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Life cycle management in upgrade and renewal of civil infrastructures

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Abstract: In the forthcoming decades, many objects in transport infrastructure networks will come to the end of their technical, economical or functional lifespan. The replacement and renovation will require substantial budgets and a timely start to secure the current functionalities. These challenges are a main concern for asset managers. However, the replacement programmes also have the opportunity not only to maintain the currently needed functionalities and quality but also for the timely adaptation of infrastructure networks to changing demands, because these will determine the value of these networks in the future. This will give added value not only to asset managers, but also to users (e.g. increased functionality), enterprises (e.g. new business opportunities), stakeholders (e.g. increase of liveability) and society as a whole (e.g. increased sustainability). Each replacement and renovation is an opportunity to make infrastructure networks more fit for future economic and environmental needs. This means a shift in thinking for asset managers to a broader view. This paper proposes strategies for asset managers to cope with the challenges and opportunities. The traditional approach focuses on the delivery, but the key for the replacement and renovation programme is to focus on the whole life cycle through life cycle management (LCM). From the LCM-approach, four perspectives are presented to strategic decision-making on replacements and renovations: (1) broadening towards a network approach as an opportunity for redesign, (2) developing innovations for increasing requirements and budget restrictions, (3) realizing adaptive networks to cope with future challenges and (4) combining functionalities to increase added value. Ultimately the goal is to maximize value for society.

Keywords: ageing infrastructures, asset management, adaptive networks, life cycle management, performance, renewal, value

1 Introduction

Asset managers of civil infrastructures are faced with increasing complexity in their networks, due to rising societal and technical demands, ageing infrastructure, limited budgets and changing environments. A safe and reliable infrastructure, managed from a multiple-perspective life-cycle view, is of vital importance for a sustainable and competitive society. Life cycle management (LCM) opts to create an optimal value for society over the life cycle of infrastructure (Hertogh & Bakker, 2016). The fact that many civil assets come to the end of their technical or functional lifespan stimulates the discussion of the contribution of LCM to the replacement and renovation of structures, in addition to raising the question on the systematic development of alternative solution strategies. These will be illustrated by examples about the replacement and renovation programmes for civil infrastructures at Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management. Rijkswaterstaat is responsible, as asset manager, for the maintenance and 24/7 operations of the Dutch main road network, the main waterway network and the main water systems in close relationship with the environment.

Many countries in Europe suffered greatly during the Second World War, and much of their infrastructure was destroyed. After the war, countries faced an enormous challenge rebuilding a society in a time of rapid population growth: the baby boom. There was a need for everything: more agriculture, factories, infrastructure and

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homes (Hertogh, 2013). Figure 1 shows the year of delivery of new bridges by Rijkswaterstaat and is an illustrative example for the increase in construction works in the post-Second World War period.

There is a clear peak in the 1960s and 70s. There are similar figures for locks and other structures. And figures with the same patterns can also be drawn for other European countries, such as Germany and Belgium.

In the forthcoming next decades, many objects will come to the end of their technical, economical or functional lifespan, if that is not already the case for some of these objects. The technical lifespan ends because of degradation. Bridge deterioration, for instance, could bring negative influence to functional performance, for instance, lower comfort level of road user, inferior structural reliability and higher maintenance cost (Pan et al., 2009). The economic lifespan ends once maintenance and renovation becomes too costly and replacement is preferable from a financial point of view. The functional lifespan ends because of external changes, for instance, more intense use, heavier loads, climate change, new regulations and so on. Because of the long lifespan of infrastructure, many structures already have limited functionalities. The reason for this is that decision-makers in the post-war reconstruction period focussed on a single purpose and adopted a mono-disciplinary approach, such as specific programmes for housing, highways, water safety, etc., without sufficient attention to negative externalities. Many of the legal procedures that come with infrastructure development today are rooted in the resistance mobilized by many mono-disciplinary, single-purpose solutions created in the post-war reconstruction era (Arts et al., 2016; Hobma & Schutte-Postma, 2010).

Maintenance costs of the existing networks can rise due to ageing structures, heavy loads and extensive use. Due to these, increasing investments are needed.

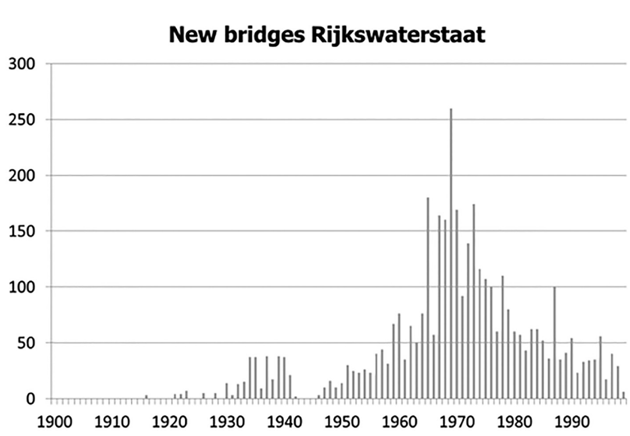

Fig. 1: Delivery of the number of new bridges at Rijkswaterstaat per annum.

In addition to this, additional budget is needed for replacement and renovation programmes. This leads to political challenges. That is why many view the increasing needs for renovations and replacements of existing structures due to technical and functional ageing of infrastructures as a burden, especially when there are insufficient, or even no, budgets available. Even in modern economies such as the USA, ageing of structures leads to a financial burden.

The philosophy of the authors, however, is that there is also a positive side to this. The necessary replacement and renovation of infrastructures can be used to make infrastructure networks more fit for future needs. The networks can be given an upgrade that is needed to cope with future economic and environmental challenges (Van Vuren et al., 2015). This will give added value not only to asset managers but also to other actors, for which we give illustrative examples as follows:

- users: increased and new functionalities, which will adapt to future needs
- enterprises: new, innovative business cases, such as a lock that generates energy, a restaurant on top of a bridge
- stakeholders: increase of liveability, possibilities for recreation
- society as a whole: more sustainable infrastructures (CO_2, sea level rise), nature development.

This means a shift in thinking. Investments in infrastructure usually go to new infrastructure primarily, but the upgrading of existing infrastructure can also be seen as a manner to improve the networks (Van der Vlist et al., 2015).

A very slow adaptation of a network to the prevalent needs leads to an inefficient infrastructure and will create a barrier to economic growth and to the welfare of people. Investment strategies are needed, dealing with both the technical and functional issues of the existing infrastructure. The timely adaptation of the infrastructure to changing demands will determine the efficiency of the infrastructure in the future.

KPMG (2016) mentions in their report ‘Foresight, A Global Infrastructure Perspective, ten emerging trends in 2016’, as the fourth trend: ‘Asset management gets sophisticated’. The report discusses that infrastructure owners shift their focus from building new assets to maximizing the performance of the assets they already own. Owners are keen not only to achieve the full-expected lifespans of their assets but also to get more productivity out of their existing operations. ‘The achievement of peak operational efficiency, the better management of demand and capacity, the reduction of maintenance costs and the delivery of improved customer service can enable owners to gain access to the full potential of their investments.' Furthermore, the advances in technology, including the use of data/analytics, are adding to the sophistication of asset management, which in the long run will shift the focus from reactive to proactive maintenance.

This paper focuses on the challenges for asset managers with the strategic investment agenda for infrastructure. What can be the next steps after the expected 'end of life' (functional and or technical) of existing ageing infrastructure is reached and how can these next steps be characterized in a systematic way.

First, the research methodology will be described in Section 2. In Section 3, the contribution of LCM to replacements and renovations of infrastructural assets will be discussed. In Section 4, four challenging perspectives are presented for asset managers in replacement and renovation programmes. The goal is maximizing value and LCM, and the four perspectives can contribute to this, but how this can be handled is the subject of the discussion in Section 5. Conclusions and recommendations are formulated in Section 6.

2 Methodology: an explorative approach

In literature, a lot has been written about LCM and the value of infrastructure for modern societies (see, for instance, Frischmann, 2012). But such a body of knowledge does not exist for ageing infrastructures and their renewal. Regarding flexibility in design, De Neufville and Scholtes wrote an important book named '*Flexibility in Engineering Design*', stressing that considering the uncertainties about future developments, flexibility in the construction of infrastructure anticipating these future developments could be a wise strategy (De Neufville and Scholtes, 2011). In addition, '*Next Generation Infrastructures*' (2004–2014), a research programme involving >40 PhD research topics, focuses on the next generation of infrastructures but does not give much attention to the ageing and replacement process. In the visionary study '*Infrastructures, Time to invest*' (The Netherlands Scientific Council for Government Policy, 2008), ageing of infrastructures is no issue.

For this research, specific publications on the history of infrastructure construction since the Second World War and articles about LCM have been studied. In addition, publications are used from specific topics that are relevant for ageing infrastructures, their renewal and the opportunities, such as about complexity theory, project management, asset management, adaptive management, risk management and value management. Because of the explorative character, we also looked at general publications about future challenges, e.g. The Institute of Asset Management (IAM, 2015) and by strategy consultants (e.g. KPMG, 2016).

But literature gave too less insights into future strategies to cope with the upgrade and renewal. That is why the authors used an explorative approach. Recent documents and insights have been used from the replacement and renovation programme of Rijkswaterstaat, and discussions took place with the authors of these specific documents. The following documents in particular are important:

1) the extensive prognosis report of Rijkswaterstaat; a prognosis of the end of lifetime of the infrastructural assets in the three networks for their replacement and renovation programme 2014–2050 (Klatter and Klanker, 2014);
2) the review report of this prognosis report by an independent expert group (senior professionals from public organizations and academy);
3) a visionary document about the strategy of replacement and renovation, the role of different parts of the Rijkswaterstaat organization and steps to be taken (De Zeeuw, 2015).

These documents illustrate the task of replacement focussing on the end of life time and steps to be taken to develop alternatives for the redesign of (parts of) the network and structures within the network. But from discussions with the authors of these documents, it became clear that they provide no indication of the content of these alternatives, except underpinning that this replacement is an opportunity to add value. But what is this added value or what could it be?

For the systematic development of alternatives to add value to (corridors of) structures that have to be replaced, input was used from expert sessions with practitioners and scientists from various programmes. Especially, three programmes were important, in which at least one of the authors of this article actively participated in the process.

The first is Grasp on the Meuse (in Dutch '*Grip op de Maas*'), a programme operating since 2015 for the replacement and renovation of seven weirs in the river Meuse, between Maastricht and Den Bosch, with an expected end of lifetime between 2028 and 2036. This development programme took place at the Dutch 'Bouwcampus', a place where parties come together in a precompetitive setting to create innovative solutions to issues such as ageing infrastructures. More than 120 companies, government agencies and research institutes are attached to the Bouwcampus.

The second is the Multi Water Works (MWW), a large programme of Rijkswaterstaat for the replacement and renovation of 52 locks in the Netherlands until 2050. For this programme also, meetings at the Bouwcampus took place in 2016 and 2017.

The third is the 2017 almost-delivered programme Room for the River, a multibillion euro programme under which the Rijkswaterstaat, water boards, provinces and municipalities have been taking measures to increase the capacity of the river Rhine and its branches in the Netherlands to cope with increasing discharges due to climate change. These measures will reduce the risk of flooding. Moreover, the measures are designed in such a way that they improve the quality of the immediate surroundings.

The combination of literature study, discussions with authors of recent documents, as well as insights from participation and discussions in the three programmes served as a fruitful basis for developing concepts and strategies for asset managers to cope with the challenges and opportunities of the upgrade and renewal programmes.

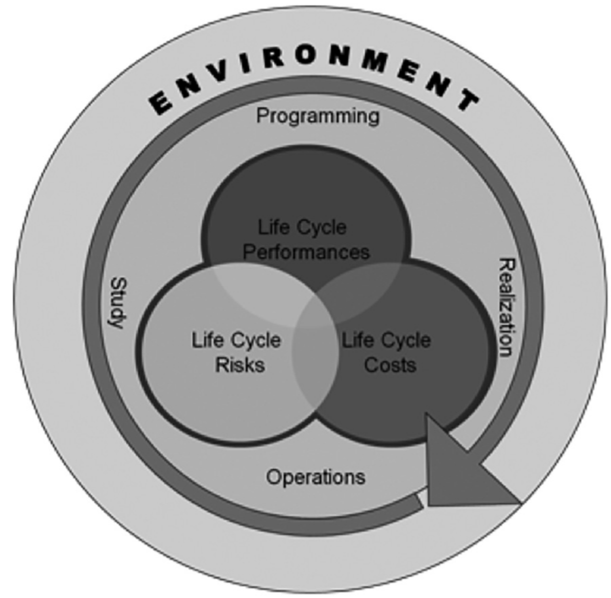

Fig. 2: Life Cycle Management (Fuchs et al, 2014).

3 The contribution of LCM of infrastructural assets to replacement and renovation programmes

There are many definitions for LCM, often depending on the context in which the word is used for. Fuchs et al. (2014) propose that LCM needs to find the most optimal balance between performances, costs and risks throughout the whole life cycle of an asset from initiation to demolition. Life cycle performance (LCP) is the degree to which the value of the infrastructure meets the expectations of all the stakeholders, who have different preferences. Stakeholders may have diverse manners to assess performance according to peculiar indicators that reflect the requirements from their own perspective (National Research Council, 1995). The term ‘life cycle costs’ (LCC) has the target of optimizing the value of assets within a limited budget and identifies all relevant costs over the life cycle and applies controlling strategies to ensure these costs are in a reasonable range (Hastings, 2015). Life cycle risk (LCR) deals with the identification, assessment, prioritization and mitigation of risks. By identifying and analyzing risks, the efficiency of the project management process will be improved and the resources can be used more effectively (Banaitiene, 2012).

Figure 2 shows how LCP, LCC and LCR are partly overlapping parameters and interact over the whole life cycle. Many decisions in the building processes or in asset management are a trade-off between these three aspects LCP, LCC and LCR. According to the authors, these LCM parameters should explicitly be managed over the life cycle.

Notice the outer ring in Figure 2, which represents the dynamic environment. This constantly developing and changing environment leads to changing performance requirements to the infrastructure, new risks and cost effects. The outer ring initiates the cycle of the arrow, resulting in upgrades to and replacements of existing infrastructures and new infrastructures.

LCM is a step forward in the asset management world. Many asset managers do not have life cycle strategies for their assets. Although ISO55000 is a clear step forward towards thinking in terms of performances, costs and risks, most asset managers limit their focus to the short-term management of these parameters. LCM helps asset managers in managing an asset throughout the whole life cycle on the basis of finding the best balance between performances, costs and risks.

3.1 LCM in decision-making

In the management of assets, there are typically three different key roles involved: the asset owner, the asset manager and the service provider (Green et al., 2016). The role of the asset manager is to manage the assets under his responsibility and have a stable relation with the service provider. Table 1 shows the different roles and main activities of these three groups (Van der Velde et al., 2012), typically introduced in Western societies. In the Netherlands, the Ministry of Infrastructure and Water Management is the asset owner. It must be able to make strategic choices between the networks and the client for the asset manager. The asset manager provides a link between asset owner and the service provider. The role of the service provider is outsourced to private companies.

In addition, there are external organizations that influence the scope of the asset management requirements, such as local stakeholders, non-governmental organizations (NGOs) and the European Commission. The minister acts on behalf of all these organizations in his role as asset owner of the national infrastructure networks. The minister is accountable for the actions of his executive arm, the asset manager. The relation between asset owner and asset manager is organized based on a Service Level Agreement. Based on this agreement, the asset manager assigns parts of the work in the contracts to the service providers.

Traditionally, contracts and Service Level Agreements deal primarily with time, price and quality, corresponding to the 'iron triangle' or 'golden triangle' in project management literature (Hertogh & Westerveld, 2010). LCM adds a new set of parameters to these agreements: *The effect on Life Cycle Performance, Life Cycle Costs and Life Cycle Risk*. This aims to avoid short-term policy decisions.

LCM deals with the optimization and management of LCP, LCC and LCR. All of these three elements have two sides: an upside and a downside (Table 2). For a balanced decision-making of all three aspects, the downside and the upside need to be judged. Especially, for costs and risks, the focus is often on the downside. Traditionally, asset managers focus on costs, but increasingly, financial benefits, as the outcome of cost–benefit analyses, are being incorporated directly in the decision-making. In risk management, an increasing number of publications are searching for a balance between threats and opportunities, for instance, Ehrbar and Kellenberger (2003), which discuss one of the first implementations of a structured approach in terms of threats and opportunities in a long-term, major construction project, the Gotthard Base Tunnel (Hertogh et al., 2008).

In the next section, LCP management, LCC management and LCR management are discussed for renovation and replacement programmes.

Tab. 1: Different asset management roles and main activities (Van der Velde et al., 2012).

Asset owner	Asset manager	Service provider
Responsibilities and tasks Overall network policy Targets for performance and condition on a network level Target for acceptable risk profile	Investment strategies, maintenance concepts Technological standards Risk management Network management	Project delivery Maintenance, execution and services Asset data management Project management

Tab. 2: Life cycle performance, life cycle costs and life cycle risk.

LCM	Upside	Downside
Life cycle performance	Positive added value (e.g. increase in availability, safety)	Negative externalities (e.g. noise, pollution)
Life cycle costs	Financial benefits (e.g. toll, rent and tax)	Costs (e.g. maintenance, replacements)
Life cycle risk	Opportunities (e.g. combining of functions)	Threats (e.g. extreme water levels)

3.2 LCM for existing structures

LCP management starts from the first initiative to create or modify infrastructure and ends when the function that this infrastructure fulfils is no longer needed. For infrastructure, this can be much longer than the lifecycle of the individual structures. Changing performance requirements often leads to replacement of structures. From the LCM view, the primary function then remains, but the performance can change. In that respect, upgrades and replacements are part of the LCM process. However, the LCM approach needs to be broadened to other perspectives, such as adding of new functionalities. These new perspectives need to be linked to the end-of-lifetime strategies.

3.2.1 LCP management

Any object in an infrastructure network has to meet specific performance requirements, based on the following:

- Performance requirements derived from the primary functions that the object fulfils in the network(s);
- Object-specific performance requirements, usually originating from the object in its environment (such as aesthetics, noise hindrance, etc.);
- General performance requirements, based on organizational, national and international regulations.

Design and construction processes aim to achieve the required performance in an efficient way. Maintenance processes are aimed at the following:

- maintaining the agreed performance level;
- monitoring the current performance versus the current and future requirements.

Monitoring of performance is an essential aspect of LCM. An insufficient current performance is an indicator for an upgrade or renewal needed. The Delft University of Technology and Rijkswaterstaat are investigating the possibility of generating a 'performance life indicator' for objects. This performance life indicator should be an indicator generated from multiple performance aspects, such as load-bearing capacity, traffic capacity, noise pollution, practical matter emissions, aesthetics, etc, for highways. This performance life indicator should help to define the weak performing objects in the network, from a multiple-aspect perspective. This indicator could support strategic investments in infrastructure.

3.2.2 LCC management

LCC management is aimed at cost efficiency in achieving and maintaining a required performance level. A very practical indicator for LCC management is the 'Economical End of Life Indicator' (EELI), developed by Rijkswaterstaat (Bakker et al., 2016; Xie, 2017). This indicator represents the ratio of the present value of all costs needed to keep the structure and replace it in a theoretically determined end of life, divided by the cost of an early replacement. If this ratio is >1, maintaining the existing structure is no longer cost-efficient compared to an early replacement. The EELI can be generated at each moment during the lifetime of an asset. The EELI can be an important parameter for strategic investment decisions in upgrade and renewal. It represents the cost-effectiveness of maintaining the existing structures in the network. The EELI of different objects can be represented on a geographic information system (GIS)-map, to get an overview of needs of renewals and upgrades. This graphical presentation supports the discussion on where to do strategic investments in network improvement (upgrade and renewal).

Can social cost–benefit analysis (CBA) be of help? Yes, these certainly do. But there are some limitations. A CBA is always incomplete, the effect estimations are always uncertain and effects that are difficult to estimate have a relatively weak position in the CBA (Mouter, 2014). Mouter mentions that key individuals frequently perceive that the fact that CBA is a tool with insolvable limitations is not problematic in itself. According to the key individuals, problems only arise when insolvable limitations are not managed properly.

3.2.3 LCR management

LCRs embrace both threats and opportunities. Risk is defined as the probability of an occurrence-times-effect. These occurrences are related to the desired performance, as well as costs and benefits, over the whole life cycle. LCR management consists of the following, according to the Risman method (Well-Stam, 2004):

- Risk inventory: knowing and quantifying the expected risks over the life cycle;
- Risk agreement: agreement over accepted risks between partners over life cycle;
- Risk monitoring: this process continues over the life cycle;
- Risk management: timely actions to keep risks at agreed levels;
- Opportunity management: timely recognition of chances to improve performance, reduce costs or reduce risks.

3.3 LCM for strategic upgrade and renewal

In this section, the contribution of LCM for strategic upgrade and renewal will be explored. This concerns the specific performance (LCP), cost (LCC) and risk (LCR). The focus can be a part of an object (e.g. installations for operation, maintenance and safety) or the object itself (e.g. a tunnel) as part of a network of interconnected objects. The conclusion is that LCM can provide important information to support decisions on the upgrade and renewal of an asset, as well as giving a reliable basis for the replacement procedure by making reliable prognoses for the end of life time of the assets.

An important awareness is that an 'end of life' for an ageing asset is a decision, not a technical fact, unless an object has completely collapsed and cannot be repaired. Practically, a replacement decision is made when the costs of repair are too high compared to a replacement or when the performance is insufficient. Occasionally, uncertainty or an external opportunity can also be the reason. Some examples are as follows:

- Costs. For instance, a steel bridge with fatigue problems. The consequences can be managed by monitoring, repair and strengthening. These costs can be calculated over the remaining life. These costs can be compared to early replacement (EELI). If the ratio is >1, replacement is more cost effective. There may, however, be reasons (budget restrictions, monumental value and traffic impact of replacement) that prevail above the EELI.
- Operational performance. For instance, a bridge is too low for ships to cross, it has a very low load-bearing capacity or it can be a bottleneck in the network due to insufficient capacity, etc.

- Environmental performance. For instance, the bridge may be a physical and aesthetic obstacle, because it is part of a road that divides a city into two parts; it may create too much noise and pollution and so on.
- Threats. There may be unaccepted risks at stake. For instance, vulnerability to earthquakes or floods, but also uncertainties towards technical safety due to, for instance, hydrogen embrittlement of pre-stressing steel. If risks cannot be managed, for instance, because it cannot be quantified or preventive measures cannot be taken, then the risk is either accepted or not accepted.
- Opportunities. For instance, development of a new industrial area may lead to adjustment of the infrastructure system. Objects may need to be replaced regardless of their current performance.

In order to support strategic investment decisions, each object in a system has quantified costs, performances and risk profiles. Strategic investments should not be aimed at just one object. It should aim at the improvement of the wider network. This is only possible if the information on cost, performance and risks of the individual components of the system is available.

The forecast for the replacement programme of Rijkswaterstaat for 2014–2050 (Klatter and Klanker, 2014) supports the preparation and decision-making of the programming of the execution programme. The goal is twofold:

1. To substantiate the long-term budget reserve for replacement and renovation for the client.
2. To present a total view of the replacement and renovation programme.

The programme is divided into three terms:

1. A short-term programme for specific objects: 2015–2020
2. A roughly estimated midterm programme for clusters of objects: 2021–2023 and 2024–2030
3. A long-term prognosis: 2031–2050

Each of the terms has a specific approach. The short-term prognoses must facilitate the decision-making for specific objects, based on an inventory on the LCM aspects. For this period, the prognoses are based on dedicated inspections and investigations. For the midterm 2021–2023, the prognoses are based on an ‘issue list’ of groups of objects for which replacement and renovation are needed and, for 2024–2030, the list is based on statistical analyses of the whole area. For the long term, the calculations are also based on statistical analyses of the whole area. An overview of the results is given in Figure 3.

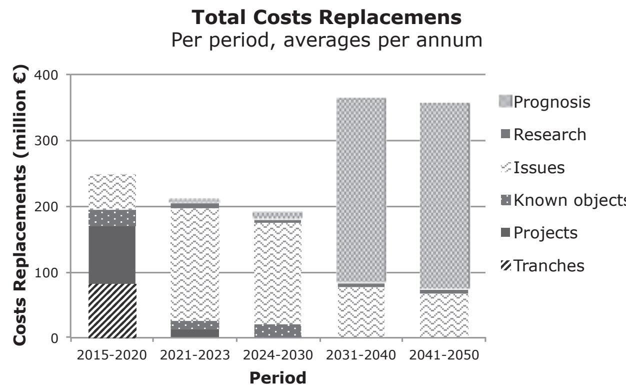

Fig. 3: Cost estimation for replacement and renovation program of Rijkswaterstaat, 2015-2050.

4 Four perspectives for a strategic investment programme for ageing assets

4.1 Broadening towards a network approach as an opportunity for redesign

Replacement and renovation programmes give room for the redesigning of (parts of) the networks. The pitfall is to replace subsequent objects and to retain the system’s design for that part of the network. Often a redesign of the system can lead to more optimal solutions and, in this way, improve the balance between LCP, LCC and LCR in the new situation. This means that asset managers should start at an early stage with the redesign of the network, because every new replacement of an object will limit the solution space and can hamper future optimizations in the network.

An example of this can be found in the river Meuse between the cities of Maastricht and Den Bosch in The Netherlands. In this corridor, the seven weirs and locks will come to the end of their technical lifespan between 2028 and 2036 (refer Section 2). Is a system with the same number of seven also the best solution for the future?

The question is this: is it necessary to replace these locks and weirs, or are there other, superior solutions? The Bouwcampus organized four meetings between June and December 2015, in which asset managers, practitioners, constructors, suppliers and academics discussed about the challenge. Around 100 attendees come from public and private organizations, as well as knowledge institutes. During this period, six teams developed six perspectives (Barneveld and Van der Vlist, 2016):

1. Heart River. Story telling is the basis for this perspective. The team is curious to hear stories about people, water,

technology and history. These stories will tell what really is (and was) going on in and along the river. The intention is to discover values and insights that form a basis for interventions. Interventions that will lead to new stories. Stories can also be of great help in the interaction with stakeholders about these interventions.
2. Radical Design. How to design a system's level from one or more leading principles? The team chose in this stage 'the Meuse as a sweet-water basin' as leading principle. This could imply the need for an extra canal to compensate for the loss of freight transport (now a dominant function). Indeed, very radical.
3. Bricks and Balloons. The current system and its structures are known. These are the bricks. Society has wishes and ambitions: these are the balloons. The team is specifically interested in the tension and interaction between the bricks and balloons.
4. The Adaptive Meuse. Embrace uncertainty! In previous times, structures have been built for a century, but the team is convinced that this is no longer desirable. The pearls the team mentioned are new technologies such as self-navigating containers, loading stations and easy-to-pass locks.
5. The Energetic Meuse. The statement is that society is on the eve of a new industrial revolution. People can generate green energy by themselves and share this in smart grids. This energy transition is an important basis for a new, global sustainable economy. When using an energy perspective for the River Meuse, what new ideas will come up? The team has ideas such as energy storage in the river, cooling and aqua farming, as well as ideas for social innovation by participation of stakeholders in the Meuse area.
6. Experience. The locks and weirs are intriguing objects and characteristic elements in the river environment, such as some beautiful locks and weirs. Unfortunately, these are not accessible, a sort of 'forbidden fruit'. The dynamics of the water and the constructive attractiveness of the locks and weirs – 'engineer's art' – cannot be experienced in their total beauty. The locks have the potential to serve as a learning place for students, a meeting place and a place for inspiration. Instead of being a barrier, the locks can be a connection in time and space.

4.2 Developing innovations for increasing requirements and budget restrictions

Ageing of infrastructure and the need for physical interventions can boost innovations because of the scale of the programme. Examples are more standardized solutions, the usage of new materials (such as composites) and more sophisticated construction methods, while substantial functionality must remain during realization (such as in the renovation of tunnels that are an essential part of the network).

At Rijkswaterstaat, the MWW programme consists of 52 locks. In the period until 2050, 37 locks are expected to come to the end of their technical lifespan, and the other 15 are expected to reach the end of their functional life, due to lack of capacity until 2050 (De Roos, 2016). First calculations indicate an investment of 2–4 billion euros.

The goal of the MWW programme is threefold, which must be seen against the broader LCM perspective, of balancing LCP, LCC and LCR:

- To optimize on LCC
- To optimize on availability and reliability
- To increase predictability of costs and time

Rijkswaterstaat has started to develop 'The Dutch Lock'. Together with the Eindhoven University of Technology, on a very fundamental basis, the functionalities, requirements and separate elements of the design are studied. The goal is not to design a lock that can be 'copy-pasted' but a range of solutions that can fit in specific contexts. To give an example, there are several solutions for the gates, not one specific solution is always the best. Accordingly, the Dutch Lock will be a 'family of locks'. MWW is carried out in close collaboration with private partners.

The strategy is that every new lock must be better. This means that Rijkswaterstaat wants to learn from the design, realization, maintenance and operation of previous locks. That is why apart from the technical products to be delivered, a learning process has also been started. This track investigates how learning processes happened in previous programmes and what can be learned for the MWW programme. This will also facilitate the adaptive perspective (refer Section 4.3).

4.3 Realizing adaptive networks to cope with future challenges

Society is dynamic, with changing demands for assets, due to external factors such as climate change, self-driving cars and heavier trucks, but also due to changing societal demands, for instance, related to sustainability issues. To cope with these changes, this perspective deals with flexible, adaptive solutions. Examples can be found in physical solutions and can be served by strategies that facilitate processes. Some examples of adaptive solutions are as follows:

- Water retention areas (such as meadows) in several Dutch rivers with only incidental use in the case of extreme discharges. This incidental use may require financial compensation of the owners and citizens of the areas for damage occurring during usage of the area as a retention basin.
- Quay walls in the harbour of Rotterdam, which are designed for future deepening of the harbour.
- In a section of a new highway in Antwerp, as part of the new Oosterweel Junction, provisions are planned for the construction of a roof that has not been decided yet. The price of the provisions can be seen as a real option.

The Dutch 'Room for the River' programme focuses on finding adaptive solutions. This programme aims to give rivers more room to be able to manage higher water levels. At more than 30 locations, appropriate measures give the river space to flood safely, as well as improving the quality of the immediate surroundings. The Room for the River programme was started in 2006 with an investment of €2.2 billion and is almost completed.

Enabling elements in the Room for the River programme to facilitate adaptive management are as follows (Zevenbergen et al., 2015):

- The adoption of a systems approach. The river system has been considered broadly to include the socioeconomic and physical characteristics at all relevant spatial scales and their relation to the discharge regime. A 'Planning Kit' has been developed to make a selection of all the available measures' visualizing options.
- Participatory decision-making. Multiple stakeholders and multiple disciplines (e.g. water safety, planning, agriculture and nature) have been included. The use of mixed centralized (national) programme steering, as well as decentralized (regional) decision-making and project execution, ensured a uniform product and process quality but, at the same time, a good connection to the local needs.
- Learning and experimenting. Interesting is the installation of specific task forces operating at the programme level to support the transfer and replication of the lessons learned from the so-called front-runner projects (which were conceived as experiments) to the other projects. Moreover, in specific projects, learning loops have been factored in.

These kinds of strategies are not suited only for river programmes. These can also be used in other networks, such as highways.

4.4 Combining functionalities to increase added value

After the Second World War, the infrastructure networks have been expanded often with a focus on one dominant function. Think of a dam for water safety, a road for mobility and a canal for shipping. There are two main problems with this mono-functional approach. The first is ecology. To increase water safety, one can cut off an estuary by a dam, but this can have tragic consequences for fishermen and nature. The second problem is that a focus on a specific functionality is often not very smart in dealing with scarce resources. On the other hand, combinations can save costs, increase yields and performance as well as satisfy stakeholders (Spiering et al., 2010). This is why asset managers and designers have begun thinking about how to increase performance by combining various functions. An interesting example is a multifunctional flood defence, such as a parking garage in a dune, as was constructed in Katwijk, the Netherlands. A dike with a road on top and houses with water-retaining walls are other examples.

The combination with functions other than flood protection in a flood defence becomes an interesting alternative if necessary improvement of existing flood defences conflict with other functions, such as housing. Multifunctional flood defences can also become a relevant option for ongoing urbanization in built-on areas. Integration of functions could also be interesting for dividing costs between several parties. Governance issues related to multifunctional flood defences, however, are very delicate because of possible conflicts in responsibilities.

A spectacular example is the Stormwater Management And Road Tunnel (SMART Tunnel) in Kuala Lumpur, Malaysia. The tunnel has two objectives: to divert large volumes of floodwater, and to relieve traffic congestion. Another example is the new double deck tunnel in the highway A2 in Maastricht, The Netherlands (Figure 4), which replaces the old highway on the ground level. This project is not only an infrastructure project, but the new space that was created by the tunnel also made room for area development, real estate development and an environmental upgrade.

How to find new functionalities or, in a boarder sense, opportunities? For this, the method of opportunity framing has been developed. Opportunity framing is an approach than can help to find new functionalities and solutions. Asset managers can use opportunity framing as a structured approach to understanding and defining opportunities that add financial and societal value to ongoing infrastructure projects. It is the starting point

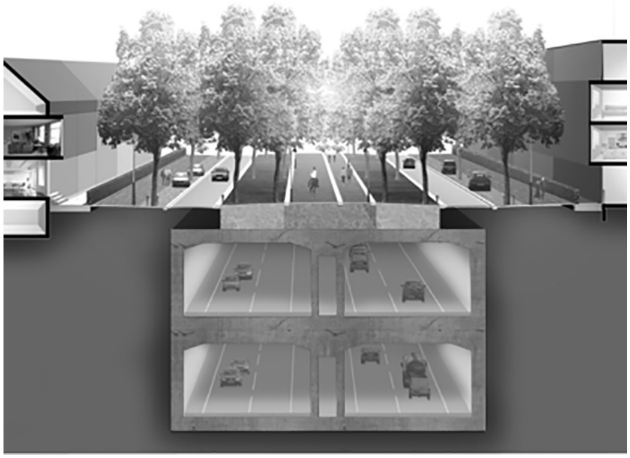

Fig. 4: A2 Maastricht.

for a robust, decision-driven process for the realization of the opportunity (Hertogh et al., 2016). There are two main challenges in opportunity framing.

The first challenge is to overcome the tendency of 'premature convergence', in which a solution is chosen early in the process, thereby excluding the many other options present at that point in time. The A2 Maastricht has a long history, but the defining moment was when the project was reframed from an infrastructure project, to the current broader city development approach. The second challenge is the relatively small window of opportunity. When a new investment is initiated, it is far easier to add scope than after it is accomplished. Asset managers should be aware of this facet and act proactively. The renovation and replacement programme can be an important window of opportunity.

5 Discussion: maximizing value for society by playing with complexity

The main question is this: how to cope with the four previous perspectives presented? An outcome of the discussions mentioned in Section 2 is that asset managers have as dominant attitude 'to keep it simple' and focus on their own assets like they always did, where improvements are usually an increase in efficiency. But is this strategy also effective in the long term? A multiple-perspective approach, looking at new solutions, will certainly add value and increase support. Let us give an example for adding extra functionalities (Perspective 4) in a highway section that is in operation, such as energy generation and underground water storage. Incorporating extra functionalities can give the asset more value, but by doing this, extra interdependencies will be introduced with impact on LCP, LCC and LCR. This can increase complexity. Asset managers are often afraid to control by increasing complexity. When functionalities are added, the question emerges: is the asset manager willing to increase complexity and often give up some of his/her autonomy? 'Who is willing to run the marathon?' is a question that is often raised during the preparation of the plans, as it would require a significant effort to develop the plans and prepare contract specifications, engage with other shareholders and stakeholders, arrange financing, make arrangements for maintenance and operation and so on. Upon adding functionalities, asset managers increasingly collaborate with others, such as fellow asset managers, public bodies, NGOs, citizens, etc. This requires specific competences for interaction. The same can be said for Perspective 1: redesign. This also increases complexity.

The question then is how much can complexity be raised in the ambition to maximize social value, while retaining an acceptable degree of controllability? Or better, how much are we 'able' and 'willing' to raise complexity? For this, a timely start, an open mind and a professional organization are essential. This is what is called 'playing with complexity' in Hertogh and Westerveld (2010).

6 Conclusions and recommendations

This paper focuses on replacement and renovation programmes of civil infrastructures, because many assets of civil infrastructures are coming to the end of their technical, economical or functional lifespan. This is one of the major challenges for asset managers for the next decades.

LCM helps asset managers in managing an asset or system of assets throughout the whole life cycle of the replacement and renovation programmes on the basis of finding the best balance between LCP, LCC and LCR. Furthermore, two new indicators are introduced to support strategic investments in infrastructure for these programmes. The first is the 'performance life indicator', which should help to define the weak-performing objects in the network, from a multiple-aspect perspective. The second indicator is the EELI, which represents the ratio of the present value of all costs needed to keep the structure and replace it at a theoretically determined end of life, divided by the cost of an early replacement. If this ratio is >1, maintaining the existing structure is no longer cost efficient compared to an early replacement.

In this paper, four main challenging perspectives are distinguished for asset managers. These are as follows: (1) broadening towards a network approach as an opportunity for redesign; (2) developing innovations for increasing requirements and budget restrictions; (3) achieving adaptive networks to cope with future challenges and (4) combining functionalities to increase added value. In the end, the goal is to maximize value for society by playing with complexity. Essential is the interaction with other actors, such as other asset managers, stakeholders and service providers.

Many stakeholders view the increasing needs for renovations and replacements of existing structures as a burden, especially when there are insufficient, or even no, budgets available. However, there is also a positive side to this. The replacement and renovation programmes can be used to make infrastructure networks more fit for future needs. On the other hand, a very slow adaptation of a network to the needs leads to an inefficient infrastructure and will create a barrier to economic growth and to the welfare of people. Investment strategies dealing with the technical and functional issues of the existing infrastructures are needed; in addition, the timely adaptation of the infrastructure to changing demands will determine the efficiency of the infrastructure in the future. These strategies will benefit society as a whole, because infrastructure will fit more to the current and future needs for the users, as well as giving opportunities for new functionalities, stricter requirements and new, innovative business cases.

It is recommended that asset managers start timely with programmes of renovation and replacement, as well as develop their organizational competences to meet the challenges in a way that infrastructure networks are fit for future needs.

A limitation of the study is that it focuses on the Dutch situation, but it can be brought into a wider international context as a follow-up. Furthermore, the research concerns road, waterway and water safety programmes, but did not study other assets, such as rail, sewage and drinking water. It has an explorative character, and it would be interesting to test the implementation of the concepts performance life indicator and EELI, as well as the four strategies, in future research.

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