A framework for life-cycle management of public infrastructure

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ABSTRACT: This paper presents a framework for life-cycle management of public infrastructure. Compared to for instance life-cycle management for industrial applications, public infrastructures offer some specific challenges. This framework aims to capture these. It is based on the different life-cycle stages and considers three decision levels: strategic decisions made by the asset owner, tactical decisions made by the asset manager and operational decision made by the service provider of the asset. In the framework both decisions on networks and systems of assets, as well as individual assets are considered and connected. The framework consists of three parts: a process scheme for life-cycle management of public infrastructure, a toolbox to quantitatively assess life-cycle decisions and a model to assess the quality of information in relation to different life-cycle decisions. Based on a set of cases the applicability of the framework is demonstrated.

1 INTRODUCTION

Infrastructural assets and systems of assets are vital elements for a well-functioning society, and therefore maintaining and improving such systems is of huge importance. As infrastructure ages over time, the infrastructure portfolio constantly demands replacement, removal, rehabilitation and improvement. This behavior is dynamic. Infrastructure assets deteriorate over time and have to be replaced, renewed or removed at the end of their lifespan, or might be improved due to changes in societal requirements. Thus life-cycle management, i.e. the integral management of assets over their life-cycle (Fuchs et al., 2014), can provide large benefits as it aligns the different phases of the life-cycle.

In the Netherlands, many of the public infrastructure assets have been built in the post Second World War period and therefore the focus in the infrastructure sector is shifting from building new things to maintaining existing systems by renovation and replacement (Nicolai and Klatter, 2015). ROBAMCI (Risk and Opportunity Based Asset Management for Critical Infrastructure) is a research program that aims to support infrastructure management by developing quantitative tools to support infrastructure asset management decisions in order to realize efficiency gains in the Dutch infrastructure sector, specifically on water related infrastructures and the subsurface. This is achieved by studying cases of different types, such as efficient coastal reinforcement, life-cycle management of systems of hydraulic structures, risk-based dredging of water systems as well as life-cycle reinforcement and monitoring strategies for flood defences. The goal of ROBAMCI is to show in a business case the large performance gains that can be achieved by adopting a risk-based approach to asset management for the Dutch infrastructure sector. Additionally in the cases studied, general tools for lifecycle decision making are developed, making a structured quantitative approach possible for any infrastructure application.

In order to align the different cases and methods, a general framework has been developed. With this framework, experiences and methods from cases on specific types of infrastructure can be aligned and used for analysis of other types of infrastructure. It aims to connect lifecycle management processes to (existing) quantitative models. In this paper first some existing knowledge and frameworks are discussed, including the problems that are encountered when implementing life-cycle management of public infrastructure. Then this is translated into a first version of a framework for public infrastructure. Using cases studied in ROBAMCI the applicability of the framework is demonstrated. The presented framework is a first version, and it will be updated based on experiences with applications on various case studies in the program.

2 LIFE-CYCLE MANAGEMENT AND ITS APPLICATION

2.1 *What are life-cycle management and asset management?*

The ISO55000 defines asset management' as the coordinated activity to realize value from assets' (ISO, 2014), a rather wide definition. Life-cycle management is generally perceived as the management of the performance, risks and cost of assets and asset systems over the life cycle.. Hence, life-cycle management can be considered an important field of interest within the broader field of asset management. It is a manner of concretizing the goal of asset management (optimal value realization from assets over their life time) in a practical way, in the longer term (optimal management over the life-cycle). This for instance includes proper arrangements in maintenance contracts, in which requirements are not only dealing with the performance and cost during the contract, but the performance, risks and cost during the entire life cycle.

In general for infrastructure, good asset management strategies will be based on optimization over the entire life-cycle, both on operational, tactical and strategic level. Hence, life cycle management should always be a part of an asset management strategy for infrastructure, and life cycle performance, costs and risk should be continuously forecasted and monitored. Figure 1 shows how life-cycle management is considered at Rijkswaterstaat, the largest asset management agency for public infrastructure in the Netherlands. The terms programming, realization, operations and study are very similar to the Plan-Do-Check-Act cycle, which is one of the most often used asset management models (Marlow and Burn, 2008). This confirms the close relation between life-cycle and asset management for infrastructure (planning).

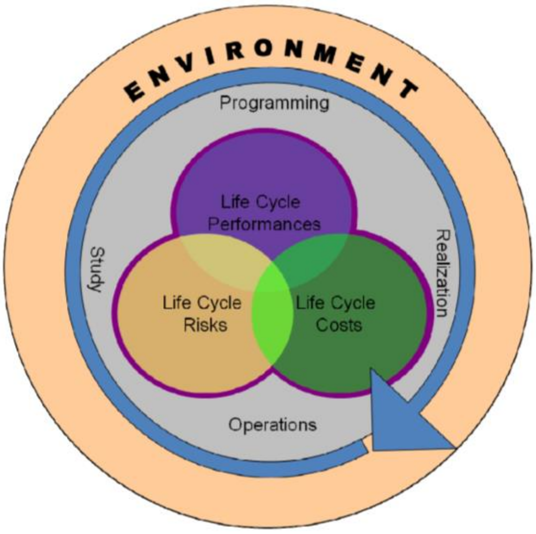

Figure 1. Life Cycle Management according to Fuchs et al. (2014)

2.2 *Practical implementation of life-cycle management*

Fuchs et al. (2014) give a comprehensive overview of the implementation of life-cycle management at Rijkswaterstaat, its successes, lessons learned and potential improvements. From this, and other examples, it is shown that a life-cycle approach can potentially result in large efficiency gains (Alegre and Coelho, 2012; ENO Center for Transportation and ASCE, 2014) and more insight in the impact of measures over a longer period of time (Barone and Frangopol, 2014; Frangopol and Soliman, 2015; Frangopol et al., 2001; Klerk et al., 2015; Padgett et al., 2010; Voortman and Vrijling, 2004). Also it is identified that adopting a structured asset management approach can improve transparency in decision making (Van Riel et al., 2012).

However there are also some clear difficulties identified regarding implementation of life-cycle management. A selection of these is summed up below:

- Implementing life-cycle management needs an organization that is ready and set-up for it (Alegre and Coelho, 2012; Fuchs et al., 2014). This means that evaluation criteria should stimulate a life-cycle approach and that people should have a clear view on what life-cycle management is. Fuchs et al. (2014) sketch the latter as people saying “We’ve been doing it already for a long time”.
- Transfer of information on assets and requirements of assets between different life-cycle stages is often difficult, but necessary for a proper execution (Boussabaine and Kirkham, 2004; Fuchs et al., 2014).
- Life-cycle strategies often concern different dimensions: an important distinction in infrastructure is the distinction between individual assets and networks of assets.
- In practical implementation it is often the case that there are different parties involved in the life-cycle of the same asset. For instance, the asset owner and service provider are not necessarily the same.

In the next chapter a framework which aims to structure the questions in the points above is presented.

3 A FRAMEWORK FOR LIFE-CYCLE MANAGEMENT WITH THREE COMPONENTS

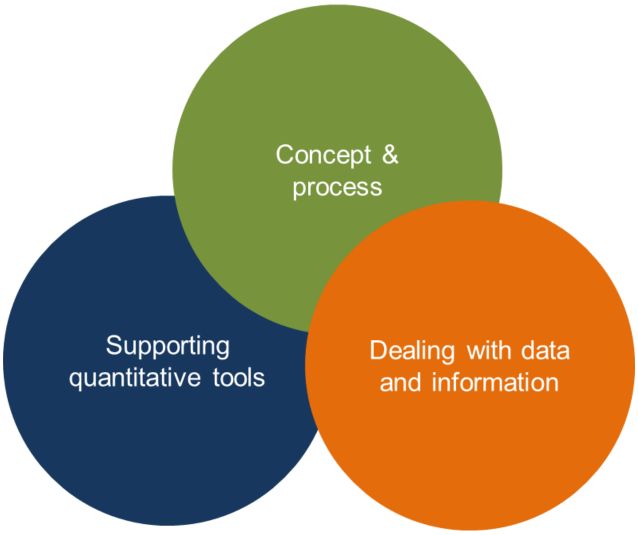

Figure 2. General set-up of the framework in three parts

3.1 *Set-up of the framework*

The framework that has been developed in the ROBAMCI project has the following main goal: "Provide a practice-based and applicable basis for quantitative life-cycle and asset management of public infrastructure."

In order to achieve this, the framework contains three components, as shown in Figure 2:

- Concept & process: a process scheme, representing the process of the infrastructure life-cycle and its decisions in different life-cycle stages.
- Dealing with data and information: a model for assessment of the quality of information.
- Supporting quantitative tools: a toolbox where generic tools for life-cycle analysis of assets and networks of assets are coupled with asset-specific physical models.

These three parts, the questions they aim to answer, and their role in the framework as a whole are outlined in the following sections.

3.1.1 *Process scheme for infrastructure life-cycle management*

The first part of the framework is a model for the life-cycle management process, which is presented in Figure 4. In literature many similar models can be found, and therefore it is not revolutionary as similar schemes have been used for decades in various disciplines (Hammer, 1981; Hudson, 1997; Labuschagne and Brent, 2005). The basis of the scheme is a standard infrastructure life-cycle model.

As it was identified from the aforementioned literature and also from practical cases that it is often difficult to integrate analysis of single assets into analysis of networks of assets, specific attention was given to the relation between network and asset, which are represented by the 'rings' in Figure 4. Both rings have different relations in different phases, for instance in operation and planning phases. Also, functional requirements of networks often lead to specific requirements to assets, which should be synchronized in the design phase to ensure proper and coherent functioning of the network as a whole. Figure 3 gives a very basic example of this, it shows the development of the performance of a system of two assets in time. In this case, both assets are improved when they reach their asset requirement. However, due to this the performance of the system is generally much higher than required. If both assets would be improved based on the system requirement, the overinvestment would be much smaller. For instance, the second investment in asset 1 is not required from a system perspective, and is thus not necessary, but still carried out as the asset requirement is not met. In order to prevent this, investments in assets should always be based on the system performance, rather than a suboptimization on asset level. A possible solution could be to (temporarily) redistribute performance requirements over assets.

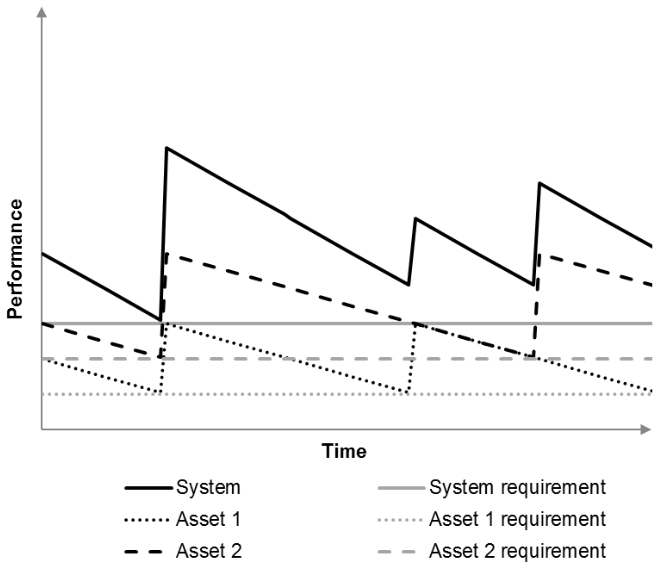

Figure 3. Example of relation between asset performance and system performance, and potential efficiency gains that can be achieved by a network or system based approach.

Another important part in this scheme is the distinction between different roles in the life-cycle: asset owner, asset manager and service provider all fulfill a different role in the life-cycle of a network and an individual asset. In practice this is often an obstacle for implementation of life-cycle management, as different organizations have different roles and thus different interests. For instance, if organization A pays for construction and organization B for maintenance, the motivation for A to build an asset

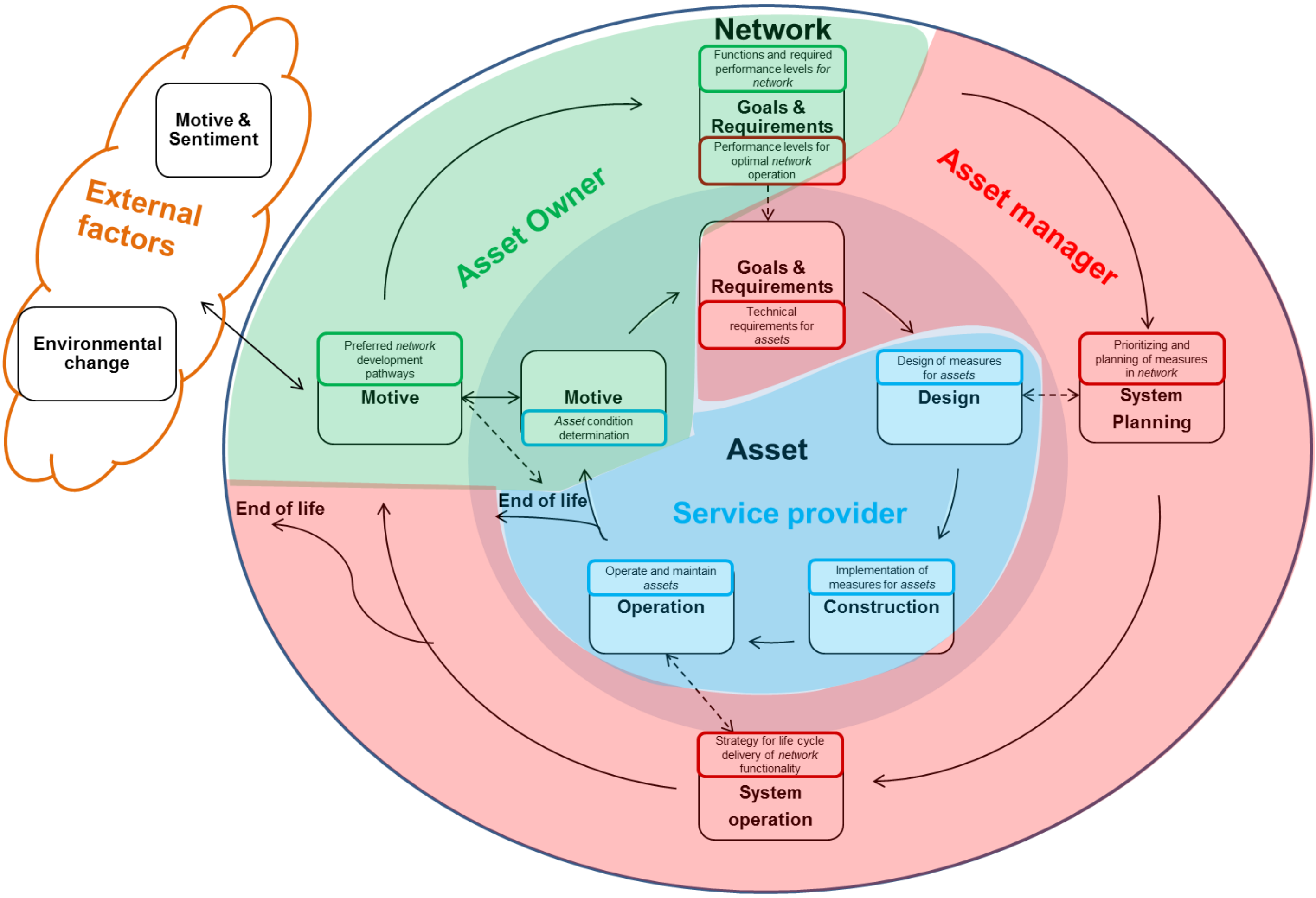

Figure 4. Process scheme as part of the ROBAMCI framework

with low maintenance cost will be very small, while it could be cheaper overall. This is a problem which is often encountered, especially in networks, such as networks of discharge locations in large water systems. Therefore it is important to clearly distinguish these roles in the overall processs. Obviously it can be the case that the same organization fulfills both the role of asset manager and service provider. For instance, Rijkswaterstaat manages the Dutch storm surge bariers (i.e. they are service provider). However they also plan measures to improve the storm surge barriers (i.e. they are asset manager). Hence, they play both roles in that case. Therefore the exact distribution of what roles different parties involved have in the phases of the life-cycle differs per situation. The last important notice regarding the scheme is the role of so-called "External factors". In principle, if nothing changes and the asset condition would develop as predicted, a life-cycle strategy could be determined for a thousand years and be completely optimal all the time. However, demands change in time due to environmental changes, advance in knowledge and changes in societal demands. Therefore in the figure there are three main contributing factors for "Motive" to evaluate the functioning and goal of infrastructural assets and networks:

- Asset condition determination: sudden changes in expected life-time of assets, for instance due to advanced knowledge on failure mechanisms can cause a re-evaluation of performance requirements. For instance, in the Netherlands in 2017 all flood defences will be assessed with a new version of the Dutch statutory safety assessment tools. This means that for some failure mechanisms, defences that were approved in the last assessment will be disapproved based on new rules.
- Environmental change: expected change in enviromental boundary conditions can cause a re-evaluation of long-term plans and performance levels. Predictions on change in rainfall patterns and sea level rise are clear examples of this.
- Motive & Sentiment: societal requirements might change over time. An example is the investment budget available for flood defences right after a (near)-disaster. In the Netherlands, after the major flood in 1953, huge investments were made in strengthening the coastal defences. In 1995, after near floods at the major rivers, huge investments were made in improving the discharge capacity of the major rivers. Such events often trigger a re-evaluation of performance requirements and thus a change in long-term life-cycle strategy.

The process scheme as presented is in itself not new, but emphasizes some of the most critical points of interest for the field of public infrastructure. By further application to actual cases the applicability can be further improved and refined.

3.2 *Model for assessing quality of information*

The second part of the framework is a model for assessing the quality of information (Bakkenist et al., 2016). In this paper a model is developed with which information quality can be assessed based on different dimensions of quality. This model can be an important aid in improving the transfer of information between different life-cycle stages, as it gives an objective framework for assessing whether the information available for a certain decision or task is sufficient.

3.3 *Toolbox for quantitative life-cycle analysis*

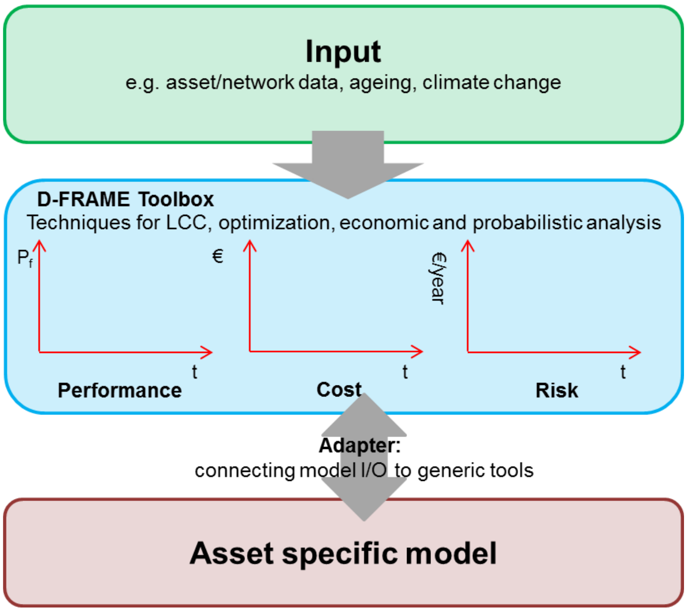

Figure 5. Set-up of the ROBAMCI Toolbox

The third part of the framework is a toolbox for quantitative life-cycle analysis called D-FRAME. The goal of this toolbox is to provide quantitative and widely applicable tools to support analysis of life-cycle strategies. The structure in which it is set-up, is very similar to the Delft-FEWS system, an early warning system for floods (Werner et al., 2013). Within Delft-FEWS, generic routines are connected to specific models by using adapters. A similar approach is used for the D-FRAME toolbox, after all, a life-cycle cost analysis for a road section is in principle not different from a life-cycle cost analysis for a flood defence, although the function and performance requirements differ significantly. A schematic representation is given in Figure 5. Based on this set-up, for every ROBAMCI case a distinction is made between generic parts and asset-specific parts. More concretely this means that with every case study carried out in ROBAMCI will either: result in new generic tools and/or new adapters for physical models, or profit from generic tools already available and physical models already connected to the toolbox.

The advantage of such a toolbox is that specialists can conduct life-cycle analysis with their specific trusted physical model.

Currently the toolbox is under development, but it can bridge the gap between physical models and expertise and life-cycle management that is now often difficult. With this toolbox it will be more easy to conduct life-cycle analysis using commonly used, verified and trusted physical models combined with verified and trusted generic tools that will be improved over time.

4 APPLICABILITY OF THE FRAMEWORK

Within ROBAMCI several explorative cases have been executed into different questions asked by various infrastructure managers. In this chapter these are outlined and the applicability of the framework to these cases is discussed. Only the applicability of the process scheme is discussed, as the toolbox and information quality model were not yet used in these cases.

4.1 *Coastal reinforcement in the Netherlands*

Within ROBAMCI a study on coastal reinforcements in the Netherlands was carried out. In this analysis different strategies for coastal nourishment are considered based on their costs and benefits (in terms of added safety and space for recreation). From this analysis it appears that the current approach, based on maintaining a base coast line is quite efficient but at some locations the benefits do not justify the amount of sand nourished. This analysis is typically an analysis of the goals and requirements to be met by the coastal nourishment program. As it considers the coast as a whole, this is typically an analysis of a network or system of interacting assets (i.e. a set of coastal sections). Figure 6.a schematically shows the area of the framework covered by this case study.

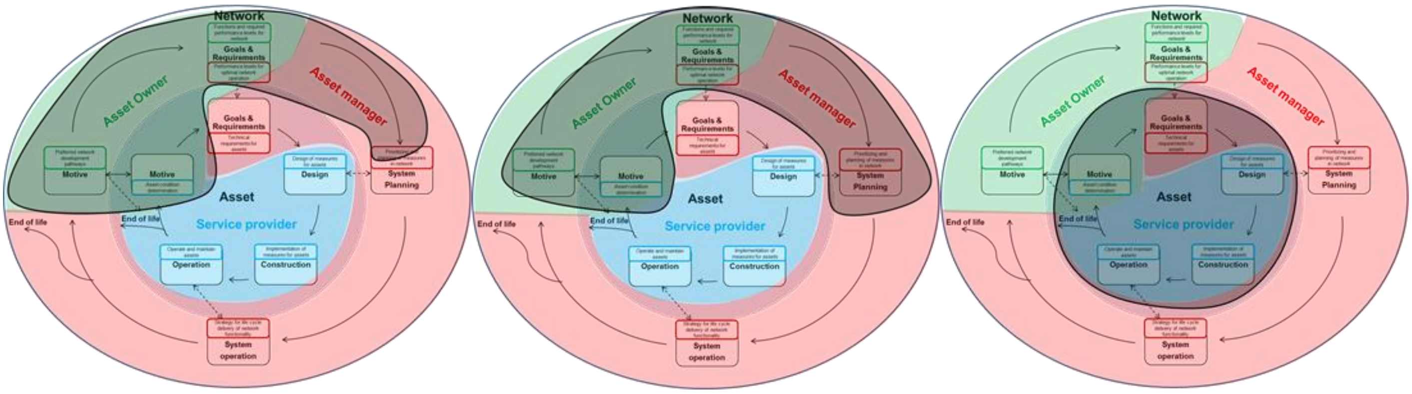

Figure 6. Positioning of three cases in the process scheme. From left to right: a. Coastal nourishment b. Hydraulic structures and c. dike

The phases and considerations covered by the coastal reinforcement case are:

- Motive: need for more efficiency at a network level, perception that sometimes suppletion volumes are larger than necessary based on the base coastline requirement.
- Goals & Requirements: are the current requirements, nourishment based on the base coastline, effective?
- System planning: only partially covered, but a nourishment planning that involves more benefit-related nourishment volumes at some locations is shown to be a potentially more efficient strategy than the existing strategy for coastal nourishment.

From this analysis it is shown that by looking at a system level, goals and requirements can be evaluated from a more general perspective. A next step according to the framework could be to make a longer term planning of nourishments, based on the costs and benefits at different locations, this will enable assessing the performance, cost and risk over the life-cycle.

4.2 *Systems of hydraulic structures*

A second case study was on long term planning in a network of hydraulic discharge structures. Results and the approach itself are discussed in more detail in (van der Wiel et al., 2016). The questions asked and answered in this case study cover more or less the same phases of the life cycle as for the coastal nourishment case study.

- Motive: the main pumping station in the considered area has to undergo renovation in the coming years and there is the impression that the capacity should be increased to make sure the discharge capacity of the system is sufficient.
- Goals & Requirements: due to the network approach the first step taken is to determine the current requirements at a network level and evaluate these based on the associated risks. While it has to be noted that the study only considers one function, it is shown that there is no clear requirement. If a requirement would be set based on the economic risk associated with flooding due to lack of discharge capacity, it would be much lower than expected, as the risk is not that high. It is important to note that only one function is considered here, it could be that the current requirements are cost-optimal for another function.
- System planning: The life-cycle costs, risks and performance of different strategies are evaluated for a period of 100 years. From this it is shown that, when solely looking at the maximum discharge capacity, there is no need for increasing the discharge capacity and it is likely that the current discharge capacity is already quite high in relation to its benefits in terms of risk reduction.

It has to be noted that the study only considers one function and expansion might be needed to ensure proper performance levels for other functions. In this case the operation of the water system is not taken into account, in other studies more specific life-cycle considerations on the management of the largest pumping station are considered (van der Wiel et al., 2013). In order to combine the network analysis with knowledge on specific assets, a less generic model for the network would be needed. However, from this study it is shown that a decision model was developed which can take all considerations in the life-cycle into account, albeit in a simplified manner.

4.3 *Influence of Structural Health Monitoring in life-cycle decisions for dikes*

In a case study on dikes the influence of Structural Health Monitoring (SHM) on life-cycle decisions was considered. A detailed description of this case study is given in Klerk et al. (2016). This case study considers different strategies for managing a single dike section over multiple life-cycles. As it considers a single dike section, it is typically a consideration on asset level. The case considers a sea dike that was disapproved for slope stability failures. However, due to the fact that this was an unexpected result the dike management organization started a monitoring project in order to further investigate the reason for disapproval. From this project it appeared that, although the dike was correctly disapproved, it was much stronger than expected based on the assessment. Therefore the total reinforcement, and thus the cost, was reduced significantly. In the case study the following considerations are made in different phases of the life-cycle:

- Motive: based on the condition of the dike and the possibilities for SHM it is considered whether this could be relevant as a long term strategy.
- Goals & Requirements: in this case the performance requirements of the dike are not considered as a variable, as these are defined by law.
- Design, Construction and Operation: various integral strategies for design, construction and operation are considered. The three main ones are:
    - No SHM, only reinforcement. This is a strategy most in accordance with how it is currently done.
    - Project-based SHM, only if a reinforcement is upcoming SHM is carried out. This is the strategy which is in accordance to what has been done in the case considered.
    - Lifecycle SHM, during the life-cycle, before the dike is disapproved SHM is carried out. This is the strategy most in accordance with the main aspects of life-cycle management: the performance and costs are continuously monitored and forecasted, and actions are based on that.

These strategies are evaluated based on their life-cycle cost, risk and performance. It has to be noted that, due to the structure of this case study Design, Construction and Operation will be considered together in an evaluation of strategies. However, in a sound asset management strategy a dike manager will evaluate on a regular basis whether his dike meets the requirements, whether it has to be redesigned, or whether his performance uncertainties are large enough to make SHM economically interesting. The developed method facilitates that regular evaluation as it can be carried out at any given moment in time, and can thus support a dike manager with efficient management based on performance, cost and risk.

5 DISCUSSION & CONCLUSIONS

In this paper a framework for quantitative life-cycle management analysis for public infrastructure has been presented. It consists of three parts: Firstly the concept & process, dealing with data and information and supporting quantitative tools. The conceptual part is well established in literature, and in the first phase of the project it has been shown that it is applicable to the cases studied. It has also added value to the analysis carried out. The other two parts still need development and practical application, which is the main goal for the second phase of the project. From this application, the feasibility of a generic toolbox for public infrastructure will have to be demonstrated. This can provide a sound quantitative basis for efficient life-cycle management, where physical behavior and general techniques are combined.

Application in cases should result in a practically applicable and objective framework for assessing quality of data and information, which can be a great aid in sensible use and collection of data, in relation to the life-cycle management decisions and processes. The question how much of what type of data is needed for decisions on strategic, tactical and operational levels is needed is often a struggle for many organizations.

The development of the framework hinges on the cases to come, these will lead to a better applicable framework, where practical questions can be connected to state-of-the-art physical and decision models.

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