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Modeling the adaptation of infrastructures to prevent the effects of climate change – an overview of existing literature

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Abstract. *Climate change is likely to affect our infrastructures and, consequently, the way society interacts with these infrastructures. For instance, higher average temperatures increase the need for electricity delivered through the grid in the summer due to augmented air-conditioning. As the scientific consensus is that climate change effects may be severe, a next step is to divert the focus from the natural system to the effects on man-made systems. Particularly, we expect that the interconnectedness of man-made systems, especially energy, transport, ICT and water infrastructures is important with respect to cascading effects of climate change. In order to gain insight into the effects of climate change on our infrastructures and possible adaption strategies for the coming decades, we describe a literature search on the intersection of literature on infrastructures and climate change. Specifically, we search for ways to adapt our energy and transport infrastructures and make them resilient against the consequences of climate change and modeling approaches that simulate these adaption strategies for our infrastructure systems.*

We have found that, although there is a vast body of literature on climate change, less attention was paid to the effects of climate change on infrastructures. Our literature analysis shows that there is ample literature measuring the effects of climate change on individual technologies and parts of infrastructures. In contrast, the literature on the systems level, the adaptation of infrastructures and infrastructure interdependencies is just emerging. We anticipate that future research attention needs to be diverted from the analysis of a technical component (when will my bridge be broken) to the technical system level (how do I judge/measure when to replace a road section (including the bridge)?) or even to one of the socio-technical system level (how can I adapt the system as a whole as to prevent the effects of a tunnel breakdown?). We conjecture that suitable simulations and models should be developed to explore adaptation strategies at these levels of aggregation.

Keywords. *Climate change, Infrastructures, Socio-technical systems, Agent-Based Modeling*

1 Introduction

Climate change is likely to affect the way in which society will function in this century (IPCC, 2007). In order to gain insight for improving our infrastructures in the coming decades, an overview of the state-of-the-art literature on the adaptation of infrastructures against the consequences of climate change is necessary. In this document, we describe a literature search on the intersection of literature on infrastructures and climate change. Our interest in this study is two-fold; first we are interested in the effects of the environment on our technical systems and how we can adapt our energy and transport infrastructures, make them resilient/robust against the consequences of climate change. Second we want to investigate what modeling approaches are used to study these effects.

Scientific consensus is in favor of accepting the climate change effect; a next step is to divert the focus from the landscape or environment to the effects of climate change on man-made systems. And although there is a vast body of literature on climate change, we expect fewer studies on the effects of climate change on infrastructures. Moreover, we expect that the interconnectedness of man-made systems, especially the energy, transport, ICT, water infrastructures and global supply chains is relevant and significant in light of cascading effects as a consequence of climate change.

Cascading effects occur on different levels. In cities, water pipes for example are often buried under roads. When the pipeline bursts, e.g. as a consequence of augmented expansion and contraction, the water flushes the sand around the burst, causing the asphalt to collapse. Possible consequences are not only technical, such as repairs of both infrastructures, but also societal as the road being blocked may increase congestion.

Man-made infrastructures are part of a complex socio-technical system. These systems are characterized by unpredictability, emergence, and cascading effects (Bauer & Herder, 2009). Purposive actors in the system influence the technical artifacts (infrastructures) and are influenced by the artifacts. These micro interactions lead to system level behavior on macro level (e.g. van der Lei et.al. 2010).

In section 2 we explore the effects of climate change on infrastructures where we see infrastructures as complex socio-technical systems (de Bruijn & Herder, 2009). We reviewed scientific literature in order to understand the effects of climate change on infrastructure. The review method is described in section 3, the results of the review in section 4. In section 5 we conclude that future research attention needs to be paid to the technical infrastructure level.

2 Climate change adaptation from a socio-technical system perspective

A socio-technical system contains a physical/technical part and a social part (Ottens et al., 2006). The physical part is represented by man-made interconnected systems like road networks, electricity networks, buildings etc. The social part is represented by humans, organizations, governments, etc. The actors in the social system behave purposively in relationships with each other but also interact with the technical system. The landscape / environment contains processes outside the system boundary that affects the socio-technical system studied (See Figure 1) (Chappin, 2011).

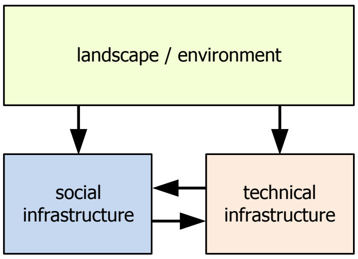

Fig. 1. Socio-technical system's perspective on infrastructure.

We are interested in the effects of climate change on the technical infrastructure system in Figure 1. As noted in the introduction, we hypothesize that many scientific papers focus on causes and magnitude of climate change and that a small portion of these papers treat the effects of climate change on infrastructures. Additionally, we expect that research results on the interconnectedness of different technical and social infrastructures in relation to climate change are hard to find. This interconnectedness drives the unpredictability, emergence, and cascading effects of the system.

More importantly we foresee that, in light of climate change, there is not so much focus on the adaptation of the infrastructure systems themselves, the investments needed to adapt to climate change effects and the way to achieve this adaptation through asset management practices. Figure 2 visualizes adaptation with respect to the socio-technical system perspective.

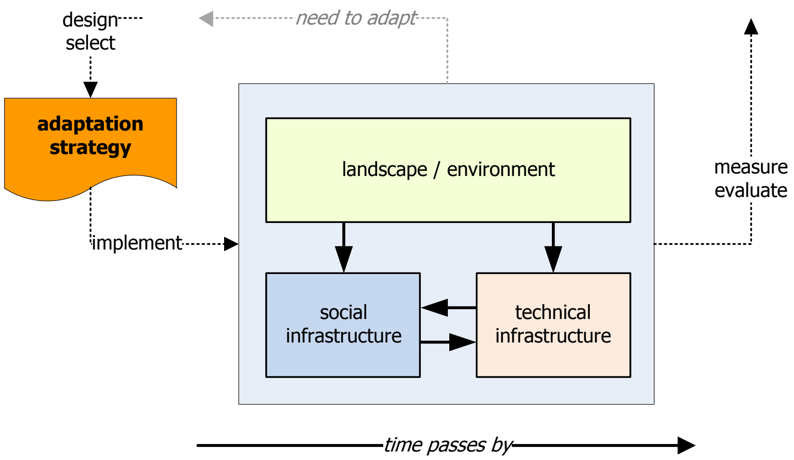

Fig. 2. Adaptation strategies and the socio-technical system's perspective on infrastructure.

Adaptation differs from the widely used term mitigation. The main difference between mitigation and adaptation is the focus on prevention that adaptation has. Using the idea of prevention as a basis, still leaves room to define adaptation. In literature, an important element of adaptation is “the cost of adjusting infrastructure systems and services to higher standards at which the experienced impact would have been avoided” (Krishen et al. 2008). An adaptation strategy for infrastructures with respect to climate change, therefore, would be any mechanism that avoids (the probability of) a negative impact of climate change on our infrastructure in future.

The broadness of this definition implies that there could be various types of adaptation strategies. Frankhauser et al. (1999) provides a description of a strategy to tackle climate change and its effects. They distinguish three dimensions of strategies:

- Reactive versus anticipatory adaptation
- Autonomous versus planned adaptation
- Substitutes from compliments.

Adaptation could, therefore, encompass a wide variety of activities – leading to questions how to come up and select strategies and how to measure their merits. This is visualized in Figure 2: after a suitable adaptation strategy is designed/selected, it can be implemented. Evaluating its effects requires measuring the performance of the system over time in comparison to alternatives or a base case. It is likely that continuous monitoring of the adaptation strategy is needed.

3 Approach to gain insight into the effects of climate change on technical infrastructure

In order to understand the state of scientific literature regarding climate change effects on infrastructures we conducted a literature search in Scopus, which currently is one of the largest databases of scientific literature. The search was conducted with the following keywords: Climate change, Global warming, (Energy and transport) infrastructure, Adaptation, Robustness, Resilience, Impact. We also included keywords regarding modeling in the search: Modeling, Simulation, Agent-based modeling as we are interested if and to what extend climate change effects are modeled.

Searches with both the keywords Adaptation and Robustness returned very little papers, less than ten. Most results (>200) were obtained with the following keywords: Climate change, Energy and transport infrastructure, Impact. We further narrowed the selection down by analysis the relevance of the papers on the basis of their title. Disregarded papers mostly focused on specific parts or components of infrastructure networks. 54 most papers with a relevant title from the search remained. From those, we obtained 39 papers.

We analyzed the papers, based on the following elements: the authors, the institute of the first author, the relevant time-scale, the domain, the methodology, the perspective, what aspects are covered, whether infrastructures are discussed, whether interconnections between infrastructures are taken into account, and whether the analysis is quantitative.

- *Time*: we distinguish long-term and short-term effects that are studied or mentioned. For example, rain is a short-term effect while investment evaluations are long-term effects. We distinguish long term (>10 years), medium term (1-10 years) and short-term (<1 year) effects.
- *Domain*: the application domain of the research described.
- *Methodology:* type of methodology used for the study.
- *Perspective*: the perspectives described in the study (recall Figure 1): the social infrastructure (institutions, economies, policy, behavior etc.), the technical infrastructure, and landscape / environment.
- *Aspects*: effects of climate change described.
- *Infrastructures*: are infrastructures being studied (road networks, energy networks etc.) here we do not include the focus on individual assets or infrastructures like bridges or tunnels.
- *Interconnected*: are infrastructures studied in relation to each other?
- *Quantitative*: is the study a qualitative or quantitative study.

The rest of this paper is devoted to the analysis of the results.

4 Results

In our review there are no individual institutes that are structurally represented more often than others. The papers studied either have a very broad or a very narrow focus. The papers that review literature are broad and describe climate change effects on biodiversity or health. Other papers have a much narrower focus and focus on individual effects of climate change, like the effect of climate change on corrosion (wat is hier de ref van uit onze tabel? Ik had dit paper niet). Few papers study the effects of climate change on infrastructures. Examples of these paper are: (Suarez & Oliva, 2005, Decicco & Mark, 1998, Davis et al., 2010, Ruth et al., 2007, Wilby, 2007, Koetse & Rietveld, 2009).

4.1 Interdependence of infrastructures

Many of the possible negative effects of climate change on infrastructures lies in the interdependence of those infrastructures. Only three of the analyzed papers studied interconnected infrastructures.

Wilby (2007) describes the urban hydrological cycle in which the soil, ground, sewage works, homes, and factories influence each other. The effects of different infrastructures shown are limited to the hydrological cycle. The focus of the paper is a description of four main areas: urban ventilation and cooling, urban drainage and flood risk, water resources, and outdoor spaces. The author does not actively link the different main infrastructure systems of the built environment to each other.

Krishen et al. (2008) explicitly analyze the interdependencies of the impacts of climate change and adaptation strategies upon infrastructure systems in urban areas. In this paper the authors do not focus on modeling the (physical) interdependencies between the different system but make qualitative estimates regarding the impacts the different infrastructures have on each other. The infrastructures that are related to each other are the infrastructures in the following systems: energy, health, transport, river flooding, sea level rise, water supply, and water quality. For example: when energy supply is disrupted, a loss of rail service in the transport system could follow.

Finally, Suarez et al. (2005) assess the impact of sea level rise on urban infrastructure. Suarez et al. (2005) describe a method that helps with the assessment of the impacts of flooding on urban transportation on system level. The main interdependency studied is how land-use conversion and climate change trends negatively affect the vulnerability of the metropolitan Boston transportation system to flooding. It is the only paper we analyzed in which a quantitative model was developed in order to study this interdependency between infrastructure systems.

4.2 Focus on landscape and technical systems

Surprising is that relatively large part of the papers focus on landscape effects – with respect to socio-technical infrastructure(s). Many papers aim to structure the discussion, or summarize results, on what effects may occur. The main effects studies are on the technical system, rather than the behavior of actors and institutions. It is beyond doubt that such understanding is necessary in order to discuss how this effect can be mitigated or prevented. Many papers include the landscape (21 times) and also many papers mention the technical system (24x) but only 18 out of these mention the physical infrastructure separately. Furthermore, much less attention is paid to the social system (13x).

There is literature in which an integrated perspective is adopted. The typical way in which this is done is to delineate to the borders of one or more cities. These papers, however, do not focus on adaptation but on assessment of the effects of climate (cf. Belzer, 1996; Wuebbles, 2010; Gasper et al., 2011). Furthermore, for larger systems (such as a whole city), the work is mostly qualitative.

4.3 Time

What is interesting about the collected papers is that the time differs widely in the papers studied. That is, both long-term and short-term effects of climate change are studied or mentioned in the papers. When the discussed time scale is *short*, a situation is sketched with the direct effects of climate change, i.e. changes in the weather etcetera. Most studies look at long-term effects, however. On such a time scale, it is mostly the emission levels that are predicted, where it is expected that the amount of greenhouse gas emissions will in time influence the weather pattern. Rising emission levels are an effect of human behavior and a result of increased use of assets such as cars and air conditioners that predominantly consume fossil fuels. Combining short-term *and* long-term effects of climate change with respect to physical infrastructure are rather scarce. Adaptation of our infrastructures may well imply influencing long-term processes by implementing changes in our infrastructures today. An example could be the potentially changing conventions for managing our electricity grids on the short term, which can be done to cope with a changing role of the electricity grid (allowing for more distributed generation and intermittent generation for instance). Such changes may lead to different long-term developments, either becoming more resilient to climate change effects or not, depending on the management conventions chosen. Therefore, the interdependence of short- and long-term aspects is extremely relevant. The fact that there is no literature on such aspects may be considered a blind for the adaptation of infrastructures with respect to climate change.

4.4 Modeling

Quantitative and qualitative papers are spread rather evenly. Seventeen of the analyzed papers are quantitative in nature. Four of these are mixed while 18 papers are purely qualitative. Some papers describe quantitative models (e.g. Stewart, 2011). In this group, modelling integrated systems is not common. Often, reference is made to the level of analysis of a *city*. The city is then often described as one unit, where infrastructures such as water and sewer may be mentioned but are not consistently modeled as physical and social components that interact in various ways. The focus is rather on aggregate system-level parameters. For example, there may be a higher chance on congestion of road infrastructures; and there is no analysis of how the behavior of people driving cars change. Modeling infrastructure adaptation can, therefore, be considered to be in its initial stages. Many opportunities for new research may be found in modelling the strategies for adaptation, combining social and technical aspects, modelling the long-term effects of short-term changes.

5 Conclusions

Climate change is likely to affect our infrastructures and, consequently, the way society interacts with these infrastructures. In this paper, we analyzed the state-of-the-art literature on the adaptation of infrastructures with respect to the possible effects of climate change. We adopted a socio-technical systems perspective to eak out how issues regarding climate change and infrastructure is assessed in the key literature.

Our findings are summarized in Fig 3. The focal points of the analyzed research are highlighted with increased font size.

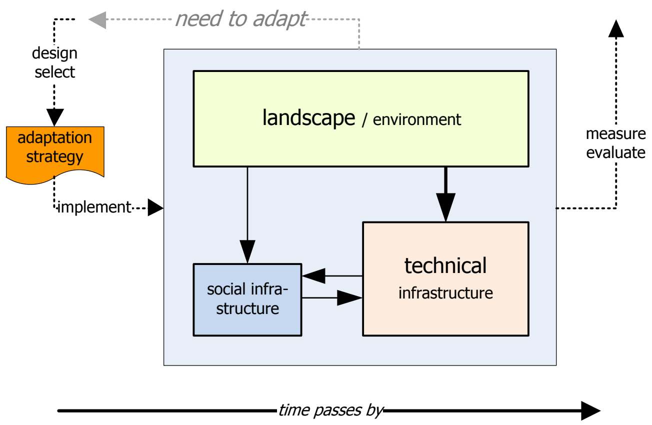

Fig. 3. Focus in the literature on adaption of infrastructure against effects of climate change.

Existing research focuses around technical elements in the infrastructure and effects in the landscape, i.e. possible effects in our environment (such as more storms and higher temperatures). There is no literature that combines short-term changes for adaptation of infrastructures with long-term effects on those infrastructures. This may be considered a blind for the adaptation of infrastructures with respect to climate change. Additionally, modeling infrastructure adaptation can be considered to be in its initial stages.

We conjecture, that every aspect within our socio-technical systems perspective should receive attention (every box in Fig. 3.). Therefore, future research attention needs to be diverted from the analysis of a technical component (when will my bridge be broken) to the technical infrastructure level: How do I judge/measure when to replace a road section (including the bridge)? And broadening further to the socio-technical system level: How can I adapt the system as a whole as to prevent the effects of the tunnel breakdown? In addition to broadening the analysis, we conjecture that suitable simulations and models should be developed to explore adaptation strategies at these levels of aggregation: they are rare in the literature today.

Reference	Institute	Time	Domain	Methodology	Perspective	Aspects	Infrastructures	Inter-connected	Quantitative
(Hunt & Watkiss, 2011)	Univ. Bath	Long short	City	Review	Landscape, technical, less social	Various	No	No	No
(Stewart et al., 2011)	Univ. Newcastle	Long	Concrete	Modeling	Landscape, technical	Advanced corrosion	Yes	No	Yes
(Molderink et al., 2010)	Univ.Twente	Short	Area	Simulation optimization	Social and technical	Energy demand	No	No	Yes
(Fuglestvedt et al., 2010)	CICERO	Short	Greenhouse gases	Modeling	Landscape	Metrics	No	No	Yes
(Stakhiv, 2010)	Inst. Water Resources	Long	Water resources	Case	Landscape, social	Management under uncertainty	No	No	No
(Davis et al., 2010)	Carnegie Inst. of Washington	Long	Energy	Modeling	Technical	CO_2 emissions	Yes	No	Yes
(Thimmapuram et al., 2010)	Argonne Nat. Lab.	Short	Energy	Simulation	Technical	Price elasticity of demand, ABM	Yes	No	Yes
(García-Montero et al., 2010)	Tech. Univ. Madrid	Long	Country	Screening	Landscape	Infrastructure plan, biodiversity	Yes	No	Mix
(Wuebbles et al., 2010)	Univ. Illinois	Long short	City	Review summary	Landscape, technical	Temperature, health, precipitation, aquatic ecosystems, energy	No	No	No
(Schwoon, 2008)	Int. Max Planck Res. School	Long	Transport	Simulation	Technical, less social	Diffusion of technology	Yes	No	Yes
(Scheer, 2011)	Univ. Stuttgart	Long	Energy	Review	Technical	CCS	No	No	No
(Liu et al., 2007)	Imperial College	Long	Energy	Modeling optimization	Technical	Energy systems, multiple outputs	No	No	Yes
(Suarez et al., 2005)	Boston Univ.	Short	City	Modeling	Landscape, technical, less	Urban transportation	Yes	No	No

					social				
(Kirshen & Ruth, 2004)	Tufts Univ.	Long	City	Modeling	Technical, less social	Water resources	Yes	No	No
(Lynch et al., 2004)	Univ. Colorado	Long	City	Modeling	Landscape	Ice smelting, extreme winds, storms	No	No	Yes
(Greenough et al., 2001)	Johns Hopkins Univ.	Long	Country, health	Description review	Landscape, technical, less social	Warning systems	Yes	No	No
(Belzer et al., 1996)	Pacific Northwest Laboratory	Long	City	Modeling	Landscape, technical	Energy consumption	No	No	Yes
(Eum & Simonovic, 2011)	Univ. Western Ontario	Short	Region	Modeling	Landscape	Extreme climate events	No	No	Yes
(Gasper et al., 2011)	Univ. Maryland		City	Description review	Landscape, technical	Extreme climate events, health, scarcity	No	No	No
(Jollands et al., 2007)	Massey Univ.	Long	Country	Review	Landscape, technical	Various	Yes	No	Mix
(Sanden & Azar, 2005)	Chalmers Univ. Tech.	Long short	Energy policy	Review	Technical	Decarbonization	Yes	No	Mix
(Woodcock et al., 2007)	London School of Hygiene and Tropical Medicine	Long	Transport	Description review	Social, less technical	Effects transport on health	No	No	No
(Easterling et al., 2000)	National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center	Long (100 years)	Biological and societal	Review modeling	Social and biological landscape	Climate change elements effects on biosphere and society	Societal infrastruc-ture	No	No
(Costello et al., 2009)	Institute for global health	Medium long	Health	Review description	Landscape social and institutional	Effects climate change on heath	Societal	No	No
(Frederick, 1997)	Resources for the Future	Medium	Water management	Description	Institutional	Use of market approach	Institu-tional	No	No
(Tol et al., 2003)	Centre for Marine and Climate Research, Hamburg University	Long (50 years)	River management	Case study	Social and technical (river as tech	Technology options		No	No

					artifact?)				
(Wilby, 2007)	University of East Anglia	Medium and long	Build environment	Description	Landscape social and technical	Urban climate change impacts	Yes	Yes	Mix
(Belzer et al., 1996)	Pacific Northwest Laboratory	Long (40 years)	Energy consumption buildings	Model	Social and technical	Energy demand in buildings	Yes	No	Yes
(Koetse & Rietveld, 2009)	Department of Spatial Economics VU	Long	transport	Review	Technical and social landscape	Effects on transport modalities, modal choice	Yes	No	No
(Mcmichael & Sari Kovats, 2000)	Departement of Epidemiology and Population Health London School of Hygiene and Tropical Medicine	Long (60 years)	Public health	Description	Social landscape	Biological, behavioral and social adaptation strategies	No	No	No
(Brown & Lall, 2006)	International Research Institute for Climate and Society, Columbia University	medium	Water scarcity	Model	Environment	impact of increased climate variability on national economies	No	No	No
(Kirshen et al., 2008)	Department of Civil and Environmental Engineering, Anderson Hall,	Long (100 years)	Urban climate change	description	Technical and social landscape	Effects of climate change on different urban infrastructures	Yes	Yes	No
(Decicco & Mark, 1998)	American Council for an Energy-E¦cient Economy	Long (30 years)	Transportation	Model and policy analysis	Technical and social	Forecast of energy consumption of transport sector possible policies	Yes	No	Yes
(Suarez et al., 2005)	Department of Geography, Boston University	Long (20 years)	Urban transportation	Method	Technical and social	Effects of flooding on transportation network	Yes	Yes	Yes
(Vellinga & Klein, 1993)	Institute for Environmental Studies, Vrije Universiteit	Medium	Coastal zone management	Method	Environment (dominant)	common methodology for the assessment of a country's or region's vulnerability to	No	No	Yes

						accelerated sea level rise			
(Davis et al., 2010)	New York University, New York	Long (50 years)	CO2 reduction	Discussion	Technical	Technology option for carbondioxide reduction	Yes	No	No
(Ruth et al., 2007)	Center for Integrative Environmental Research, university of Mary\land	Medium	Water infrastructure planning	Model	Technical and social	Impacts of climate change on water consumption and drinking water supply	Yes	No	Yes
(Krol et al., 2006)	Discipline Group Water Engineering and Management, Faculty of Engineering Technology, University of Twente	Long (50 years)	Water management	Model	Environment, social and technical (implicit)	Integrated modeling of climate change effects on semi-arid regions	No	No	Yes
(Warren et al., 2008)	Tyndall Centre, School of Environmental Sciences, University of East Anglia	Long	Integrated assessment of climate change	Description of software model Community Integrated Assessment System	Environment and economics	mitigation scenarios aimed at reducing emissions of CO_2	No	No	Yes
(Fankhauser et al., 1999)	World Bank, Washington	-	Description	Strategy for climate change adaptation (economics, social, institutional)	Environment, policy environment	Climate change adaption strategy for increased flexibility and resilience	No	No	No

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