	2100	Impact
Delay in communicating traffic changes	C1	18.20%	16.25%	18.85%	18.64%	Minor
Wrong provision of information	C2	2.27%	2.03%	2.34%	2.32%	Minor
Hailstorm	C3	4.14%	3.70%	4.23%	5.30%	Minor
Extreme shower	C4	26.83%	23.96%	21.09%	20.85%	Limited
Extreme temperature	C5	8.73%	7.80%	10.61%	10.49%	Limited
High precipitation voulme	C6	2.19%	1.95%	2.42%	2.39%	Limited
Exceedance of vehicle capacity	C7	1.79%	1.60%	1.74%	1.72%	Critical
Fire by an electric car crash	C8	35.84%	42.72%	38.73%	38.29%	Critical

6.3.4.: Function D

Basic event D1: Damage in digital installations

The hailstorm assumptions of basic event A15 are used in this case as well. However, not every hailstorm event can cause external damages in the digital installations of a road tunnel section. It is assumed that 10% of the cases will be catastrophic for such facilities for the 2050 era and 15% for the 2100. Moreover, less than 1 day is assumed as MTTR for the road tunnel to become available for operation again.

2020-2039: λ:0.019 * 0.1 -> λ: 0.0019

MTBF:1/λ, MTBF=526.32 days

NA:1/(MTBF+1), NA=0.0019

2040-2059: λ: 0.0019

MTBF:1/λ, MTBF=526.32 days

NA:1/(MTBF+1), NA=0.0019

2060-2079: λ:0.03 * 0.15 -> λ: 0.0045

MTBF:1/λ, MTBF= 222.22 days

NA:1/(MTBF+1), NA=0.00448

2080-2100: λ: 0.0045

MTBF:1/λ, MTBF= 222.22 days

NA:1/(MTBF+1), NA=0.00448

Impact on organizational values

The impact of this basic event on the organization values is expected to be *Minor* because the damage restoration can be quick with few or without considerable issues.

Basic event D2: Intense raining

The wet days with precipitation more than 10mm are increasing based on the KNMI'14 report. In the period 2050, they are expected to be 9 days, in average and in 2100, 11. Reflecting this information into the four time periods, it is assumed that the frequency rate for the periods 2020-2039 and 2040-2059 will be 2.5% and for the other two, 3%. However, not every intensely rainy day leads to technical malfunctions of road tunnel installations. Therefore, for the first two time periods, it is thought that 10% of those cases would lead to failures and for the periods 2060-2079 and 2080-2100, this will be 15% because of the increasing rainfall intensity which is expected after the second half of 21st century. Finally, 1 day is considered as average time for MTTR.

2020-2039: λ:0.025 * 0.1 -> λ: 0.0025

MTBF:1/λ, MTBF=400 days

NA:1/(MTBF+1), NA=0.0025

2040-2059: λ: 0.0025

MTBF:1/λ, MTBF=400 days

NA:1/(MTBF+1), NA=0.0025

2060-2079: λ:0.03 * 0.15 -> λ: 0.0045

MTBF:1/λ, MTBF= 222.22 days

NA:1/(MTBF+1), NA=0.00448

2080-2100: λ: 0.0045

MTBF:1/λ, MTBF= 222.22 days

NA:1/(MTBF+1), NA=0.00448

Impact on organizational values

It is thought to be *Minor* because it reflects exactly the descriptions of *Table III.*

Basic event D3: Hot day

The same perspective as in the basic event C5 is supported in this case as well.

2020-2039: λ:0.1 * (1/50) -> λ:0.002

MTBF:1/λ, MTBF= 500 days

NA:4/(MTBF+4), NA=0.00794

2040-2059: λ:0.002

MTBF:1/λ, MTBF= 500 days

NA:4/(MTBF+4), NA=0.00794

2060-2079: λ:0.13 * (1/35) -> λ: 0.00371

MTBF:1/λ, MTBF= 269.23 days

NA:4/(MTBF+4), NA=0.0148

2080-2100: λ: 0.00371

MTBF:1/λ, MTBF= 269.23 days

NA:4/(MTBF+4), NA=0.0148

Impact on organizational values

The impact could be *Limited* as exactly it is stated in *Table III.*

Basic event D4: Ice day

Based on *Table II,* there is a decrease of the ice days in 2050 and 2100, 60% and 80% respectively. The frequency rate of those days is 4,1% and 2,2% for the corresponding periods. Again, not every ice day leads to technical malfunction in digital installations that communicate road traffic messages to the road users. Therefore, it is assumed that once per 50 incidents for the era 2050 and once per 70 for the era 2100 will be the case. Regarding the MTTR of such technical issues, it is assumed to be 1 day.

2020-2039: λ:0.041 * (1/50) -> λ:0.00082

MTBF:1/λ, MTBF= 1,219.5 days

NA:4/(MTBF+4), NA=0.0008

2040-2059: λ:0.0002

MTBF:1/λ, MTBF= 5000 days

NA:4/(MTBF+4), NA=0.0008

2060-2079: λ:0.013 * (1/35) -> λ: 0.000371

MTBF:1/λ, MTBF= 2,692.31 days

NA:4/(MTBF+4), NA=0.00148

2080-2100: λ: 0.000371

MTBF:1/λ, MTBF= 2,692.31 days

NA:4/(MTBF+4), NA=0.00148

Impact on organizational values

The impact could be *Limited* as exactly it is stated in *Table III.*

Basic event D5: Insufficient audio guidance

The frequency of thunderstorms in every time period is proposed as 1.9%, 1.9%, 3% and 3.8% respectively. Moreover, it is assumed that once per 50 thunderstorm events potential audio guidance will be hardly to communicate to the road users because of the noise nuisance that is caused. The road tunnel will not be able to fulfill its requirements which is reflected as unavailability for operation properly. Finally, four hours are assumed as mean time to repair for the road tunnel to become available for operation again.

2020-2039: λ:0.019 * (1/50) -> λ: 0.00038

MTBF:1/λ, MTBF=2,631.58 days

NA:0.166/(MTBF+0.166), NA=$6.31*10^{-5}$

2040-2059: λ: 0.00038

MTBF:1/λ, MTBF=2,631.58 days

NA:0.166/(MTBF+0.166), NA=$6.31*10^{-5}$

2060-2079: λ:0.03 * (1/50) -> λ: 0.0006

MTBF:1/λ, MTBF=1,666.67 days

NA:0.166/(MTBF+0.166), NA=10^{-4}

2080-2100: λ: 0.0006

MTBF:1/λ, MTBF=1,666.67 days

NA:0.166/(MTBF+0.166), NA=10^{-4}

Impact on organizational values

This basic event indicates that the impact on the organization values would be *Negligible* because the restoration of the problem will be affordable, easy to be done and the effects on the social environment and safety can be managed without casualties.

Basic event D6: Weak mobile signal

The frequency rates of basic event D5 are implemented in this basic event as well but the mobile signal weakness is assumed to happen once per 10 such events. The MTTR remains the same, 4 hours.

2020-2039: λ:0.019 * (1/10) -> λ: 0.0019

MTBF:1/λ, MTBF=526.32 days

NA:0.166/(MTBF+0.166), NA=0.000315

2040-2059: λ: 0.0019

MTBF:1/λ, MTBF=526.32 days

NA:0.166/(MTBF+0.166), NA=0.000315

2060-2079: λ:0.03 * (1/10) -> λ: 0.003

MTBF:1/λ, MTBF=333.33 days

NA:0.166/(MTBF+0.166), NA=0.0005

2080-2100: λ: 0.003

MTBF:1/λ, MTBF=333.33 days

NA:0.166/(MTBF+0.166), NA=0.0005

Impact on organizational values

This basic event indicates that the impact on the organization values would be *Negligible* because the restoration of the problem will be affordable, easy to be done and the effects on the social environment and safety can be managed without casualties.

Basic event D7: Exceedance of vehicle capacity

The justification of the reasoning for this basic event derives from the one o basic event C7, it is exact the same. As frequency of such an issue is proposed, once per 20 years and MTTR, 60 days.

2020-2039: λ:(1/20) * (0.2) -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2040-2059: -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2060-2079: λ:(1/20) * (0.3) -> λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

2080-2100: λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

Impact on organizational values

It will be *Critical* because an effect on the ventilation system of the road tunnel, the organization values would be affected intensely, especially the parameter of safety, asset quality, finance, and reputation.

Basic event D8: Essential tunnel evacuation

The road tunnel can become unavailable for its users to communicate with the emergency services just like in the basic event D7. This means that the values of basic event D7 are used in this event as well.

2020-2039: λ:(1/20) * (0.2) -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2040-2059: -> λ: 0.01

MTBF:1/λ, MTBF=36,500 days

NA:60/(MTBF+60), NA=0.00164

2060-2079: λ:(1/20) * (0.3) -> λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

2080-2100: λ: 0.015

MTBF:1/λ, MTBF=24,333.33 days

NA:60/(MTBF+60), NA=0.00246

Impact on organizational values

The impact would be *Critical* whether the road tunnel become unavailable for communication with emergency services when this is needed.

Table VIII: Synopsis of the values of unavailability rate of each basic event for every time period and qualitative characterization of the associated impact referring to Function D

Basic events		2040	2060	2080	2100	Impact
Damage in digital installations	D1	14.00%	14.00%	17.23%	17.23%	Minor
Intense raining	D2	18.43%	18.43%	17.23%	17.23%	Minor
Hot day	D3	58.86%	58.86%	57.52%	57.52%	Limited
Ice day	D4	5.89%	5.89%	5.68%	5.68%	Limited
Insufficient audio guidance	D5	0.46%	0.46%	0.38%	0.38%	Negligible
Weak mobile signal	D6	2.32%	2.32%	1.92%	1.92%	Negligible
Exceedance of vehicle capacity	D7	0.02%	0.02%	0.02%	0.02%	Critical
Essential tunnel evacuation	D8	0.02%	0.02%	0.02%	0.02%	Critical

6.3.5.: Function E

Basic event E1: Tunnel design for nuisance prevention

As it has been written, an increase in the number of commuters in the future could be expected potentially in the location of a road tunnel system. The noise and visual nuisance to the surrounding inhabitants would be of such a scale which would require a road tunnel design update to deal with such an issue in the future. It is assumed that such interventions would be required once per 40 years, responding to the time periods of 2050 and 2100, which would make the road tunnel unavailable for operation. Moreover, the frequency could potentially even be enhanced, therefore, it is assumed for the time period 2020-2039, 5%, in the period 2040-2059, 10%, in 2060-2079, 15% and in 2080-2100, 20%. Finally, as MTTR, 90 days are assigned for intervention works.

2020-2039: λ:(1/40) * (1.05) -> λ: 0.02625

MTBF:1/λ, MTBF=13,904.76 days

NA:90/(MTBF+90), NA=0.00643

2040-2059: λ:(1/40) * (1.1) -> λ: 0.0275

MTBF:1/λ, MTBF=13,272.73 days

NA:90/(MTBF+90), NA=0.00674

2060-2079: λ:(1/40) * (1.15) -> λ: 0.02875

MTBF:1/λ, MTBF=12,695.65 days

NA:90/(MTBF+90), NA=0.00704

2080-2100: λ:(1/40) * (1.2) -> λ: 0.03

MTBF:1/λ, MTBF=12,166.67 days

NA:90/(MTBF+90), NA=0.00734

Impact on organizational values

The impact of such a basic event on safety, social environment, asset quality, finance, reputation, and availability would be *Critical* based on the descriptions of *Table III.*

Basic event E2: Maintenance works

The impact of the climate variables on a road tunnel system has been elaborated as considerable the next decades. Long-term maintenance works are executed every 25-50 years, however, considering these effects, some works should be done sooner or more frequent that it was expected. Therefore, it is assumed a frequent rate of once per 20 years in average for major interventions for the time periods 2020-2039 and 2040-2059 and once per 15 years for 2060-2079 and 2080-2100. Finally, 90 days of works are considered to define the MTTR.

2020-2039: λ: 1/20 -> λ: 0.05

MTBF:1/λ, MTBF=7,300 days

NA:90/(MTBF+90), NA=0.0122

2040-2059: λ: 0.05

MTBF:1/λ, MTBF=7,300 days

NA:90/(MTBF+90), NA=0.0122

2060-2079: λ:1/15-> λ: 0.066

MTBF:1/λ, MTBF=5,475 days

NA:90/(MTBF+90), NA=0.0162

2080-2100: λ: 0.066

MTBF:1/λ, MTBF=5,475 days

NA:90/(MTBF+90), NA=0.0162

Impact on organizational values

The impact of such frequent major interventions would be categorized as *Critical* for the organization values of safety, social environment, asset quality, finance, reputation, and availability.

Basic event E3: CO_2-induced penetration/Carbonation

The unavailability rates are resulted from the same frequency rates as they are described in basic event A4. Moreover, the needed MTTR is assumed 50 days too.

2020-2039: λ: (1/20) * 1,2 -> λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2040-2059: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2060-2079: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

2080-2100: λ: 0,06

MTBF= 1/λ, MTBF: 6,083.33 days

NA=50/(MTBF+50), NA=0.00815

Impact on organization values

The impact is indicated as *Critical* mainly because of the severe consequences on availability, safety, asset quality and finance.

Basic event E4: Chloride ions-induced penetration

The unavailability rates are resulted from the same frequency rates as they are described in basic event A5. Moreover, the needed MTTR is assumed 50 days too.

2020-2039: λ: (1/30) * 1,06 -> λ: 0,0353

MTBF= 1/λ, MTBF: 10,330.19 days

NA=50/(MTBF+50), NA=0.0048

2040-2059: λ: (1/30) * 1,06 -> λ: 0,0353

MTBF= 1/λ, MTBF: 10,330.19 days

NA=50/(MTBF+50), NA=0.0048

2060-2079: λ: (1/30) * 1,15 -> λ: 0,0383

MTBF= 1/λ, MTBF: 9,521.74 days

NA=50/(MTBF+50), NA=0.0052

2080-2100: λ: (1/30) * 1,15 -> λ: 0,0383

MTBF= 1/λ, MTBF: 9,521.74 days

NA=50/(MTBF+50), NA=0.0052

Impact on organization values

The impact is indicated as *Critical* mainly because of the severe consequences on availability, safety, asset quality and finance.

Basic event E5: Inadequate architectural design

Inadequate architectural design can be caused by the extensive changes of climate. At the same way as in basic event E2, it is assumed a frequent rate of once per 20 years in average for major architectural design interventions for the time periods 2020-2039 and 2040-2059 and once per 15 years for 2060-2079 and 2080-2100. Finally, 90 days of works are considered to define the MTTR.

2020-2039: λ: 1/20 -> λ: 0.05

MTBF:1/λ, MTBF=7,300 days

NA:90/(MTBF+90), NA=0.0122

2040-2059: λ: 0.05

MTBF:1/λ, MTBF=7,300 days

NA:90/(MTBF+90), NA=0.0122

2060-2079: λ:1/15-> λ: 0.066

MTBF:1/λ, MTBF=5,475 days

NA:90/(MTBF+90), NA=0.0162

2080-2100: λ: 0.066

MTBF:1/λ, MTBF=5,475 days

NA:90/(MTBF+90), NA=0.0162

Impact on organizational values

Such major interventions and changes would impact the organization values in *Critical* way, as it is described in *Table III.*

Basic event E6: Unstable land

As it is stated in basic event B1, any positive groundwater level change in the road tunnel location would impact any civil or soil structure. It was assumed that 30%, 45%, 60% and 75% of the road tunnel will experience such changes for each time period starting from 2020 until 2100. Moreover, it is postulated that this GWL change would result in unstable land once per 50 years considering the potential degrading soil banking structures in the future which in turn would even result in tunnel structure design failure. Finally, 60 days are proposed as MTTR.

2020-2039: λ: (1/50) * 0,3 -> λ: 0,006

MTBF= 1/λ, MTBF: 60,833.33 days

NA=60/(MTBF+60), NA=0.000985

2040-2059: λ: (1/50) * 0,45 -> λ: 0,009

MTBF= 1/λ, MTBF: 40,555.55 days

NA=60/(MTBF+60), NA=0.00147

2060-2079: λ: (1/50) * 0,6 -> λ: 0,012

MTBF= 1/λ, MTBF: 30,416.67 days

NA=60/(MTBF+60), NA=0.00197

2080-2100 λ: (1/50) * 0,75 -> λ: 0,015

MTBF= 1/λ, MTBF: 24,333.33 days

NA=60/(MTBF+60), NA=0.00246

Impact on organizational values

The impact is assessed to be *Critical* in this case.

Basic event E7: Urban recreation

The works for urban recreation around the road tunnel if the last need adjustments to continue fulfilling its requirements could happen once per 20 years only if major interventions on the structure are required. Therefore, for the time period 2020-2039, it is expected as 30% to happen, and for every next time period, 80% less chance of the previous one. So, in 2040-2059, 24%, in 2060-2079, 19% and in 2080-2100, 15%. As MTTR, 90 days are expected to be needed.

2020-2039: λ: (1/20) * 0,3 -> λ: 0,015

MTBF= 1/λ, MTBF: 24,333.33 days

NA=90/(MTBF+90), NA=0.00369

2040-2059: λ: (1/20) * 0,24 -> λ: 0,012

MTBF= 1/λ, MTBF: 30,416.67 days

NA=90/(MTBF+90), NA=0.00295

2060-2079: λ: (1/20) * 0,19 -> λ: 0,0095

MTBF= 1/λ, MTBF: 38,421.05 days

NA=90/(MTBF+90), NA=0.00234

2080-2100 λ: (1/20) * 0,15 -> λ: 0,0075

MTBF= 1/λ, MTBF: 48,666.67 days

NA=90/(MTBF+90), NA=0.00185

Impact on organizational values

The effects on the organization values are thought to be *Critical* if a road tunnel become unavailable by this basic event.

Basic event E8: Excessive strain on the existent structure

The basic event is highly caused by the positive GWL, the land subsidence and generally higher traffic loads over the next decades. Based on the data regarding the GWL and land subsidence, it is assumed that such a basic event could happen once per 20 years by multiplied, for each time period, a reduction factor which reflects the expected percentage of road tunnels that will experience such an issue. For the time period 2020-2039, 30% of tunnels could be dealt with that, in 2040-2059, 45%, in 2060-2079, 60% and in 2080-2100, 75%. The increase of traffic load is expected to happen in any case. Finally, the MTTR is expected to be 70 days to deal with any required works that make the road tunnel unavailable for operation.

2020-2039: λ: (1/20) * 0,3 -> λ: 0,015

MTBF= 1/λ, MTBF: 24,333.33 days

NA=70/(MTBF+70), NA=0.00286

2040-2059: λ: (1/20) * 0,45 -> λ: 0,0225

MTBF= 1/λ, MTBF: 16,222.22 days

NA=70/(MTBF+70), NA=0.0043

2060-2079: λ: (1/20) * 0,60 -> λ: 0,03

MTBF= 1/λ, MTBF: 12,166.67 days

NA=70/(MTBF+70), NA=0.0057

2080-2100 λ: (1/20) * 0,75 -> λ: 0,0375

MTBF= 1/λ, MTBF: 9,733.33 days

NA=70/(MTBF+70), NA=0.0071

Impact on organizational values

The impact of such a basic event on the organization values is estimated to be *Critical.* The unavailability of the road tunnel will be extended because extensive interventions on the tunnel structure would be needed. The social environment would criticize the operability of the road tunnel affecting the organization's reputation, financial terms and asset's quality. Finally, the impact on safety parameter would be very serious in case of structural collapse would happen because of excessive strain.

Table I: Synopsis of the values of unavailability rate of each basic event for every time period and qualitative characterization of the associated impact referring to Function E

Basic events		2040	2060	2080	2100	Impact
Tunnel design for nuisance prevention	E1	12.50%	12.74%	11.16%	11.33%	Critical
Maintenance works	E2	23.86%	23.18%	25.92%	25.24%	Critical
CO_2-induced penetration-carbonation	E3	15.87%	15.42%	12.94%	12.59%	Critical
Chloride ions-induced penetration	E4	9.32%	9.05%	8.23%	8.01%	Critical
Inadequate architectural design	E5	23.86%	23.18%	25.92%	25.24%	Critical
Unstablle land	E6	1.90%	2.76%	3.11%	3.78%	Critical
Urban recreation	E7	7.15%	5.55%	3.69%	2.84%	Critical
Excessive strain on the existent structure	E8	5.54%	8.11%	9.03%	10.96%	Critical

Appendix – subchapter 8.1.

8.1.2.: The scoring tables for ordering the Mitigative Measures

Function A

		Impact						
		Safety	**Social Environment**	**Asset quality**	**Finance**	**Reputation**	**Availabiility**	**Score**
A1	M.A.1.i	1	0	2	0	2	3	1.333
	M.A.1.iv	2	1	3	-1	2	2	1.5
A2	M.A.2.i	2	0	1	-1	2	1	0.833
	M.A.2.iv	3	0	2	-2	3	2	1.333
A3	M.A.3.i	1	0	0	0	1	1	0.5
	M.A.3.iv	2	1	2	-2	1	2	1
A4	M.A.4.i	2	0	2	1	2	-1	1
	M.A.4.ii	3	0	2	2	2	-1	1.333
A5	M.A.5.i	1	0	1	0	0	0	0.333
	M.A.5.ii	2	1	2	-1	1	-1	0.667
	M.A.5.iii	3	1	3	-2	1	-1	0.833
A6	M.A.6.i	0	0	1	0	0	1	0.333
	M.A.6.iii	1	1	0	0	0	1	0.5
A7	M.A.7.iv	1	0	2	0	1	-1	0.5
A8	M.A.8.i	1	1	1	0	1	1	0.833
	M.A.8.iii	2	1	2	-1	2	2	1.333
	M.A.8.iv	3	2	3	-2	3	2	1.833
A9	M.A.9.iv	2	1	2	-1	0	2	1
A10	M.A.10.i	1	1	1	1	1	1	1
	M.A.10.iv	3	2	3	-2	3	2	1.833
A13	M.A.13.i	3	1	2	1	1	3	1.833
A18	M.A.18.ii	2	2	2	0	2	2	1.667
	M.A.18.iv	3	2	2	-2	1	1	1.167
A19	M.A.19.ii	2	2	2	0	2	2	1.667
	M.A.19.iv	3	2	2	-2	1	1	1.167
A20	M.A.20.ii	2	2	2	0	2	2	1.667
	M.A.20.iv	3	2	2	-2	1	1	1.167
Legend:	− 2: Large negative impact, − 1: Negative impact, 0: No or Minor impact, +1: Positive impact, +2: Moderate impact, +3: Very positive impact							

Function B

		Impact						
		Safety	Social Environment	Asset quality	Finance	Reputation	Availabiility	Score
B4	M.B.4.i.	1	1	2	0	1	0	0.833
	M.B.4.ii	2	1	3	-1	1	-1	0.833
B5	M.B.5.iv	1	1	2	0	1	0	0.833
B6	M.B.6.ii	3	2	1	-1	2	2	1.5
	M.B.6.iv	2	2	2	0	1	1	1.333
B10	M.B.10.iv	3	1	0	-1	0	1	0.667
B12	M.B.12.iv	3	2	1	0	1	1	1.333
B14	M.B.14.ii	3	1	2	2	1	3	2
Legend:	− 2: Large negative impact, −1: Negative impact, 0: No or Minor impact, +1: Positive impact, +2: Moderate impact, +3: Very positive impact							

Function C

		Impact						
		Safety	Social Environment	Asset quality	Finance	Reputation	Availabiility	Score
C4	M.C.4.i	2	2	1	0	0	0	0.833333
	M.C.4.iv	3	2	2	-1	2	0	1.333333
C5	M.C.5.i	1	1	1	2	1	0	1
	M.C.5.ii	2	2	2	-1	2	1	1.333333
	M.C.5.iv	1	1	2	1	2	1	1.333333
C6	M.C.6.i	1	1	1	2	1	0	1
	M.C.6.ii	2	2	2	-1	2	1	1.333333
	M.C.6.iv	1	1	2	1	2	1	1.333333
C7	M.C.7.i	1	0	1	-1	0	1	0.333333
	M.C.7.iii	2	0	2	-1	1	2	1
C8	M.C.8.i	2	2	1	0	0	1	1
	M.C.8.ii	2	1	2	-1	1	1	1
	M.C.8.iv	3	1	3	-2	2	2	1.5
Legend:	−2: Large negative impact, −1: Negative impact, 0: No or Minor impact, +1: Positive impact, +2: Moderate impact, +3: Very positive impact							

Function D

		Impact						Score
		Safety	Social Environment	Asset quality	Finance	Reputation	Availabiility	
D3	M.D.3.ii	1	1	1	1	0	0	0.666667
	M.D.3.iv	2	1	1	-2	0	1	0.5
D4	M.D.4.ii	1	1	1	1	0	0	0.666667
	M.D.4.iv	2	1	1	-2	0	1	0.5
D7	M.D.7.ii	1	0	2	0	2	1	1
	M.D.7.iv	1	1	3	-2	2	2	1.166667
D8	M.D.8.i	1	0	2	0	2	1	1
	M.D.8.iv	1	1	3	-2	2	2	1.166667
Legend:	−2: Large negative impact, −1: Negative impact, 0: No or Minor impact, +1: Positive impact, +2: Moderate impact, +3: Very positive impact							

Function E

		Impact						Score
		Safety	Social Environment	Asset quality	Finance	Reputation	Availabiility	
E1	M.E.1.i.	0	1	2	-1	1	0	0.5
	M.E.1.ii.	0	2	2	-2	1	0	0.5
	M.E.1.iv.	0	3	2	0	1	0	1
E2	M.E.2.i.	1	2	1	-1	2	3	1.333333
	M.E.2.ii.	2	1	2	-2	1	3	1.166667
E3	M.E.3.i.	2	0	2	1	2	-1	1
	M.E.3.ii	3	0	2	2	2	-1	1.333333
E4	M.E.4.i.	2	0	2	1	2	-1	1
	M.E.4.ii.	3	0	2	2	2	-1	1.333333
E5	M.E.5.i.	0	1	0	1	2	2	1
	M.E.5.iii.	0	2	1	-1	2	2	1
	M.E.5.iv.	0	3	2	-2	2	2	1.166667
E6	M.E.6.ii.	1	2	2	1	1	1	1.333333
	M.E.6.iv.	2	2	3	-1	1	2	1.5
E7	M.E.7.i.	0	1	3	1	1	1	1.166667
	M.E.7.iv.	0	2	3	2	1	0	1.333333
E8	M.E.8.ii.	2	2	1	2	0	1	1.333333
	M.E.8.iv.	2	1	2	1	0	1	1.166667
Legend:	−2: Large negative impact, −1: Negative impact, 0: No or Minor impact, +1: Positive impact, +2: Moderate impact, +3: Very positive impact							

Appendix – subchapter 9.2.

9.2.1.: The structured methodology of DAPP model

Here, after receiving the permission of the interviewers to record our conversation, the exact answers of Nikeh Booister (15/09/2020) and Peter Vermey (11/09/2020) are elaborated as they were given in our oral interview meeting.

<u>Question 1:</u> Do you reckon that by using the methods/tools (Hamburger model, Fault Tree Analysis, Criticality Assessment, BowTie Analysis) the steps of Figure I. can be sufficiently reflected to lead to the modelling of adaptation strategies?

<u>Nikeh Booister</u>

To be honest I am not sure if I know enough about these methods to actually answer this because I know BowTie analysis and that is basically every certain event leads to something and then you see what you can do, to mitigate effects or prevent incidents. I was triggered because I know it is used on oil drilling platforms and focuses on risk management and by watching you how you use this tool I was wondering if it is a reacting approach but now I realize that you can use a BowTie analysis to analyze what can happen and what you can do to mitigate the effects of those happenings. Regrading Fault Tree analysis, I understand what it is about in your research and I conclude that, even though this method is mainly for short-term and reactive decision-making, if you use it in a smart way, it can help you to structure your thoughts in events that trigger actions in long-term horizon. I have the feeling that it might be a long way to get what you want considering also the Hamburger model and the criticality assessment but maybe they are necessary to conclude the modelling of adaptation strategies.

<u>Peter Vermey</u>

I think that the Hamburger model has good functionality, Fault Tree analysis is good, the matrices that combine the impact and unavailability percentage contribution of the basic events bring about an excellent result and are a great way of visualizing the products of criticality analysis. I think this is extremely important result of the whole exercise. If these would be correct and you could produce something like this for an asset manager then you can decide on which kind of measures (preventive, mitigative) you take immediately on your investment phase. So, the question for me is the product you make. If this is correct, then I am pleased to say that your whole model is validated, is working. There were many steps in criticality assessment, there were a lot of assumptions because it is quite difficult to be more accurate as there is lack of data and I can also see that you look into frequencies, not immediately in costs. It looks like you found important if the frequencies are high but maybe because there is a lot of unavailability and maybe it is correct. If you look at this result, it is a result that gives an extra value as supposed to intuition or just common sense or anything else. Although your criticality assessment involves many assumptions, your exercise is valuable as it gives better insight, better data for decision-making than other methods and the steps are robust. I was surprised by the results. For me, BowTie is an alternative to Fault Tree analysis method with causes and consequences. So, I do not see any added value of Bowtie analysis here, but it does not really matter because you are just looking at preventive and mitigative measures. As far as the modelling of adaptation strategies is concerned, although the questions of Phase I and Phase II are answered and the right product is *delivered/validated, after that you have a method of looking of what strategies are possible but there are also other possible strategies. Your method is correct but not conclusive, although it is fine, we cannot say that in 20 years for all tunnels of Holland, we must take these measures and after 20 years some other measures. There may be much more other alternative strategies. However, what we can conclude for sure for all tunnels is which the top risks of climate crisis are based on the outcomes of Phase I and II.*

<u>*Question 2:*</u> *Regarding the comprehensibility of this methodology, do you reckon that a person, which implements this methodology, could face difficulties in executing the phases?*

<u>Nikeh Booister</u>

I am not sure about all these different tools and methods and still I have the feeling that quite a lot different tools that you use to get what you want to come. I believe that if you follow less steps you can make it easier for yourself and the ones who implement this methodology because for me it feels quite complex of what you have done. It might be easier following simply the DAPP approach although I understand that you might need Fault Tree and BowTie. But I see you use many methods to come to your result but still I do not know much for those methods. For me, the execution of DAPP approach is by workshops and sections to come to different analysis which depends on if I am looking at a DAPP approach on policy level or practical level, like in your case, but mainly I use it for policy level. There is a difference on what kind of tools you do need. If we see in Polder Water Management, we need polder water management model, we need to model what happens, so we need input. output and to see when something happens and what are the trigger values and what we can do with them. It depends a lot on what you want to achieve and in which field you work on, but still it feels you use a lot of methods which makes it complex.

<u>Peter Vermey</u>

If you know which assumptions are very important and sensitive, then it is easy to use this methodology and you can also say that the results of Phase II are valid for all tunnels. On Phase III you must come up with some creativity yourself. If you can establish the sensitivity of the results of Phase II, then I guess it is very easy to use this methodology because it is pretty much generic.

<u>*Question 3:*</u> *Do you see any prospect of improvement by adding or excluding something on the existing structured methodology of those three phases (in a phase or overall)?*

<u>Nikeh Booister</u>

You start with a lot of different tools and methods. You must reflect your methodology and understand somehow what you want to explain to the people and, sometimes, what you do not need to explain in detail. The visualization of your methodology should be done in a way to clearly show the steps you have followed and whether it is necessary to allow to go to the details.

<u>Peter Vermey</u>

The establishment of sensitivity analysis in Phase I and II is something that could be added on the existing structured methodology. It would be good if a sensitivity analysis were implemented in Phase I and II. I would recommend testing somehow if you have been forgotten an event, or you overestimated the frequency of a basic event and see how solid the assumptions are. I would like to *have the feeling that this is robust, and I can trust and rely on it. Sensitivity analysis is what is needed in such cases. Your method and steps are very robust and fine if the results are not dependent and sensitive on the input. Otherwise, if the result is very sensitive to input somewhere to data then we have a problem and must know which type of input/data or assumption the result is very sensitive to. Then, we can take our measures knowing better where our focus is. Moreover, a cost benefit analysis would be needed about the proposed actions. The rest of methodology is fine, and no adding is needed. It is a good way of visualizing the thoughts and it is more a game, you must play with it and get used to handing it. So, it is fine.*

9.2.2.: Generalized implementation for LC decision-making

Here, after receiving the permission of the interviewers to record our conversation, the exact answers of Nikeh Booister (15/09/2020) and Peter Vermey (11/09/2020) are elaborated as they were given in our oral interview meeting.

<u>Question 4:</u> *DAPP is widely known in Water Management. What is your point of view regarding the use of DAPP for life cycle decision-making in road tunnel infrastructure management? What about when this use aims the asset's adaptation on the upcoming effects of climate change?*

<u>Nikeh Booister</u>

I believe it is a very good thing that you are doing this, and you motivate your examination committee to use this. I like it a lot because you give people something that may need. If I look in the DAPP approach, I think it goes ahead of life-cycle decision-making. Lifecycle for road just might be 10-20 years, however, a road is a network and a network create that you build houses, city, industries around it. If you want to improve a property you might need to do it completely different but you really have to look at long-term climate change effects and others effects, for example, complete change on how we build the environment, which is adaptation for me too. I think it is good to look at this methodology because you add something in the long-term aspect of decision-making for road tunnel infrastructure when upcoming effects like of climate change can be considered differently and besides adaptation could also mean creating something new in your asset.

<u>Peter Vermey</u>

The way you use DAPP for life cycle decision-making in road tunnel asset management seems to work also considering the upcoming effects of climate change.

<u>Question 5:</u> *Would you agree and why/why not that there would be a difference in implementing the DAPP model in road infrastructure management in general (e.g. bridges, highways)?*

<u>Nikeh Booister</u>

I think there should not be a difference in implementing DAPP but I think the outcome might be completely different and also, the thought of a decision-maker when using the DAPP approach in relation to the current approach, I think it might be to this direction. So, I think more using it in *general or not changing it so much (in other kind of road infrastructure) because it is more important than having differences between the different kind of assets. I think mainly the thought of using DAPP is what we might need to be, future-proof.*

<u>Peter Vermey</u>

I have to say that DAPP was used here in different steps and you came up in every step with which tools you can use, and I would say that your DAPP version seems to work in road tunnels. I think that the DAPP model does not work for highways because the lifecycle of highways is basically seven years in contrast with tunnels which are built for 100 years and it is difficult to change. So, you need to take correct decisions at the beginning. This is the typical consideration for a tunnel. On the other hand, the consideration in bridges is between highways and tunnels. In highways, DAPP is not useful at all and in bridges, DAPP could be useful only in big bridges if it were implemented only once in a generic way just to know what to look at. In bridges, you may need a customized approach due to the uniqueness of a bridge structure. For tunnels, as the investments can hardly change, DAPP seems more important there.

9.2.3.: Interested parties

Here, after receiving the permission of the interviewers to record our conversation, the exact answers of Nikeh Booister (15/09/2020) and Peter Vermey (11/09/2020) are elaborated as they were given in our oral interview meeting.

<u>Question 6:</u> Do you recognize any incentive (or discouragement) for the asset managers to implement thoroughly this structured methodology of the DAPP model for road tunnel asset long-term adaptation planning on the effects of climate change and why?

<u>Nikeh Booister</u>

It would be discouragement because in any case it might be more costly, different, and new approaches which are seen complex. It is difficult to adapt to anyway, always, because change management, transition management take ages, it does not take only two-three years. From my experience in water assets, people say that someone should try to see if you can use for the things that are changeable, lower climate adaptation scenario and if the things are not changeable, use the most intense climate adaptation scenario. It is a new way of thinking which says if you can save money now people are willing to look at it, but in the adaptive approach we look at long-term planning which goes over the political periods, which means you need to preserve money in 20 years and even 30 years again or 5 years again, and this is difficult to understand. So, in case of a road infrastructure, you might need to come back after 10 or 20 years and do again some adaptations, because the environment imposes that, which people do not like it at all. Therefore, the actual use of the methodology depends on the economic and political means, and the acceptable social environment and ecological disturbance by frequent adaptation works. These play decisive role. However, there are some project examples like the train station Lelystad-Zuid, where adaptation on the future demands did not work eventually. So, we need to be very clear at the beginning on what and why we need to build something in a specific way.

Peter Vermey

If the results are surprising, like in this case, then I would agree that there is an incentive for implementation. If the outcome is known already, I am not sure that someone would like to use it to avoid further disturbance of bringing out the same results but through a different way. Knowing something new by following the steps of this structured methodology is an incentive to look at it further. Otherwise, it works as discouragement for asset managers whether the reasoning behind the measures is not clear.