Critical infrastructure and disaster risk reduction planning under socioeconomic and climate change uncertainty

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ABSTRACT: Planning of infrastructure and disaster risk mitigation measures is carried out under significant uncertainties. In particular, the effects of climate and anthropogenic change are associated with large uncertainty, but most extreme events are poorly understood even under stationary conditions. To address these uncertainties, the designers/decision makers can follow different strategies, such as conservative designs, flexible (adaptable) designs or delaying the decisions to later times when more information is available. The optimal adaptation strategy depends on multiple factors such as system type, regulatory framework, the degree and type of uncertainty and the amount of learning that is possible in the future. Based on quantitative Bayesian decision models, we derive general recommendations on optimal design approaches. Our results show, for example, that flexible systems are especially beneficial in cases where uncertainty is high and where the learning effect in the near future is expected to be significant. They are typically less advantageous in the context of a risk-based decision framework (where the aim is to find a balance between the residual risk and cost) than in a rule-based regulatory framework (where safety requirements are prescribed, e.g. that flood protection must be designed against a 100-year event). In the former case, it is often more effective to add safety margins, which is a no-regret strategy.

Keywords: Climate adaptation, uncertainty, flexibility, robustness.

1. INTRODUCTION

The planning and implementation of infrastructure systems and integrated disaster risk reduction is associated with large investments and long lifetimes. For example, 3,4 billion Euro is to be spent in Bavaria alone on flood protection measures before 2020 (Rimböck, 2015). The identification of optimal decisions is hindered by the uncertainty on the frequency of extreme disaster events, on the future effects of climate change as well as the future changes in societal vulnerability and damage potential.

Strategies exist for dealing with these uncertainties. These include the application of safety factors on the system capacity or the implementation of flexible systems that can be adjusted in the future without excessive costs or delaying of decisions to later time when more information is available (Hallegatte, 2009). The selection of the appropriate strategy should consider many factors. A full optimization of these strategies under uncertainty therefore requires sophisticated extensive modelling that is not practicable in specific projects. We examine the key factors that decision makers should consider when selecting the adaptation strategy: system characteristics, regulatory framework, frequency of system revisions, type and degree of uncertainty and potential for future learning. We discuss the optimality of different design approaches in function of these key factors. Our discussion and recommendations take basis in quantitative Bayesian decision models described in Špačková and Straub (2016), Dittes et al. (2016) and Straub and Špačková (2016).

3. PLANNING APPROACHES: FLEXIBILITY AND SAFETY FACTORS

Flexibility describes the potential of a system to be changed in the future without excessive costs. The terms adaptability, reversibility or changeability are also used in this context, with slightly different meanings (Ross et al., 2008). Examples of flexible infrastructure systems include

- flood protection systems whose possible future upgrades are facilitated by reserving land for future building of additional flood defences or heightening of existing dikes (Vrijling et al., 2009), as illustrated in Fig. 1(a);
- urban drainage systems whose backbone parts are overdesigned to allow extension of the system in the future or which enable cheap adjustment of the retention capacity in the future (Radhakrishnan et al., 2014).

In Špačková et al. (2015), a measure of flexibility φ was proposed, which expresses how costly it is to adjust a system, relative to the initial investment. $\varphi=0$ corresponds to an inflexible system and $\varphi=1$ to a fully flexible system. If an inflexible system has to be altered, the associated cost are the same as if the system is built completely anew. If a flexible system is adjusted (e.g. if its capacity is increased), the costs are significantly lower, because the existing system is used. For fully flexible systems, the number of steps to reach the final capacity is irrelevant; the total costs are the same if one builds to the final capacity at once or if one adjusts the capacity gradually.

The safety factor is a measure of the reserve capacity that is built into the system to account for uncertain future changes in demand; it is defined as the ratio between the actual capacity of the system and the minimum required capacity without accounting for uncertain future changes in demand. In other words, it measures the over-design of the system. Safety factors against uncertain future changes are used in practice; for example in Bavaria a safety factor of 1.15 – i.e. a 15% reserve – is applied to the design flood discharge when planning new flood defences to account for climate change uncertainty.

Recommendations for system overdesign, i.e. safety factors, do not explicitly consider the flexibility or the projected lifetime of the systems. It is intuitively understood that different safety factors should be applied for flexible and inflexible systems: Flexible systems can be easily changed in the future and their safety factors (reserve) should thus be lower than for inflexible systems whose future changes are costly. Similarly, a system with shorter lifetime is unlikely to require a big reserve to account for climate change effects, since these are likely to take effect only further in the future. The characteristics of the system (flexibility, lifetime) should therefore be taken into account when deciding on system overdesign.

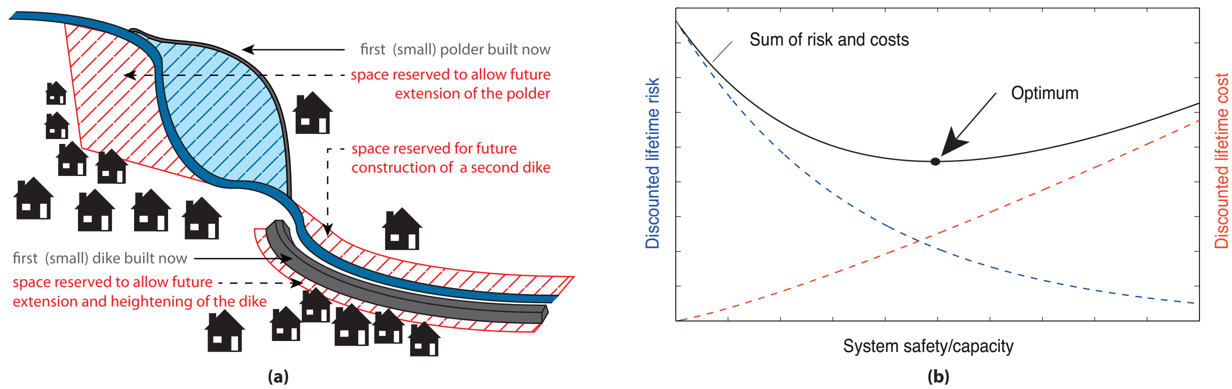

Fig. 1: (a) Illustration of a flexible flood protection system. (b) Risk-based optimization of system design.

3. KEY FACTORS INFLUENCING THE OPTIMAL PLANNING

Besides the characteristics of the system (flexibility, lifetime) described in the previous section, multiple other factors influence the optimal planning. These are discussed in this section.

With respect to regulatory framework, two main directions can be distinguished: (A) Risk-based (sometimes referred to as performance based) planning, where the optimal design is identified as the one providing a reasonable balance between the safety of the system (the residual risk) and the costs for its implementation and maintenance. The optimal design minimizes the lifetime sum of discounted risk and cost (Špačková and Straub, 2015), as illustrated in Fig. 1(b). (B) Rule-based (or prescriptive) planning, where the system is subject to prescribed safety requirements. For example, most new flood protection systems in Germany must be designed for a 100-year event, and some levees in the Netherlands are required to withstand a 10 000 –year event (Vrijling et al., 2009). In this case, the optimal design is the one that minimizes the discounted lifetime costs while complying with the regulatory requirements.

Three different types of uncertainty in infrastructure and disaster risk reduction planning are considered here: (1) Climate uncertainty associated with the effect of the climate change on the frequency of extreme events. (2) Socio-economic uncertainty associated with the development of society leading to changing demands on the infrastructure, e.g. through increased development in flood plains or changing vulnerability to natural hazards. (3) Statistical uncertainty associated with determining the frequency of extreme events even under stationary conditions, due to limited historic records and imperfect models (Dittes et al 2016).

The degree of uncertainty determines the significance of the uncertainty. For example, there exists uncertainty in changes of average temperature and precipitation due to climate change, but the uncertainty on the effect of the climate change on the frequency of extremes is significantly higher. Similarly, the statistical uncertainty on estimating the magnitude of a 100-year discharge is not negligible when 100 years of discharge measurements are available, but it is higher with only 30 years of data.

Finally, future learning, i.e. the type of information that will be gathered in the future and used for informing the future decisions is a crucial factor that should be considered in making the current design decisions, as was shown in (Pozzi et al., 2016). In most problems, also the future decisions will be made under uncertainty. For example, statistical uncertainty on the 100-year flood will be reduced with additional observations of annual maxima, but it will never fully disappear. The amount of learning in the future will be larger if the present uncertainty is larger. This follows from classical statistics, which dictates that the statistical uncertainty reduces with $\sqrt{t}$, with t=time, if the amount of data collected is constant over time. In contrast, climate change is gradual and its effects are likely to materialize at a later time in the future. Therefore, uncertainty on how the climate change influences extreme flood events will likely not be much reduced in 20 years from now.

4. IMPLICATIONS FOR PLANNING

The planning of disaster risk reduction measures and infrastructure need to take into account the system characteristics and key factors discussed in the previous sections. The decision makers can face different situations: (1) When the flexibility of the system is given, the decision maker has to select the safety factor for the system. (2) When the flexibility can be selected or the choice is between systems with different flexibilities, the decision maker has to additionally determine the Value of Flexibility (VoF), i.e. up to how much should one pay to make the system flexible? Flexible systems are typically more costly initially: reserving the land in the example of Fig. 1(a) is associated with additional cost.

In the following, the general design recommendations are listed, some of them are additionally illustrated in Fig. 2. These are based on the numerical investigations of Špačková and Straub (2016) and Dittes et al. (2016).

- Flexible systems require lower safety factor (less conservative design) than inflexible ones (Fig. 2a), because they can easily be changed in the future without excessive costs.
- The higher the degree of uncertainty, the higher should be the safety factor (Fig. 2a), i.e. the more conservative should be the design.
- If there is a significant learning expected in the near future (e.g. reduction of statistical uncertainty due to gathering new data), the Value of Flexibility is high. In contrast, if there will not be much new information at the time of future system revisions (which is likely to be the case for climate change effects on extreme events), the VoF is much lower, because the decision maker is not likely to change the system in the future (Fig. 2b).
- The higher the degree of uncertainty, the higher the VoF.
- In risk-based approach, VoF tends to be lower and applying higher safety factors is recommendable since it is a no-regret strategy (a more conservative design leads to a reduction of residual risk under all future scenarios).
- In rule-based setting, in which the safety requirements on the systems are prescribed (e.g. the flood protection that has to be designed for 100-year event), VoF is higher than in the risk-based approach (Fig. 2b). This is due to the fact that the estimate of the 100-year event is likely to change in the future requiring modifications to the system, which are cheaper for flexible systems.
- Systems with short lifetime (e.g. < 30/50 years) do not need high safety factors to account for uncertain gradual changes (such as climate change). However, when statistical uncertainty is significant, even systems with short lifetime should be designed with high safety factor.

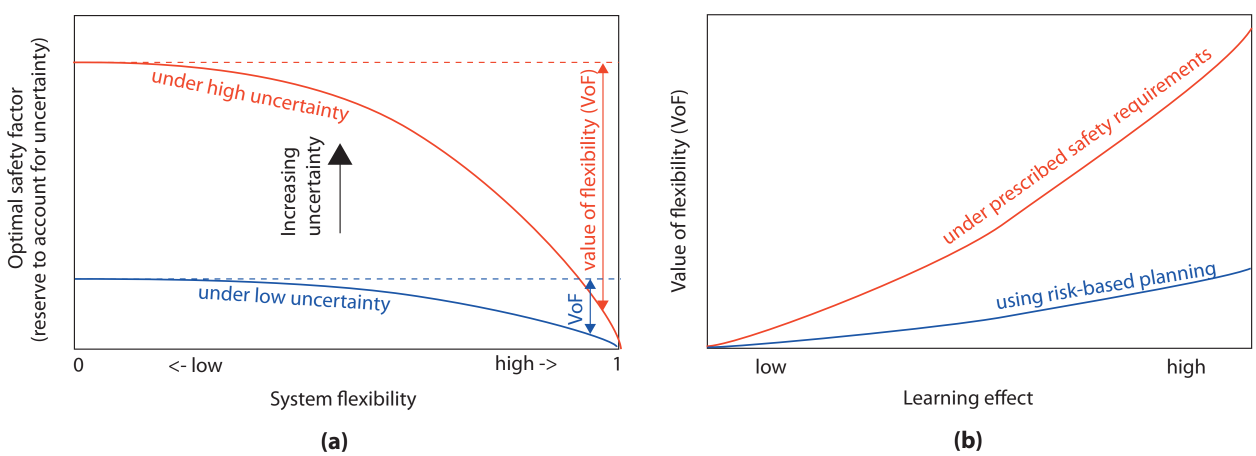

Fig. 2: (a) Optimal safety factor as a function of system's flexibility and degree of uncertainty. (b) Value of Flexibility (VoF) as function of future learning effect under two regulatory frameworks – with prescribed safety requirements or using risk-based planning.

5. CONCLUSIONS & ADDED VALUE FOR INTEGRATIVE RISK MANAGEMENT AND URBAN RESILIENCE

Huge investments to disaster risk reduction and climate adaptation will be necessary in the coming decades. To use the available but limited resources efficiently, the planning of disaster risk reduction measures and infrastructure must proceed with caution. The decisions to be made are particularly complex as they are made under significant uncertainties such as: How will the climate change affect the frequency of extreme weather events? How will the society evolve in the next 50 years? The aim of this work is to support such decisions and to help the decision makers with selecting the best disaster risk mitigation option. We identify key factors influencing the optimal design and provide generalized recommendations on how these should be reflected in the decisions. For example, we show that incorporating flexibility into the systems, which is typically considered as a good solution for dealing with future uncertainties, is not necessarily beneficial in all cases and that, in some cases, it may be preferable to invest into an inflexible system with conservative design.

The presented results and the models underlying them are novel attempts to base adaptation decisions on quantitative analysis of uncertainties and characteristics of the designed system. The need for such investigations has been identified recently and there are several open questions that require future research, such as the planning under combined uncertainties, the derivation of quantitative recommendations on safety factors and Value of Flexibility, or confirmation of the presented general findings on concrete applications to different planning problems.

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