Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
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End-of-life rule checking for transport infrastructure: The case of navigation locks

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ABSTRACT: Determining the end-of-life of infrastructures is an important decision in the Netherlands, where the large stock of assets currently reaches their design life. The Dutch Road Authority has set up a research program to address this on a national level. Currently, there are various documents describing the rules of aging. Yet information specifications are not defined. This forces the experts to focus on technical aging only and consider structures that are aged/too expensive to maintain in later stages. Since the scoping and budget assignment is based on the earlier prognosis, the process becomes suboptimal. There is a need for a holistic approach to identify ageing rules for the assessment of different object types. This paper presents an information model for navigation locks as a first step of such approach. It declares information needed to check rules automatically via case studies and proposes utilization of a technology as a future step.

1 INTRODUCTION

Public asset managers, particularly in the infrastructure domain, are challenged with renewing the large number of infrastructure due to physical ageing. Only in the Netherlands, there are 85,000 bridges and viaducts, 83,000 culverts, 2,400 km of quays and 7,800 pumping stations (Bleijenberg, 2021). A substantial amount of structures will reach the end of their service life in the coming decades given their design life time of 80 to 100 years (Klanker et al, 2016). For resources to be allocated on time, a long term prognosis of future renovation and replacement needs is required. In this context, the Dutch Road Authority (RWS) has set up a research program called Replacement and Renovation (V&R) to address the aging of infrastructures on a national and portfolio level. The first step of this program refers to an intake decision, where the 'candidates' are selected based on their end of service life and the budget prognosis is determined. This selection is important, since the objects in V&R are financed nationally and not by regular maintenance budgets of the regions at RWS. There are various documents established by different public entities for the selection process. They describe theoretic conditions categorized under technical, functional, and economic end-of-life (e.g. I&M (2013), VONK (2012)). There are also studies performed by RWS where the aging of structures is approached from a life cycle perspective and a metric (Economic End of Life Indicator -ELI) is established by Bakker et al (2016).

Currently, there are fundamental challenges in analyzing objects on portfolio level. Between various organizations, differences are observed in how they identify the theoretic end of life rules that are used as a eligibility to the V&R Program. Although these rules are explicitly defined and categorized as the technical, functional, and economic end-of-life in official documents, the rules are high-level, human-interpreted, do overlap and reside in various forms of documentation. Information specifications per rule are not always well defined and interrelations of shared issues are not set yet. This forces the experts to focus solely on technical ageing that they are the most familiar and exclude the other rules while assessing the end-of-life of an object. Another challenge is the large amount of available data that are collected by RWS and

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also by the regional asset managers. The data from these two sources does not always match, has complex structures and takes cumbersome effort for the V&R expert to obtain a relevant dataset. This is challenging to do per object type and even more difficult to do on a large number of objects. In relation with the two challenges above, a categorization of objects is often done based on common issues and extrapolations: Objects that are prone to similar technical problems are grouped in relation with their theoretic life time and included in the intake. This was done based on characteristics rather than actual condition data of the objects.

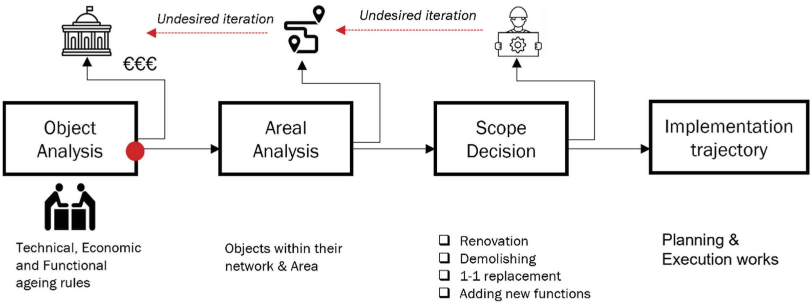

Figure 1. The V&R process and the intake decision moment as Step 1 (Bektas, 2021).

Considering this situation, the ultimate aim of this research is to develop an integral end-of-life model as an automated rule checking system that supports the V&R experts with more objective and accurate analysis leading to improved scope definition. This research proposes to (1) objectify aging rules under functional, economic and technical ageing, (2) specify information and data use per object type and (3) enable automatic checking of those rules which can optimize the intake decision making. This would lead to a more accurate scope and budget definitions and ease communications between involved parties.

Automated rule checking has been identified as a potential to provide significant value to the AEC (Architecture, Engineering and Construction) industry from both regulatory and industry perspectives. It is used to translate rules based on human language to computer interpretable rules, so that the object's compliance against the rules can be determined (e.g. building regulations compliance, safety regulation compliances). In this field, the key scholars are Eastman et al (2009), Solihin (2015), Solihin & Eastman (2015), Pauwels et al (2011); Pauwels et al (2017); Pauwels & Zhang (2015), Nawari (2012), Song et al (2018); Song et al (2020). The four stages of Eastman et al (2009) are: 1) Rule interpretation, 2) Model preparation, 3) Rule execution, 4) Rule reporting and visualization. This approach has been widely used in the building design domain particularly for objectifying human-language rules as building regulations, quality assurances and mostly on BIM (Building Information Model) data. Yet there is little evidences on the use of this approach for infrastructure domain, particularly on the aging of structures. Through such an approach, available technical information that is scattered across design documentation, inspections and planning are acquired, interpreted, and translated to the end-user. In that way, scattered data aims to be translated to decision information. This can provide a great insight into the identification of issues for the portfolio level of objects in an faster and explainable way.

In this paper, the focus is given on navigation locks and a multi-case study method is used. Four cases were selected as examples of navigation locks in the Netherlands, namely the complexes of Delden, Hengelo, Eefde and Volkerak. In Section 2, critical design characteristics that can have an influence on defining the end-of-life of these locks are listed. Later, the changed conditions over time (i.e. common issues) are identified and discussed under different aging categories. The ultimate result from the case studies become the main component of an automated rule checking system: Information Model for Locks that is presented in Section 3. This corresponds to the Stage 1 of Eastman et al (2009). Based on this, a proposed approach is selected for model preparation (Stage 2 of Eastman et al (2009)). This information model can be seen as a kernel of the programming activities that will be conducted in the future to build the final rule checking engine that is explained in Section 4. Conclusions are given in Section 5.

2 CASE STUDY: END-OF-LIFE RULES FOR NAVIGATION LOCKS

2.1 *General information on the navigation locks*

The main purpose of a navigation lock is to overcome the water level differences between two water stretches for shipping, while maintaining the difference in water level. They are also used for water management purposes, e.g. to discharge a predefined amount of water within a certain period of time. A lock consists of a lock chamber, closed by different types of closing elements (e.g. gates) which are located in the lock heads. Below and adjacent to the structure, cut-off walls are usually used to prevent seepage and/or piping. Raising or lowering the water level in the chamber can be achieved by letting in/out the water through the gates or a by-pass pipe. Considering the operational aspects of a lock for shipping purposes, three main design requirements are defined. Firstly, lock dimensions must be sufficient enough to allow the normative ships to pass in the considered waterway. Secondly, the lock capacity (i.e. number of ships passing within a certain time interval) must be sufficient considering the present and future requirements (e.g. traffic intensity). Lastly, the time losses during a passage must be kept at a minimum (Molenaar & Voorendt, 2020).

In order to define the end-of-life aging rules, four navigation locks are analyzed, namely the complexes of Delden, Hengelo, Eefde and Volkerak. They are part of the main water network. A rich set of data is collected from inspection reports, FMECA analysis, 6-yearly inspection data, planning and measurement data as well as integral reports. The integral reports of the four locks, such as Arcadis (2012a; 2012b; 2014a; 2014b), become governing documents to identify potential V&R issues under aging rules. In the following sections, the critical design characteristics that can have an influence on defining the end-of-life are identified and also changed conditions over time are listed in Table 1. The differences and categorization became a conversation starter with the asset manager who decides whether large interventions are required and thus the objects become eligible to enter to the V&R Program of the RWS.

2.1.1 *Case Delden*

The Delden complex consists of a lock (1933), a pumping station, a fixed bridge over the lower head, several buildings, an emergency power plant and a channel leading to the pumping station. Due to the increase in shipping, ship sizes has reacted its maximum value for this lock (CEMT class IV and limited Va) which minimizes the space between ships and chamber walls and the gate. This causes a higher risk of collision damage. The scaling up of the shipping class also means that there is an increase in engine power and the development of concentrated propeller jets creates a higher load on the bottom protection. This leads to damage on the bottom protection in the chamber and around the lock. Due to climate change, large flows have to be discharged more often. The composition of shiploads has changed significantly since construction, with an increase in the number of ships with dangerous cargo. This has possible consequences for safety on the lock itself, but also on the external environment safety around the complex.

2.1.2 *Case Hengelo*

The complex Hengelo also consists of a lock (1936), a pumping station, a fixed bridge over the lower head, a railway bridge and a channel leading to the pumping station. Similar to Delden complex, there is a higher risk of collision damage due to increase in shipping class. The consequences of a collision is expected to be greater due to the increased ship size. Large flows have to be discharged more often. Damage on the bottom protection in the chamber and around the lock is expected due to the increase in engine power which creates concentrated propeller jets.

2.1.3 *Case Eefde*

The complex Eefde consists of a lock (1933), a front lock (1952), pumping stations, drainage systems and various waiting locations and berths. Increase in ship size and engine power is also a common issue for this lock. Due to heavier and larger ships, there is a restriction with regard to vertical clearance of the lifting doors. Changed safety factors for the loads and materials are more unfavorable than was considered during the design. As a result of the increased capacity of the drainage systems and pumping stations, greater flow velocities occur which affects the safety of shipping traffic. Due to heavier loads and modified standards, the assessment of fatigue is less favorable than at the time of design.

2.1.4 *Case Volkerak*

The Volkerak complex is the busiest and largest inland navigation lock complex in Europe. It consists of three adjacent locks (Locks 1 to 3) for commercial vessels and a yacht lock for recreational vessels. There are two bascule bridges across Lock 1, which allow an unlimited vertical clearance. Increase in ship size and engine power is also a common issue for this lock. Studies are currently being conducted to speed up the shedding process by increasing the lifting speed of the leveling gates. This can cause greater loads on the ships in the chamber and on the bottom protections. Arcadis (2014b) concludes that the loads on the ships are already too high and that the lifting speed must be reduced rather than increased. In the recent years, the number of ships has increased sharply. Despite the expansion of the third chamber ten years after the construction, it is expected that a fourth chamber is needed to keep waiting times within the accepted value.

Table 1. Critical characteristics of the complexes of Delden, Hengelo, Eefde and Volkerak.

Characteristics	Delden	Hengelo	Eefde	Volkerak (Lock 1)
Dimensions	Passage height: 6.20 m Chamber length: 128 m Chamber width: 12 m	Passage height: 5.30 m Chamber length: 119.7 m Chamber width: 12 m	Passage height: 6m Chamber length: 140 m Chamber width: 12 m	Passage height: unlimited Chamber length: 308.9 m Chamber width: 24.1 m
CEMT class	Suitable for class IV & limited suitable for class Va	Suitable for class IV & limited suitable for class Va	Suitable for class Va with draft limitation of 2.80 m	Suitable for class VIb
Built year	1933	1936	1933	1957-1977
National monument	Yes	Yes	Yes	No
Diff. in water level	6 m	9 m	6 m	
Function of the canal	Main waterway (Vw2)	Main waterway (Vw2)	Main waterway (Vw2)	Main waterway (Vw2)
Material of the chamber walls	Steel sheet piles	Concrete	Concrete	
Max discharge capacity	34.5 m^3/s	-	100 m^3/s	
Type of the gates/doors	Lifting gates	Upper head: lifting gates Lower head: two roller gates with levelling slides	Lifting gates	Electro-mechanically driven steel pointed gates
Vertical clearance	Limited	Limited	Limited	Unlimited
A flood defense?	No	No		
No. of ship per year	8400	1400	5650	
Average lock time	30 mins	30 mins	> 30 mins	

2.2 *Identifying the aging rules*

In order to define the object-specific aging rules, a database is constructed which includes the important key parameters of the locks that are investigated above. As a next step, a list of issues related to locks are analyzed to check whether there is a major problem regarding their structural safety or function. If the issues that cannot be solved by a regular maintenance and require a large intervention, they are then identified as a potential V&R issue. Later, the object-specific aging rules for locks are developed based on the theoretical aging rules that are found in the literature. These identified issues are then linked to the specific aging types by considering the rules that are given in Table 3. Lastly, the findings are enriched by inspection reports, external data and interviews with V&R experts. Some examples are given in Table 2.

One of the identified technical aging issue for a lock chamber is the corrosion of the sheet piles. If the chambers are made of steel sheet piles, major corrosion can lead to a thickness reduction of the walls. In this case, the stability and strength of the walls may not be ensured. Therefore, this issue is indicated as a technical end-of-life for a lock chamber wall. Another example of a technical aging issue is the critical components of the lock, such as gates, being obsolete. In this case, the lock cannot function properly until the related parts are changed. Since in this case the replacement is not possible, the gates reaches their technical end-of-life. Another common issue that is observed in all case studies is the CEMT classes being no longer suitable due to the increased ship size and relatively low gate heights (i.e. limited vertical clearance). This is an accurate example of the lock being reached to its functional end-of-life. When these issues are checked with the theoretical aging rules, they define more specific starting point of departures for V&R experts to analyze aging conditions for navigation locks. Table 3 presents this synthesis.

3 INFORMATION MODEL FOR NAVIGATION LOCKS

The information model synthesizes and declares all the parameters that are necessary to compute and check ageing rules. The scope of this information model is the rules defined in Table 1. Table 2 illustrates the main concepts modelled for navigation locks and end of life rules. The model has four realms. The first realm is *Network and Corridor Information*. Here the data concerning functional requirements number of ships passing, useful shipping dimensions, waiting time, width/length/depth of canal, maximum allowed ship classes as well as asset management district can be exemplified. The second realm is *Physical Decomposition Information*. The data here deals with specific objects forming the lock complexes, peak water discharge capacity, water level differences, lifting speed, chamber details, gate types and dimensions, network details and material of components. The decomposition is arranged based on the NEN 2667-4 standard. The third realm is *Condition of Navigation Locks*. Any red flags as aging rules use this information linked to the physical decomposition. It contains degradation mechanisms, damage assignment. The main source of the data is inspection results here. The fourth realm is *Risks and Measures for Navigation Locks.* The risk associated to the condition findings and planned measures are detailed here. Thus the information model contains data concerning functional requirements, decomposition, technical condition and cost of maintenance. It then becomes possible to use relevant data for selected functional, technical and economic ageing rules.

4 FOLLOW-UP TOOLING

The ultimate result of the case studies become the main component of an automated rule checking system: Information Model for Locks. This corresponds to the Stage 1 of Eastman (2009). Based on that a proposed approach is selected for model preparation (Stage 2 of Eastman (2009)). The information model is a kernel of the programming activities conducted in future to build the rule checking engine (to be presented in future as Stage 3 and 4). There are different approaches to build a rule checking model such as procedural or declarative programming. The follow-up of this project will follow declarative programming based on the benefits listed by Pauwels et al. (2011). The approach will particularly focus on a semantic model that declares domain concepts and properties to be able to control the data for rule checking. Semantic knowledge models aim to capture domain knowledge and can make it available for non-domain decision makers. The information model will be (automatically) translated to a semantic model by the help of open

Table 2. Critical V&R issues related to the locks that are assessed and linked to the specific aging type.

Aging Reason	Issue	Cause of the issue	Limit statement	V&R Measure	Mng. object (NEN 2767-4 lev.1)	Component (NEN 2767-4 lev.2)	Element (NEN 2767-4 lev.3)	Function	V&R Rules
Technical	Reduction of thickness	Corrosion	x% of the wall thickness	Replacement of Sheet pile walls of the chamber.	Lock	Chamber	Wall	Shipping and water level management	[T1]
Functional	Increased load on the bottom protection	Scaling up the shipping class	x% increase in the average engine power	Replacement or Adding Bottom Construction.	Lock	Chamber	Bottom	Shipping	[F1]
Technical	Pits at the bottom construction	Erosion, Sedimentation, even Subsidence	x% material loss due to pits.x° inclination angle of the pits	Replacement or Adding Bottom Construction.	Lock	Chamber	Bottom	Shipping	[T1]
Functional	High risk of collision with a greater damage	Increase in ship size	Max dimensions for the relevant shipping class	Widening, deepening the chamber.	Lock	Chamber	Chamber dimensions	Shipping	[F1]
Functional	Larger flows have to be discharged more often	Climate change	Discharge capacity of the pump(s) + gate	Renovate whole pumping station/ Upgrade pumps.	Pumping station	Pump	Capacity	Water level management	[F1]
Functional	Collision with a greater risk	Increase in number of ships with dangerous cargo	Length of ships in relation to length of chamber /waiting area	Widening, deepening or renewing the chamber.	Lock	Chamber, Waiting Area	Chamber dimensions, Waiting Area dimensions	Shipping	[F1]
Technical	Cracks (with or without leakage)	Fatigue	Size of the cracks (mm)	If obsolete, replacement of gate (whole system).	Lock	Lock Head	Doors	Shipping & water level management	[T2]
Technical/ Functional	High truss forces from the translation waves	Relatively high lifting speed of the top door during locking process	x% increase in the forces	-	Lock	Lock Head/ Gate	Doors	Shipping & water level management	-
Technical	Obsoleteness of a critical component	(varies)	Special door types not produced anymore	Custom-made or replacement of the whole gate system.	Lock	Gate	Doors	Shipping	[T2]

Table 3. The overview of the theoretical and object-specific aging rules.

Theoretical aging rules	Object-specific aging rules (via the cases)
Technical end-of-life	
[T1]When a structure has serious structural defects	When the lock chamber is made by steel sheet piles, and there is a corrosion-led thickness reduction, and structural risk is registered
[T2]When a (critical) component is obsolete.	When the lock doors of their chamber are not produced anymore (thus obsolete) and not in-stock.
Functional end-of-life	
[F1]When an asset no longer fulfils its designed function due to changing environment, requirements, demand.	When the total discharge capacity of the pump(s) + gate is no anymore sufficient to handle peaks (m3/s), as larger flows need to be discharged
[F2] When there are new functions needed from the asset itself or the location where the asset is.	When a lock (waiting area + chamber + lock-head) is limited to allow bigger ship sizes (CEMT classes Va vs V). And/or When the movable bridge is lifted bridge that has insufficient clear height.
Economic end-of-life	
[E1]When ELI indicator of Bakker et al (2016) comes closer to 1.	When EELI is > e.g. 0.8
[E2] When an asset is too expensive to maintain.	

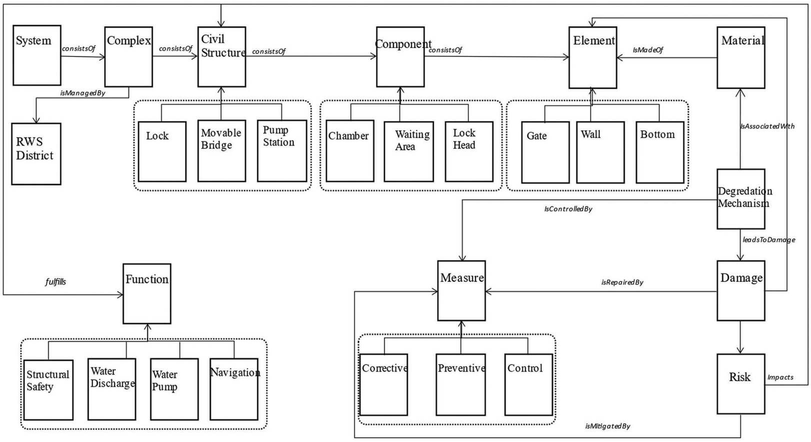

Figure 2. The top-model of the information model (simplified version excluding data properties and cardinality constrains).

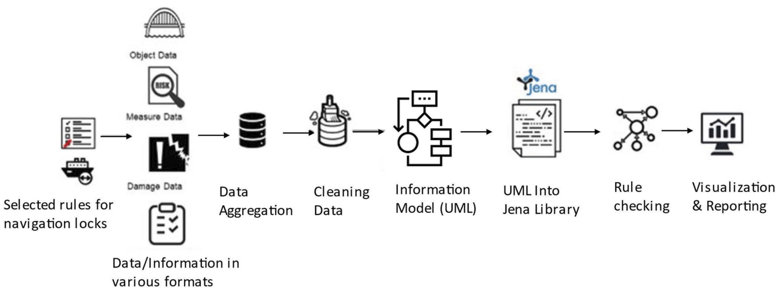

Figure 3. The proposed pipeline for the tooling process.

frameworks (i.e. Kehlio for Java). When the real life objects are defined according to these models, knowledge graphs are generated and inferencing and rule checking is done via the graphs. The open source tooling based on Apache Jena is foreseen as a follow-up since it is a free and open source Java framework composed of different APIs interacting together to process RDF data and build Semantic Web and Linked Data applications. Figure 3 illustrates the main development steps for the tooling.

5 CONCLUSIONS

The end-of-life model with a rule driven approach aims to assist V&R experts and regional asset managers with clear, explainable, and justifiable assessments for the V&R intake. The information model is a kernel data model that clarifies links between data and concepts from network to component level. It is an outcome of in-depth case analysis in order to understand typical representative problems for each object type. Available yet scattered data and information (across RWS systems and accessible openly) has been utilized. The information model binds relevant data from an object perspective, i.e. decomposition, condition, planning, functional data with a holistic view. The model can also be used as a data acquisition template for a large number of navigation locks as a minimum-set of information and can provide a common agreement between third parties and RWS. In the future, the proposed model will systematically identify how characteristics of certain components contribute to the network performance of objects and how network characteristics influence the object performance. By this, a large number of objects (thousands) can be scanned quickly and efficiently in future for a more comprehensive prognosis.

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