PROGRESSING ROAD INFRASTRUCTURE RESILIENCE FROM DIFFERENT INSTITUTIONAL DEVELOPMENT PERSPECTIVES

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ABSTRACT
Critical infrastructures such as road and transport networks are essential to the functioning of our society. These infrastructure systems need to maintain their function and provide their desired level of services in a very dynamic environment, subject to changes due to socio-economic developments, climate change, changing regulations and new technologies. The threat of natural hazards is substantial. In this dynamic and multi-actor environment road authorities are ever more concerned with increasing the resilience of the road network and for this reason are performing risk assessments and are developing adaptation plans.

At the same time the discipline of resilient infrastructure is developing very fast. Where ten years ago a qualitative assessment was state of the art, nowadays often a quantitative, more probabilistic and multi-hazard approach is advocated for the risk assessment. When considering an action plan for identified hotspot locations, strengthening and retro-fitting used to be keywords. Nowadays often a Decision Making under Deep Uncertainty approach is applied and application of Cost Benefit Assessments and other socio economic analysis methods that incorporate the cascading effects for society are often felt necessary to underpin the need to take action and implement the adaptation strategies into practice. These methodologies are great to assess and evaluate the risk profile for road networks and are at the basis of the development of most favourable adaptation strategies.

However, based on the authors' experience it has become evident that the available methods not necessarily coincide with the institutional development level at which road operators are working. Based on a review of available methodologies and approaches at different levels of complexity for critical infrastructure risk assessments and development of adaptation strategies, this paper introduces the "Critical Infrastructure Development Pyramid" as a framework that provides insight, for various institutional development levels, on how to tailor the methodological effort to the objectives of the assessment and the way these need to be implemented.

1 INTRODUCTION

Transport systems are critical infrastructure essential for the maintenance of vital societal functions (EC 2008). And such systems are challenged to maintain functionality and serviceability in a very dynamic environment, subject to changes due to socio-economic developments, climate change, changing regulations and new technologies. In particular, the realization of a context of increasing costs from natural hazards (World Bank and United Nations 2010) has led to an increased interest by decision makers and infrastructure owners and operators in studying the effects of natural hazards on their networks. Already now, the consequences of climate change for instance are at a stage where roads are affected noticeably more frequently than they were a few years ago (Grauert, Johansson, and Axelsen 2016).

Ideally, such concerns should be addressed when planning and designing new infrastructure (Costa et al. 2018) but that has not been necessarily the case for many systems currently in operation. It is thus necessary to understand and assess the risks for the existing infrastructure and make decisions that improve its resilience.

While the uncertain aspects of the future are common for virtually any infrastructure, the capacity for implementation and the sustainability of near-term goals of different infrastructure owners and operators varies markedly. This is something that we, the authors, have observed while working in projects towards resilient road infrastructure in different settings. It is our experience that the sustainability of increased infrastructure resilience is deeply connected to the ability to tailor the methodologies to both the present level as well as the aimed level of institutional development.

Discussing the applicability of risk assessment methodologies under different perspectives, this paper presents and exemplifies criteria that distinguish different approaches. The criteria are not mutually exclusive and conceptual overlap exists. Different methodologies with ample use in practice exist for performing risk assessments. The paper differentiates these methodologies by using the identified criteria, as is summarized in Table 1.

Based on the review of methodologies and approaches at different levels of complexity for critical infrastructure risk assessments and development of adaptation strategies, this paper introduces the “Critical Infrastructure Development Pyramid” as a framework that provides insight, for various institutional development levels, on how to tailor the methodological effort to the objectives of the assessment and the way these need to be implemented.

2 STATE OF THE ART

2.1 Risk Assessment

Risk assessments are, nowadays, common practice for understanding the impacts of extreme events on critical infrastructure and transportation networks in particular. For the most part, such assessments include an identification and characterization of the hazards, an identification and characterization of the infrastructure exposed to such hazards and its vulnerabilities. These elements are a natural result of the definition of risk (UNISDR 2016) as illustrated in Figure 1 and thus incorporated in most cases.

Figure 1 - Components of risk (UNISDR (2016))

The level of detail with which these components are explored in a risk assessment, however, is dependent on the context and purpose of the analysis. It reflects the needs of the end-user of the project and the operating levels of the infrastructure, which in the case of roads, can range from the basic utilitarian function of transporting people and goods between two locations up to the opposed extreme of the spectrum, aiming for resilience towards high levels of performance. Furthermore, multiple risk assessment methodologies exist, reflecting different factors such as the target audience perspective (policy makers, infrastructure owners or operators or other stakeholders) or the domain of applicability (asset level, infrastructure/system level, system of systems level) (Giannopoulos, Filippini, and Schimmer 2012) among others.

One major difference between analyses is whether solely the effects on the road infrastructure itself are taken into account, or whether the impacts for the users of the road are also acknowledged. In this paper we use the following distinction between the two, assuming a risk assessment that is performed having the road owner or operator as the target audience. In this context, we apply (Figure 2) the term vulnerability for gaining an understanding of the degree of physical damage to the road and which scope is under the jurisdiction of the road owner or operator. The definition by the UNISDR (2016) accounts for this by stating that: "[…] vulnerability is defined as a characteristic of the element of interest ([…] or asset)". Furthermore we apply the term cascading effects for all impacts for society when the road is not functioning as it is constructed for. These are outside direct influence of the road operator, but within the primary objective of having road infrastructure which is to serve society.

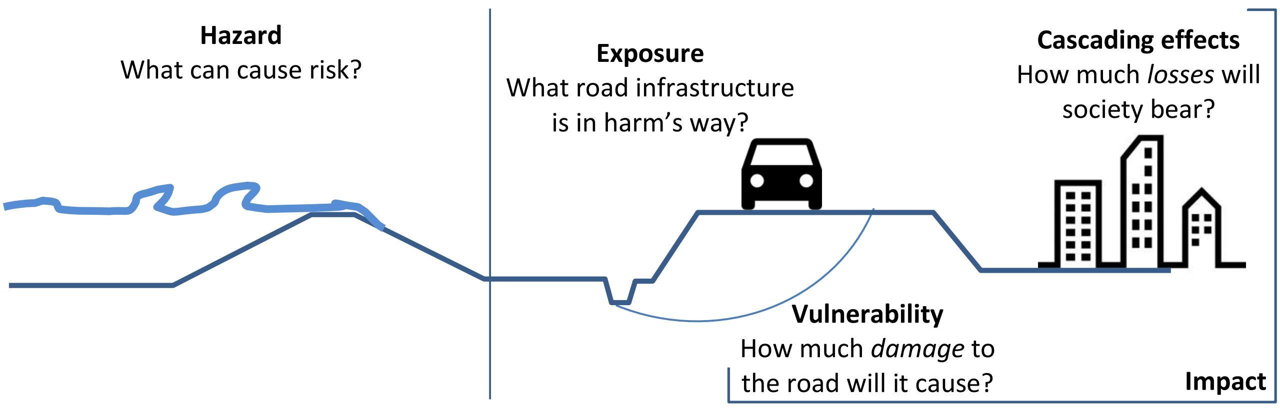

Figure 2 - Schematic overview of the concept of risk in this paper

The concept of risk is widely discussed in literature. There is a build-up of consensus regarding the steps from hazard to vulnerability as defined by the UNISDR (2016). However, when it comes to measuring the effects of an event, loss estimates often mix several concepts and both double-counting and underestimation may influence the results (World Bank and United Nations 2010). Addressing these issues, Hallegatte and Przyluski (2010) propose a definition that includes the assessment of disaster impacts by two categories: direct and indirect losses, each further sub-divided into market and non-market losses. Nonetheless, other terminologies exist (Rose 2004; Mileti 1999). The term criticality is used as a way to show the importance of the road in serving the societal needs. In most cases, it includes a combined quantitative and qualitative estimation to show which parts of the road network are more or less critical for use. In grammatical terms, a road *has* a certain criticality for society which, when it gets disrupted, *leads to* certain losses of the society. As will be shown in the paper, the complexity of the concept of risk should be taken into consideration, when performing risk assessments for different institutional development levels.

2.2 Criteria to differentiate risk assessment approaches

This section presents and exemplifies criteria that distinguish different approaches for risk assessment. The criteria are not mutually exclusive and conceptual overlap exists.

2.2.1 Risk assessment and evaluation of actions

Risk assessments include the identification of risk factors, the analysis of the risk and its evaluation (ISO 31000:2018) through the definition of acceptable risk levels. When the risks are greater than defined acceptable levels, risks need to be addressed and multiple risk treatment options exist. Some methodologies focus on the risk assessment part only. Other methodologies also make the step to providing insights regarding the best course of action. The UNISDR (2016) categorizes the different possible types of actions into: prospective disaster risk management, corrective disaster risk management and compensatory disaster risk management, also called residual risk management. By incorporating the treatment of risk through the planning and prioritization of actions, and additionally the monitoring and communication of risk, several methodologies cover in fact risk management.

2.2.2 Quantitative and qualitative risk assessments

Risk assessments can be performed in different levels of detail and can be either of quantitative or qualitative nature. There can be different reasons why to opt for one of the approaches. A relation exists with the objectives of performing the risk assessment. When the purpose is related to creating awareness or a first screening to identify the relevant hazards, one more likely will choose a qualitative approach (Bles et al. 2016). A qualitative approach also allows for a smooth integration of input from experts or infrastructure users into the equation. Qualitative (and combined) assessments can intrinsically work as stepping stones to understand the value of these analyses and gather momentum to establish the groundwork necessary to evolve to an elaborate quantitative analysis.

A quantitative approach can be used when a profound understanding is necessary and available for the evaluation of the risk and prioritization of actions. Performing quantitative risk assessments is based on the ability to quantitatively characterize hazards, such as the likelihood and magnitude of threats as well as the ability to quantify consequences of those given threats. Thus, the application of quantitative risk assessments to extensive and complex road networks is data intensive, requiring data collection on past events, and relies on advanced modelling and validation of what can be very local events. This requires detailed analysis and a mature institutional context regarding natural hazards. Often, combinations of quantitative and qualitative are employed, making use of readily available quantitative data for some factors and qualitatively overcoming gaps in others.

2.2.3 Deterministic and probabilistic

Prevention Web (PreventionWeb n.d.), the knowledge platform on disaster risk reduction managed by UNSIDR, defines deterministic approaches as the consideration of the impact of a single risk scenario as opposed to probabilistic risk approaches considering all possible scenarios, their likelihood and associated impact. The ability to perform such probabilistic assessments thus requires the characterization of inherent uncertainties, related to the randomness of hazards and also related to an incomplete understanding and measurement of hazards, exposure and vulnerability (OECD 2012).

A comprehensive probabilistic description of the hazards is seldom available for risk assessments, which prevents a full-blown probabilistic risk assessment to be performed. In addition to this, the quantification of all uncertainties in exposure and vulnerability can be extremely complex. In this context, Bommer (2002) discusses the need to tailor the approach to the nature of the project including the quality and quantity of data while arguing that a combination of probabilistic and deterministic elements is often employed and desirable. In fact, deterministic risk calculations are commonly performed for a set of scenarios capturing different hazard return period events and even uncertain climate change as a compromise towards probabilistic approaches.

2.2.4 Desk study and collaborative approach

A desk study approach is based on collecting and using existing data and knowledge. It is suitable in many settings, including initial planning stages, where a sound understanding of the problems, potential risks and implications are crucial, but also equally important for the application of detailed engineering knowledge that has been built over decades of practice and which has been tested and critically reviewed through formal procedures. Fully collaborative studies on the other hand rely on incorporating data or knowledge of another kind. This approach can accommodate the stakeholders' experiences, local priorities and preferences, and provide access to data that is not publicly or formally available. A collaborative approach can be valuable in preliminary studies, to gain an understanding of the situation, potential risks and local circumstances, as well as ensuring the studies fulfil the purpose. The collection of expert judgement, for instance, is one element in collaborative approaches that should be facilitated through structured elicitation processes to ensure that high quality data is delivered (Goossens, Cooke, and van Steen 1989).

Often, a combination of desk studies and collaborative processes for stakeholder input and validation or verification of results is used in practice. The collaborative approach can contribute greatly to the value and usability of the results by providing a framework that is customized to the end user's needs and local situation. Furthermore, a collaborative approach allows for other benefits, including the stimulation of cooperation between local stakeholders due to a better understanding of the different interests and limitations, and contributing to knowledge sharing that underpins sustainable actions and decisions.

2.2.5 Single-hazard or multi-hazard

Most road infrastructure is subject to multiple natural hazards, particularly at the network level, due to its characteristic spatial extent. On the other hand, at the object level or in highly predominant hazards, risk assessment may focus on specific targets. Furthermore, analogously to sectoral approaches to risk (transportation, energy, housing, etc.),

developments in risk assessments have traditionally evolved at different paces for different hazard-related disciplines (earthquake engineering, floods, subsidence, etc.). However, multi-hazard approaches are more complex than the sum of single-hazard considerations due to (Kappes et al. 2012): different hazard characteristics and respective analysis methods, cascading hazards, diverging impacts from the hazards on the elements at risk and the need for comparison of different quantification measures associated with different risks. Furthermore, performing multi-hazard assessments commonly involves the use of data and methodologies at varying maturity stages (Yusta, Correa, and Lacal-Arántegui 2011). Still, a multi hazard approach may start by bringing together the risk profiles of the single hazard risk assessments for prioritizing hot spots from a multi-hazard perspective.
Despite the underlying challenges, and particularly when risk management actions have different effects for different hazards, effective risk reduction can only be achieved through the consideration of the existing interactions.

2.2.6 Methods for evaluating measures

Efficiency assessment refers to analyses made for the purpose of identifying how to use scarce resources to obtain the greatest possible benefits of them (Hakkert and Wesemann 2005). It is important and often necessary due to budget constraints, to assess the (relative) attractiveness of different risk reducing measures and prioritize. The selection of methods to do so depend on the decision criteria: what is the general policy on decision criteria? Is the general policy to decide based on risk and cost-minimization or cost-effectiveness? Are social and environmental aspects taken into account?

Four possible methods can be distinguished (Bles et al. 2018), in order of increasing data needs; Multi Criteria Analysis (MCA), Life Cycle Costing (LCC), Cost Effective Analysis (CEA) and Cost Benefit Analysis (CBA). The choice of method is largely dependent on the objectives of the analysis, the level of detail required (i.e. high level or detailed analysis) and the type and suitability of the data available i.e. quantitative (CBA), qualitative (MCA), semi-quantitative (LCC, CEA) to carry out the Socio-Economic Analysis. For example, an MCA may be used for creating consensus building among stakeholders to create a common understanding between various disciplines if little or no quantitative information is available. A CBA however requires that sufficient quantifiable data is available as all benefits and costs are converted into monetary terms. In a CEA all alternative measures are compared in their effectiveness in which they contribute to achieving one specific goal (reducing risk). In a CBA the costs of a project are compared to the benefits, or the welfare effects. A CBA helps to make trade-offs between different, maybe even conflicting, policy objectives.

2.2.7 Scope of analysis: Transport system or system of systems level approach

Risk assessment methodologies can be differentiated by their scope of analysis. An assessment of the transport network as one element of a system of critical infrastructure systems requires that cross-sectoral interdependencies are taken into account (Giannopoulos, Filippini, and Schimmer 2012), for instance with other transport modalities or flood defence infrastructures. And interdependencies also play a role in intra-sectoral assessments, for instance the risk assessment of a national road network is deeply related to the interrelation between the local, national and highway systems. Furthermore, the domain of applicability is deeply related with the audience that is the target of the risk assessment and that has the oversight of the domain. The higher level of interdependencies is, in general, related to policy making and a higher level of abstraction of the analysis using an area-oriented process, whereas the general focus of road operators and asset managers lies on narrower domains at detailed levels, like the road network or even individual assets.

Such considerations also influence the way in which the impacts are measured (World Bank and United Nations 2010; Hallegatte and Przyluski 2010). The redundancy of a road system as a central measure for the impacts of disruption is not properly captured if only part of the road system is taken into account. Or, for instance, the damages to the road will generate economic activities in the reconstruction process that have impacts in other economic sectors. As such, the estimation of wider losses for society becomes more significant, and can be properly captured, on a system of systems level approach when compared to an analysis that is focused on the road network.

2.2.8 Status quo and looking towards the future

Natural hazards lead to complex risks which are often characterized by multiple causes, difficult estimation of consequences, and high uncertainty. There are several driving forces that can influence the (magnitude) of the risk, amongst which, human dynamics (policy changes and demographics), environmental changes and climate change, technological changes, institutional changes and spatial developments. The current situation, the status quo, can be identified, explored and analyzed. In some cases historic data is available or traceable. The future however is uncertain and not all methodologies take this fully into account. Scenario analysis is a way of structuring thinking about the future and allows for improved decision-making as a result of identifying and considering a range of potential outcomes and their implications, and increased preparedness to handle them. A scenario is a ‘story’ which illustrates visions or aspects of a possible future.

Scenarios can relate to the different aspects of the risk assessment framework. For the assessment of the magnitude and likelihood of the hazard, different climate change scenarios can be used in the case where a socio-economic analysis is required “socio-economic pathways” could be used that describe possible scenarios that society may develop to in the future. This is especially important when considering cascading effects of disruption. Both possible evolution of the demand using traffic and transport development scenarios (Zmud et al. 2013; McKenzie 2016) as well as the evolution on the supply side based on future infrastructure plans need to be considered.

2.2.9 Decision making under (deep) uncertainty

For investments in transport infrastructure, where capital expenditures can be high and asset lifespans long, decision makers need to be confident the decisions they take today will continue to apply in the future. They also need to be confident that the planned infrastructure is designed to cope with the changing conditions. “Uncertainty is that what disappears when we become certain” (Goossens, Cooke, and van Steen 1989) Uncertainty analysis is an essential part of responsible decision making, especially applicable when dealing with quantitative models associated with potentially large uncertainties, when the consequences predicted by the models are associated with utilities and disutilities in a non-linear way and the choice of course of action might change as different plausible scenarios are explored with the models (Cooke and Goossens 1999). Analysing uncertainties does not solve the decision making problem, but does provide additional insight into the robustness of different measures and strategies for different uncertain futures.

Many investment and policy decisions require “near-term” decisions, but have significant, long-term consequences. For decision makers facing a deep uncertain future due to for example climate change, scenario-based analysis methods may not be enough.

2.3 Comparison between methodologies

Different methodologies with ample use in practice exist for performing risk assessments. The paper differentiates these methodologies by using the identified criteria in the previous paragraph. The results are presented in Table 1. The paper does not aim at being exhaustive but rather illustrative of the capabilities of the state of the art.

Table 1 – comparing risk assessment methods with identified criteria

Criteria	**ROADAPT QuickScan** (Bles and Woning 2014)	**ROADAPT 'full'** (Bles et al. 2016)	**FHWA toolkit** (Muiswinkel et al. 2018)	**Prioritization of road interventions** (Espinet and Rozenberg 2018)
Risk assessment and evaluation of actions	Both; the risk assessment enables a risk evaluation after which basic directions for adaptation are identified.	Both; the ROADAPT methodology provides detailed guidance on how to perform a risk assessment, as well as on how prioritize measures to reach an acceptable level of risk.	Both; the toolkit provides tools and guidance on how to assess the risks, but note that adaptation is described briefly and in relatively general terms.	Both risk assessment and the prioritization of actions and their evaluation are considered.
Quantitative and qualitative risk assessments	Semi quantitative using classes for estimating the likelihood and consequences	Semi-quantitative to enable risk assessments in data scarce environments as well as guidance on how to perform a fully quantitative risk assessment	Qualitative, semi-quantitative, quantitative	Quantitative risk assessment combined with quantitative and qualitative criticality indicators for prioritization
Deterministic and probabilistic	Deterministic; both the likelihood and consequences of risk are determined but uncertainty is not explicitly addressed	Deterministic; guidance is provided on how to deal with uncertainties, but a probabilistic approach is not advocated	Deterministic; guidance is provided on how to deal with uncertainties, but a probabilistic approach is not advocated	Deterministic damages are calculated for each scenario and EAD (Expected Annual Damages) are calculated assuming the probability of occurrence as the inverse of the return period.

Criteria	**ROADAPT QuickScan** (Bles and Woning 2014)	**ROADAPT 'full'** (Bles et al. 2016)	**FHWA toolkit** (Muiswinkel et al. 2018)	**Prioritization of road interventions** (Espinet and Rozenberg 2018)
Desk study and collaborative approach	Collaborative approach using expert input via workshops with some desk study	Desk studies are advocated for the risk assessment; workshops are recommended for verification and data gathering purposes	This is not clearly specified. The use of the toolkit will mainly be performed via a desk study	A desk study combining indicators used to express possible decision-makers priorities, although expert elicitation is not formally discussed.
Single-hazard or multi-hazard	The approach looks at multiple hazards but separately	The approach looks at multiple hazards but separately	The approach looks at multiple hazards but separately	Flood hazards combining riverine and storm surge.
Methods for evaluating measures	Global strategies are compared using multi criteria analysis	The ROADAPT approach provides tools for Cost - Benefit assessments for a road stretch, road network and system approach	The FHWA toolkit does not provide assistance how to evaluate measures	Cost Benefit Analysis (CBA) is used as the basis to evaluate the robustness of strategies.
Scope of the analysis	The scope is on the road, ranging from asset level to network level	As with the quickscan, the primary focus is on the road but for estimating the impact of disruptions the area perspective is taken into account	The scope is on the road, ranging from asset level to network level	The risk assessment focuses on the transport network damages and prioritization is based on additional socio-economic impacts.
Status quo and looking towards the future.	Climate change scenarios are considered	Climate change scenarios are considered.	Climate change scenarios are considered	Demand and economic future scenarios are considered.
Decision making under (deep) uncertainty	No	ROADAPT does provide recommendations on how to take climate change uncertainties into account in a CBA and mentions the need to also think about (socio-)economic changes	The FHWA toolkit does not specifically provide recommendations for decision making towards an uncertain future	The robustness of different actions is analysed.

3 INTRODUCING THE "CRITICAL INFRASTRUCTURE DEVELOPMENT PYRAMID"

3.1 Introduction

For this paper we made a selection of three different projects in which the authors were involved. The selected projects provide an overview of different approaches on how to perform a climate change risk assessment for road networks and how this can be used to make the step to development of an action plan towards the future. The projects have been executed in different countries with different characteristics of the road network and surroundings, as well as different levels of institutional development. Bases on an evaluation of these projects (and other projects) we have identified that a mismatch may exist between what is theoretically possible (the state of the art) and what is desired by the road operators with a certain level of development. Such a mismatch may cause difficulties for implementing or re-assessing the results of the project by the road operators. For this purpose we present in this chapter a 'critical infrastructure development pyramid' which could be of help for thinking of aligning needs and possibilities.

3.2 State of the practice

3.2.1 Building Resiliency to Climate Events in the Road Network in Paraguay

This pilot project was executed for the World Bank with the goal to aid the Government of Paraguay, specifically the Ministry of Public Works and Communications (MOPC). Purpose was to develop an effective strategy to manage climate risk of Paraguay's road network through a vulnerability assessment of the country's roads to climate change and through improving climate resilience planning. The approach required a risk and vulnerability assessment as well as building an adaptation strategy and providing recommendations for both an alert and response plan and for the Road Asset Management System (RAMS). The approach was applied as a pilot on two CREMA corridors of approximately 318 km length in total.

For this project, the ROADAPT Quickscan approach was used to identify vulnerable locations and prioritize the risks. The Quickscan was done together with local stakeholders during several workshops in Paraguay. These workshops provided a sound basis of understanding, both for the road operator and the consultants. At the same time it created awareness of the necessity to think about climate risk affecting the road network. Output of the quickscan was a list of top risk that needed further attention. For these top risks exposure maps have been made, using publically available information since very little road and hazard data was available. This helped for prioritizing locations that need detailed data gathering for a detailed risk assessment in the future. During the inventory of the vulnerable locations it was also noted that lack of regular maintenance is (one of) the important factors leading to problems.

For a number of locations, several measures were identified and illustrative adaptation pathways were determined. It proved however to be difficult to fully apply DMDU principles. Application of DMDU relies on complete and accurate data. Also, the current primary focus of the road operator is on providing a resilient road network for the current situation with installation of maintenance actions for the next years and an asset management system. Thinking of situations in the far future will be a next phase. In other words, thinking about adaptation pathways did not completely fit the actual needs and the organisation development level.

3.2.2 Developing a Climate Adaptation Strategy for the A58 highway in the Netherlands

Climate change induced extreme weather events are expected to affect the functionality of Dutch highways and therefore pose a risk for safety and traffic flow. As the asset manager of the main road system in The Netherlands, Rijkswaterstaat has to ensure that road networks continue their operational functions, both now and in the future. Therefore adaptation strategies are needed to develop and maintain climate resilient infrastructure, integrated in the environment. The aim of the InnovA58 project (Leijstra et al. 2018) is, among others, to increase the robustness and resilience of the A58 highway and its surrounding environment for the effects of climate change, while undergoing big reconstruction works. In this, the challenge was to use risk and vulnerability assessment tools in such a way that the most cost effective approach is chosen, taking both short and long term into account for both the road and the surroundings. Attention was payed to the surrounding environment, since possible measures that contribute to the resilience of the road can be found in the surrounding environment. However, increased resilience in one place may lead to decreased resilience elsewhere.

The process consisted of three steps. In the first step, climate threats, key risks and potential measures were scanned, through two joint workshops, with experts and asset managers from Rijkswaterstaat, Deltares and local stakeholders, like municipalities, water boards and provinces. In the second step, the key risks were mapped to determine the places where the key risks can occur on the road. The output of the first two steps were then analysed on costs, benefits (for both Rijkswaterstaat and road users) and effectiveness. Finally, an adaptation strategy was developed by applying the concept of Dynamic Adaptation Policy Pathways.

It was concluded that the approach was useful for the road infrastructure to assess vulnerability, risk and potential measures using adaptive design principles. It proved however to be difficult to adopt fully an area-oriented approach which is needed, since climate resilience requires regionally tailored solutions. The collaborative approach for identifying risk and measures was however useful to create awareness of the need to think from an area perspective and also lead to identification of ‘matching solutions’ for both the road and the area. With hindsight one could say that the applied more qualitative approach for the risk assessment could have been improved by applying a more fact based and quantitative approach. For incorporating climate change resilience in road design and maintenance, such facts are essential ingredients. Rijkswaterstaat is currently undertaking a stresstest in this respect while using a quantitative approach.

3.2.3 ‘Climate resilient road assets’ in Albania

This project was executed for the World Bank with the goal to assist the WorldBank and Albanian stakeholders in the prioritization of current and future climate, and seismic resilient investments in road assets. The objective was to be achieved through applying a climate and seismic vulnerability assessment on the national road network in Albania, proposing mitigation measures and improving climate and seismic resilient design, construction and maintenance standards for national roads and local roads.

For this project a quantitative approach was requested, which required making use of available (detailed) information, concerning hazards, traffic densities and socio-economic data. This data was not readily available, resulting in the need to make multiple assumptions which affected the reliability of the results.

Moreover the use of DMDU was requested within the project, with the objective to ensure that the results of this project can be used for implementing long term investments that need to be effective in the future as well as to help decision makers identify, evaluate and decide on robust and adaptive strategies. However during the risk assessment, it became clear that much required information that is essential for such an analysis was not available. For example local rainfall data and associated catchment run off data were not available. To effectively implement long term adaptation strategies, the logging of such data is important as these provide steering parameters that aid in deciding if/ when a mitigation strategy is expected to become obsolete and a new strategy needs to be adopted (changing of pathways). Moreover, the Albanian government implied that they were understaffed and did not have the capacity, nor sufficient continuity within the road authorities' organisation, to implement such a long term-strategy.

3.3 The Critical Infrastructure Development Pyramid

From the projects that are described in the previous paragraph it can be identified that the method for a climate change risk assessment does not necessarily always reflect the needs of the end-user of the project. There seem to be different levels at which road operators are operating. We have identified that applying the Maslow pyramid (Maslow 1943) for the case of infrastructure operations provides clear insights in this respect. This led us to think about the road operators or owners' needs on the Maslow levels which are (names are slightly adapted to accommodate the use for road infrastructure):

- Primary needs. For mankind in general, Maslow has stated as bare basics these are aspects like food, water and warmth. When translated to transport infrastructure, this boils down to the bare basic of being able to transport people and goods from A to B.
- Safety needs. The next step on the pyramid is providence of safety. Similar to this the next step in the Critical Infrastructure Development Pyramid is to provide safety for the road users.
- Social acceptance. To reach a level of social acceptance of infrastructure developments, the user needs to be ensured that at least under normal circumstances a sufficient functional and convenient use of the infrastructure is possible, which is in balance with acceptable impacts on the surroundings. Road operators/owners may still apply a more utilitarian view with a primary focus on the road network itself, but in the same time want to minimize negative impacts for the surrounding area. While infrastructure developments normally are a key driver for development of societies, at some moment there appears a down side to infrastructure developments, being that infrastructure may have negative impacts on the surrounding environment. Here a need comes at stake that costs and benefits need to become more and more balanced. The higher one is in the pyramid, the more important it becomes to take this into account when an action perspective is being formulated after evaluation of the results of the risk assessment.
- Esteem comes at stake when infrastructure users get trust in the system. This is, when the system becomes reliable, predictable and comfortable, even in situations when under stress. For the surroundings of the infrastructure it means an even higher level of acceptability. This comes when infrastructure starts to maximize opportunities in the surroundings which is more than solely the main function of moving people and goods. Road operators/owners apply a more balanced view where also people outside the transport network are taken into account for decision making to avoid negative impacts/spilling outside the road system. As a consequence road networks will become more complex and integrated in the surroundings of the road.
- Self actualization. This is the top of the development pyramid and the highest level that road operators can reach. At this stage the operators are fully aware of all levels down the pyramid and act like this in a professional manner while interacting with all stakeholders in the environment. At this stage they are also fully aware of the fact that the system they are operating is not static and will change towards the future. Climate

change, socio economic developments, technical and juridical developments are taken into account using principles of decision making under deep uncertainty.

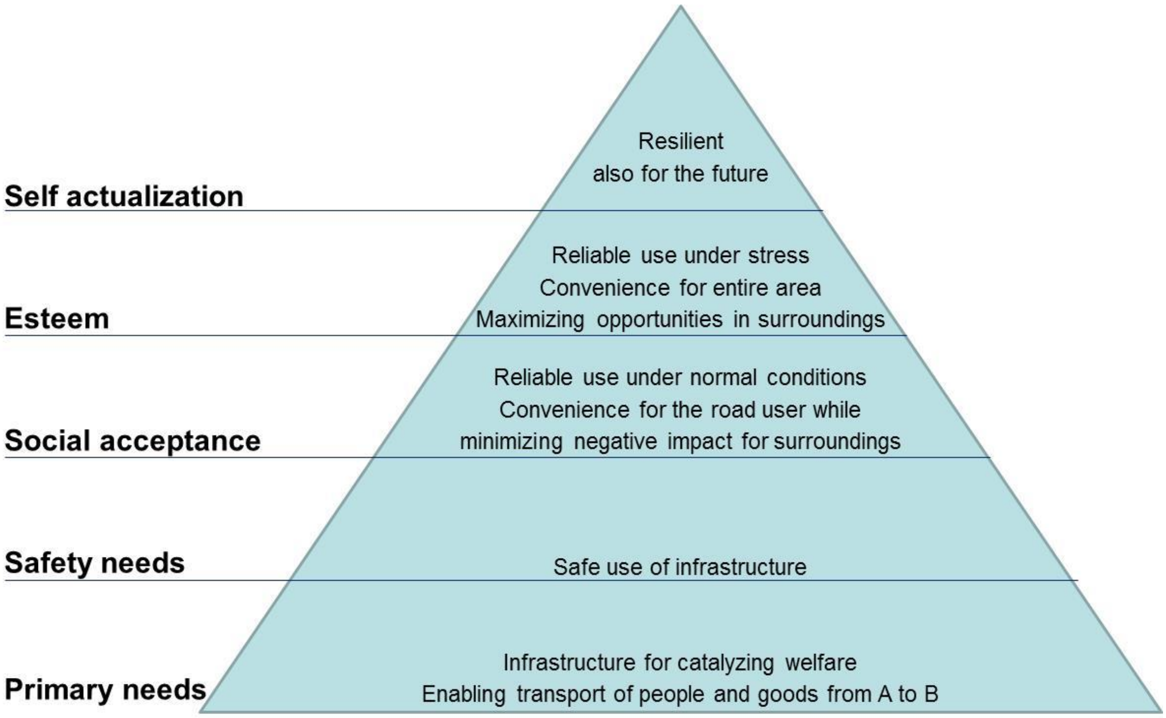

Figure 3 – the Critical Infrastructure Development Pyramid

When we try to put the road authorities of the described projects in the pyramid we see the following. In Paraguay, the focus is on the basic functions of the road network. Safety is more and more being addressed. As such we would place the Paraguayan road operator making the step from level 1 to level 2. The work that was performed however aimed for a higher level in the pyramid level 4 or even 5. This may explain the challenges in implementing the results.

In the Netherlands, focus is on an integral perspective of the road network serving the society. The road authority is and acts like one of the partners in the spatial domain. The level at which the road authority is operating is as such on level 4 and currently big steps are being made to reach the highest level with the ambition to have a climate resilient national road network in 2050. The analysis that was performed contributed to reach this step by raising awareness for the need to think from an area perspective. The performed quickscan however merely provided qualitative insights where fact based decisions are needed on the top level of the pyramid.

Finally, Albania focusses on the basic functions of the road network, which includes safety issues. Steps are being made to include requirements for shorter reaction times after disruptions in the maintenance contracts, in order to reach a level of reliable use under normal conditions. As such it is making the step to level 3 in the pyramid. The performed analyses were also considering aspects that are more related to top levels of the pyramid. This may explain the challenges in data gathering and the way the results are to be implemented in practice.

3.4 Relating the risk assessment criteria and Pyramid levels

Both risk assessment and risk management can be applied at all levels proposed in the critical infrastructure development pyramid. The character of risk treatment however is likely to be different at the 5 levels. In the bottom levels it is more likely that needs for proper maintenance and emergency response are emphasized whereas in the higher levels prevention and robust construction considerations may prevail.

In terms of performing qualitative and quantitative risk assessments, data availability is usually a larger problem at the lower levels; thus, a qualitative assessment in combination with focus on completeness and accurateness of data can therefore be a good solution at lower levels 1 and 2. The higher the level, the more important it becomes to provide quantitative support for decision-making.

As discussed previously, a fully probabilistic approach is difficult at all levels and not necessarily the best approach. Nonetheless, the requirements for formal expression of uncertainty increases towards the top of the pyramid and the consideration of hazard scenarios of different return periods is necessary from level 3 and higher, in order to properly capture the effects of natural hazards on the infrastructure.

A fully collaborative approach can raise awareness and support and as such can be successfully applied at the lower 2 levels of the pyramid. A fully collaborative approach will however not give enough information for the higher levels. Given the previous points on the increasing need for a more probabilistic and quantitative approach for the higher levels, it makes sense that also the need for desk studies increases with higher levels on the pyramid. The authors advocate taking use of advantages of combining desk and collaborative approaches at all levels. The benefits of a combined collaborative approach prove to be very beneficial also at the higher levels for awareness, verification and validation purposes.

Additionally, road infrastructure is commonly exposed and vulnerable to multiple hazards and it is important to take all relevant hazards into account at all levels of the pyramid. However, a fully integrated multi-hazard approach with explicit consideration of the interrelated causes and effects may be difficult to implement or outside the scope of the analysis, particularly at the lower levels where predominant hazards may be the focus.

In relation to the scope of the analysis, and having the road owner and operator as the target audience, the levels 1 and 2 are typically bounded to the transport network itself. There may be (but not necessarily in all cases) a higher focus on damages and immediate losses to the road users when compared to wider and cascading economic losses. At the top levels the wider societal impacts of the road disruption assume a greater relevance and it is essential to consider interrelations through a system of systems approach.

In addition to the analysis of the status quo, the consideration of future outlooks should be adjusted to the level of involvement of the road owner or operator and the improvements that the assessments aim to achieve. At the top of the pyramid the high standard of operation even for very low probability high potential consequences type of hazards. Furthermore, this should be done in a context of dynamic supply and demand scenarios. Data availability for future projections is likely to be more at stake at lower levels of the pyramid.

Although the authors consider that uncertainties related to the future are desirable for decision making at all levels of the pyramid, it is our experience that the lower the pyramid level, the less common and/or feasible this will be. At lower levels, applying socio economic evaluation tools like CBA may already be faced with challenges that make the consideration of DMU impractical. Nonetheless, the methodologies employed should take into account the level in the pyramid corresponding to the current level and the target level that is aimed with the risk assessment, as well as the needs in capacity building on how the road operators can themselves use DMU principles for decision making.

4 CONCLUSIONS

Road infrastructure systems are challenged to maintain functionality and serviceability in a very dynamic environment, subject to changes due to socio-economic developments, climate change, changing regulations and new technologies. To address these challenges road operators more and more are putting effort in increasing the resilience of their road networks. For this purpose several risk assessment and adaptation methodologies have been developed and used in practice in the past years.

This paper does not aim to give a complete overview of these methods. We have however presented an overview of criteria that can be used to distinguish the different methods. For a small selection of methodologies the criteria have been applied to show how the methods differ from each other.

Based on the authors' experience it has become evident that the available methods do not necessarily coincide with the institutional development level at which road operators are working. If the divergence between the institutional development level and applied methodologies is too large, there appears a risk of unsustainability of the results in the daily practice of the road operators. For that purpose a 'critical infrastructure development pyramid' has been developed. It shows different levels or steps that a road operator needs to take to operate and plan for a resilient road network. It can be used to ensure a proper fit for practice of elements of methodologies, given the current level and the step that needs to be made to reach the next level in the pyramid. When we apply the pyramid on three case studies we clearly see that the case studies can benefit from using the different development levels.

Finally, a proposal has been made on which criteria (that distinguish the risk assessment and adaptation methodologies) can best be used for the different levels on the pyramid. It becomes evident that insight in the institutional development of the road authority for whom the analysis is performed is key in deciding for the method that needs to be applied. Not necessarily the latest state of the art coincides with the development level of the road authority.

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