Intergenerational transfer of engineering expertise
knowledge continuity management in storm surge barrier engineering

Kamps, Merlijn; van den Boomen, Martine; van den Bogaard, Johannes; Hertogh, Marcel

DOI
10.1108/BEPAM-10-2023-0179

Publication date
2024

Document Version
Final published version

Published in
Built Environment Project and Asset Management

Intergenerational transfer of engineering expertise: knowledge continuity management in storm surge barrier engineering

Built Environment Project and Asset Management

Merlijn Kamps
Department of Materials, Mechanics, Management and Design, Section Integral Design and Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands and Department of Civil Engineering, Institute of Built Environment, Rotterdam University of Applied Sciences, Rotterdam, Netherlands

Martine van den Boomen
CoE HRTech, Rotterdam University of Applied Sciences, Rotterdam, Netherlands and Department of Hydraulic Engineering, Section of Hydraulic Structures and Flood Risk, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands

Johannes van den Bogaard
Department of Water Barriers, Netherlands Ministry of Infrastructure and the Environment, Utrecht, Netherlands, and

Marcel Hertogh
Department of Materials, Mechanics, Management and Design, Section Integral Design and Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands and Department of Public Administration and Sociology, Erasmus School of Social and Behavioural Sciences, Erasmus University Rotterdam, Rotterdam, Netherlands

Received 13 November 2023
Revised 29 January 2024
8 April 2024
Accepted 23 May 2024

The authors are grateful for the enthusiastic and high-level contributions of the engineering professionals at the Dutch storm surge barriers. The lively interactions, sincere interest and constructive feedback were very much appreciated.

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Built Environment Project and Asset Management
Emerald Publishing Limited
2044-124X
DOI 10.1108/BEPAM-10-2023-0179

Abstract

Purpose – Engineering knowledge continuity is crucial for the life cycle management of long-lived and complex assets, such as nuclear plants, locks and storm surge barriers. At the storm surge barriers in the Netherlands, engineering knowledge continuity is not yet fully assured, despite long-standing efforts. This study aims to explore the relationship between system characteristics, the organizational demarcation of maintenance and operation and the challenges in achieving engineering knowledge continuity and provides suggestions for improvement of theory and policy.

Design/methodology/approach – Ten semi-structured interviews were conducted with professionals from various backgrounds in construction, engineering and asset management of the Dutch storm surge barriers, augmented with visits to barriers and barrier teams. A thematic analysis was used to identify and describe the challenges to engineering continuity, their origins and potential solutions. We reviewed knowledge management policy documents and asset management consultancy reports to validate the findings. Additionally, we engaged in frequent interactions with professionals at the barriers. We achieved saturation and validation once no new issues were raised during these discussions.

Findings – The thematic analysis developed multiple themes describing the challenges to engineering continuity, their origins and potential solutions. The key findings are that expert engineers are critically important to deal with redesigns induced by obsolescence. Moreover, due to barrier uniqueness, long redesign cycles and reliability requirements, conventional knowledge continuity tools are insufficient to enable new engineers to reach expert level. Finally, the thematic analysis shows that, in some cases, outsourcing should be reduced to facilitate internal learning.

Originality/value – The study introduces the application of the knowledge-based view of the firm and the concept of requisite knowledge redundancy to the long-term management of complex assets. It calls for more attention to long gaps in the use of unique knowledge and the effect on knowledge continuity.

Keywords Knowledge management, Continuity management, Asset management, Knowledge transfer, Critical infrastructure, Storm surge barrier, Obsolescence, Redesign, Outsourcing

Paper type Research paper

1. Introduction

The sustainment of existing critical infrastructure is essential for society. In the Netherlands, a significant part of the primary infrastructure was built during the 1950s and 1960s. Many complicated nodes of infrastructure, like locks and movable bridges, are currently due for extensive renovation because of technical, economical and functional aging (Hertogh *et al.*, 2018). Renovation requires restoring the compatibility of an asset with current standards in software, hardware, reliability, occupational safety and environmental impact. Adapting and renewing complicated legacy systems is a challenging task that requires up-to-date documentation and a qualified engineering staff. Assuring their continued availability is called knowledge continuity management (Dalkir, 2017). Challenges with knowledge continuity have been previously described for assets such as nuclear power plants (Boyles *et al.*, 2009), navy vessels (Massingham, 2010), nuclear weapons and delivery systems (Kirschbaum, 2020), software (Anquetil *et al., 2007*), rail (Abbas *et al.*, 2022) and the International Space Station (Herd and Piretti, 2022).

The Dutch Directorate-General of Public Works (Rijkswaterstaat, hereafter referred to as RWS) has discerned that among its many assets under management, knowledge continuity is especially vulnerable at its storm surge barriers. This study investigates the continuity of engineering knowledge within the context of the Dutch storm surge barriers. Storm surge barriers protect low-lying coastal areas from flooding. Because they are closed only during exceptionally high water levels, the waters behind them remain accessible for fish and navigable for ships. RWS is responsible for the maintenance and operation of six storm surge barriers. Storm surge barriers show a remarkable variety in design (Mooyaart and Jonkman, 2017). Many of these barriers are unique and are described by Vrolijk and Walraven (2018) as "built as their own prototype." Storm surge barriers share several characteristics that set their asset management apart from other infrastructure (Kharoubi *et al.*, 2023). Their uniqueness, complexity, longevity, low frequency of use and high reliability requirements affect how continuity of their engineering knowledge can be achieved.

This paper shows that the most challenging tasks from a knowledge continuity perspective are those that require in-depth engineering knowledge of the unique barrier behavior but happen so infrequently that the instances of the tasks are multiple career spans apart. In these cases, the conventional approaches to knowledge continuity, such as mentoring, apprenticeships and documentation, do not provide satisfactory results. The paper then provides recommendations to improve engineering knowledge continuity and proposes further research on projects sharing these specific characteristics.

2. Literature

This section approaches the challenge introduced in the introduction from the perspective of three distinct bodies of literature. It explores the existing knowledge regarding the assurance of engineering knowledge continuity, the strategic positioning of the organization to address this challenge and the knowledge continuity of intermittent tasks.

2.1 Managing tacit engineering knowledge

The most important distinction between knowledge types is between tacit and explicit knowledge. Although frequently described as a dichotomy, it was originally conceptualized by Polanyi (1891–1976) in his books from 1958 to 1966 as a continuous scale, with personal knowledge extending from tacit to explicit at the scale's extremes (Grant, 2007). Tacit knowledge is the difficult-to-articulate part of a person's knowledge and is built through experience. An important aspect of tacit knowledge is the mental model of the world, linking what is to what will be (Nonaka and Takeuchi, 1995; Ericsson and Pool, 2016). This tacit knowledge is enacted through performance and decision-making. The explicit part of knowledge can be articulated and transferred to others or used to describe the reasoning behind a decision. When the design of the Maeslant Storm Surge Barrier was revisited many years after its construction, it was observed that the design calculations were well documented. Still, some assumptions underlying these calculations were unclear. It was concluded that important design decisions had been made based on the tacit engineering knowledge of the barrier's designers, and it took a great effort to reconstruct these and make them explicit. As time passes, the tacit dimension of designs becomes more difficult to unravel, as later generations of engineers have less in common with their predecessors.

The barrier's engineering is extensively documented, but the amount of available documentation can also make things harder to find. More than 25 years after completion, the few remaining engineers involved with the Maeslant Barrier's design still act as an important guide to the barrier's engineering documentation. The importance of senior employees as guides to documentation is recognized by Joe *et al.* (2013). Their study found that the distribution of knowledge, held by people and documents, is more difficult to transfer and more tacit than content knowledge. The asset-specific tacit knowledge of an experienced engineer, therefore, remains vital to getting the most out of documentation.

2.2 The knowledge-based view of the firm

The knowledge-based view of the firm (Grant, 1996) views knowledge as the most important resource for predicting the success of a firm. Grant explores how the knowledge of a firm can best be utilized through the coordination of the work of individuals who each hold a different part of it. A firm should bring together individuals with complementary knowledge bases and allow them to work together effectively. Some overlap in individuals' knowledge is considered necessary to be able to communicate effectively. This is known as "requisite redundancy of knowledge" (Nonaka and Takeuchi, 1995). Grant (1996) details four principles of coordination of knowledge work, three of which deal with routine operations. The fourth, "group problem solving," concerns handling exceptional challenges at the firm. Redesigning complicated barrier systems after decades of routine operation is an exceptional challenge.

The knowledge-based view of the firm also provides principles for a firm's vertical and horizontal demarcation. The first principle, as described by Grant (1996), is that knowledge creation works best when a firm focuses on a narrower domain, a concept he refers to as "economics of scope." The knowledge domain of a firm should, however, be broad enough to support a product portfolio that attracts a sufficient volume of customers. This latter requirement is known as "economics of scale." Grant views the economics of scope and scale as two opposing forces that determine suitable horizontal boundaries for firms. RWS is not a firm in economic competition, but it does try to maximize the delivered value for the taxpayers' money spent. Therefore, Grant's principle of balance between scale and scope also applies to RWS. According to Nonaka and Takeuchi (1995), many firms find their optimal demarcation by centering their activities on one "core competence." The core competence of RWS is to manage the overall performance and assets of the primary flood-defense system of the country. At the storm surge barriers, this core competence is enacted through the dedicated risk-based asset management approach RWS has developed (Kharoubi *et al.*, 2023). Design and physical maintenance of assets are outsourced, and this arrangement agrees quite well with the core competence principle.

2.3 Knowledge continuity management

The continuity of knowledge across generations of professionals is an existing branch of knowledge management. Incoming professionals must be supplied with the knowledge to do their job well. This knowledge is typically held primarily by their predecessors. Failure to transfer this knowledge effectively will result in new hires wasting time searching for knowledge or developing their own by making costly mistakes (Beazley *et al.*, 2003). The participants in the interview research by Delaney and O'Donnel (2005), in a context similar to RWS, considered mentoring to be the most important tool for knowledge continuity. Mentoring is also the tool most suited for the transfer of tacit knowledge (Dalkir, 2017; Leonard-Barton *et al.*, 2015).

Not every mentoring relationship is successful. Beane (2019) examined the effects of the introduction of robot surgery on the training of surgeons. He found that in the robot-mediated surgical procedure, there is no low-risk part in the procedure, such as making stitches. Therefore, apprentices can no longer quickly start making authentic contributions, and in this new environment, the learning of the apprentice surgeons was impeded. Successful mentoring requires time spent on the authentic task, reflection and feedback (Dalkir, 2017; Leonard-Barton *et al.*, 2015). In the environment of the storm surge barriers, partial redesigns that require the use of the unique engineering knowledge of the barrier are far apart, which limits the use of this knowledge during an apprenticeship. In the literature, Walker (2018) describes a case in the medical department of the British armed forces, where this challenge is also encountered. Wounds sustained by soldiers during a war require specific experience from the surgeon for the best results. Walker found that the quality of surgical care for British soldiers improved through the course of wars. During peacetime, when shrapnel and gunshot wounds were rare, the staffing levels and capabilities of army medical departments tended to decrease. Following Walker's study, some medical departments have taken action to preserve knowledge continuity. Sweden, for example, now sends their army field surgeons on an internship in South Africa, where gunshot wounds are more common (Jensen *et al.*, 2020). The nuclear power industry provides engineers the opportunity to experience and contribute to the design and construction phase of nuclear reactors in other countries through the Nuclear Education, Skills and Technology (NEST) program (Iracane and Trapidani, 2019). These examples show that for successful knowledge continuity, it is important to take into account the opportunities for authentic use of knowledge during the transfer period.

3. Method

3.1 Research setting

RWS is the Dutch asset manager for primary public infrastructure. The design and management of the flood safety system is an RWS task at the national level, but each infrastructure asset is managed by the RWS district where it is located. The district in the southwestern part of the Netherlands manages four out of six RWS storm surge barriers. In addition, this district welcomes a research group on asset management for storm surge barriers, as it recognizes the growing importance of the barriers' life cycle management. Physically, the research was conducted at the RWS office next to the Dutch IJssel Barrier (HIJK). The HIJK is maintained and operated from this office, which also acts as a space for collaboration between other storm surge barrier professionals within the district. The office provided the setting for most of the interviews with professionals, while others were interviewed at their barriers. Three barriers were visited under the guidance of senior experts. Here, several recent and planned improvements to the barriers were shown and explained in detail, followed by group discussions with barrier asset management teams. In these meetings, plenary discussions were held and intermediate results of the current study were shared, resulting in a deeper understanding of knowledge management challenges at the barriers.

3.2 Data collection

Data collection at RWS comprises three main sources: records of semi-structured interviews, internal policy documents and consultancy reports on the barriers' knowledge and asset management. The research started with initial exploration and interview preparation using the knowledge management policy documents and consultancy reports. Ten semi-structured interviews were held with selected current and former engineering and asset management professionals at the barriers. All engineers involved in the design and construction phases that were found still available were interviewed for the study. Additionally, several senior engineers who currently bear responsibility for the storm surge barriers were interviewed. These were selected based on obtaining a representative distribution of multiple barriers and professional roles. An overview of the interview participants and the internal knowledge management policy documents is provided in Table 1. Minutes of barrier visits and plenary discussions with the teams were added to the interview records to use in the thematic analysis. Most of the research was conducted on site, allowing for frequent additional discussions with the barriers' professionals. Senior professionals frequently visited the researchers out of interest, resulting in plenary discussions on the research findings and progress of the research team. A journal was kept for recording feedback, opinions and insights that emerged while being on site. This became a key source of both information and validation, and it made the research more emic (from the inside) and immersive.

3.3 Data analysis

Policy documents and consultancy reports were first analyzed to understand how asset management and knowledge management evolved over time. An early form of knowledge management going back to at least 1983, but enduring into the present, is an annual counting of the available experts by discipline. It was observed that skill descriptions shifted over time from single engineering disciplines, like hydraulic engineering, to multidisciplinary knowledge-descriptors such as integral knowledge of the storm surge barriers. Early consultancy documents for the Maeslant Barrier detail the design of the first digital knowledge management system to store all design and engineering information. Later policy documents and consultancy reporting on knowledge management became more human-centered, with a first recommendation for a master-apprentice program in 2006. Master-

Participating professionals Role	Status	Barrier
Design manager	Retired	Maeslant Barrier
Senior engineer	Retired	Maeslant and Eastern Scheldt Barrier
Design manager	Past involvement	Maeslant Barrier
Barrier manager	Past involvement	Multiple barriers
Senior engineering consultant	Recently involved	Multiple barriers
Asset manager	Current	Dutch IJssel Barrier
Senior reliability engineer	Current	Maeslant Barrier
Asset management engineering advisors (2)	Current	Eastern Scheldt Barrier
Maintenance manager	Current	Maeslant Barrier

Title	Year	Scope
Policy documents: knowledge management		
Consulting and research for water works	1983	Storm Surge Barriers and other hydraulic
Note on the maintenance and operation of the Eastern Scheldt SSB	1987	Eastern Scheldt Barrier
Aspects of quality assurance knowledge management system Europort Barriers	2002	Maeslant and Hartel Barriers
Knowledge strategy risk-based maintenance storm surge barriers	2010	Barriers
RWS interactive knowledge tree	2010	RWS-wide
RWS: grip on knowledge?	2010	RWS-wide
Knowledge course	2016	RWS-wide
Audit learning and improving: realization and maintenance proces RWS	2017	RWS-wide
Knowledge strategy storm surge barriers	2018	Barriers
Knowledge profile main knowledge domain asset management	2020	RWS-wide
Training and education plan	2020	Ramspol Barrier
Working with knowledge at the storm surge barriers	2020	Barriers
Total cost of ownership storm surge barriers: pilot Ramspol	2021	Ramspol Barrier
Strategic personnel plan storm surge barriers	2021	Barriers
Training and education plan 4SVK	2022	South-West Netherlands barrier district
Policy documents: contracting and outsourcing		
Business Plan RWS: getting on with it, Indeed	2004	RWS
Realization program: getting on with it, Indeed	2004	RWS
Market vision	2016	RWS and others
Future challenges RWS: perspective on civil engineering sector	2019	RWS
Market consultation: two-phase contracts	2022	RWS

Source(s): Table by authors

Table 1. Case resources: participants and internal policy documents

apprentice and mentoring programs feature prominently in the knowledge management documentation hereafter.

The analysis of the interviews and site-visit minutes followed the six-step procedure for thematic analysis outlined in Braun and Clarke (2021). The coding of qualitative data was done in Atlas.ti. Thematic analysis was a suitable choice of method for this research because it assumes situated research and allows for both inductive and deductive theme generation. Interviews were semi-structured to allow professionals to talk freely about their view of and experience with knowledge management at the storm surge barriers. Staying true to these collected personal experiences requires an inductive generation of themes. On the other hand, reviewing policy and consultancy works introduced the question of why the results of earlier knowledge management efforts were unsatisfactory. This called for more deductive and targeted theme construction.

Professionals were interviewed about their involvement with the barriers, personal experience with knowledge continuity challenges, their views on knowledge management challenges at the barriers in general and ideas for improvement. Based on the review of internal policy documents, questions were added regarding the adequacy of documentation and experiences with mentoring. Retired professionals talked more about challenges, transferring their deep understanding of the barriers to current and future engineers. Another major topic among retired engineers are initial-design assumptions that were not fully documented and the efforts to retrieve or reconstruct them later. Current professionals are most concerned with being able to navigate the vast collection of engineering documents stored and keeping it up-to-date with changes.

The first analytic research phase of "familiarization" (Braun and Clarke, 2021) featured reading through interview records and discussing the initial impressions with the participants and other professionals at the barriers. The interviews were initially coded in a semantic fashion, grouping statements from participants along with concepts from knowledge management theory. These codes roughly followed the stages used in knowledge-cycle models like storing, sharing, re-using and creating (Dalkir, 2017). As a consequence, coding and theme generation was found to closely follow conventional knowledge management theory. To move beyond and get more insight into the specific challenges encountered at the barrier, the data were coded a second time. This coding was more latent than semantic, focusing more on what professionals want to achieve while working with engineering knowledge. This round eventually resulted in the development of themes like avoiding obsolescence and working relationships with external parties. These were then grouped as challenges, origins of challenges and thoughts about solutions.

The inability of barrier professionals to develop to a full engineering expert level emerged as the central theme of the final phases of analysis. Iterative movements between the themes and literature related to each theme refined the logic of the remaining themes. Themes were developed into an interrelated and nuanced narrative explaining how obsolescence challenges necessitate expert-level engineering expertise, yet barrier characteristics largely preclude professionals from reaching expert level during the barrier's sustainment phase. Table 2 displays the main themes and subthemes as a result of the coding.

Outsourcing policy and its relation to knowledge continuity also emerged from the thematic analysis and required more investigation. A second round of research on the evolvement of outsourcing at RWS (Brink, 2009) was conducted. An overview of the policy documents on outsourcing is provided as the final section in Table 1. This led to a better understanding of the relationship between outsourcing policy and knowledge management challenges. Additional insights on outsourcing improved the deeper understanding of the interview data.

Barrier asset management teams have been coping with knowledge management challenges for decades. This caused them to gain experience working around knowledge management challenges to some degree. Coping strategies are covered in Section 5, based on subsequent discussions with professionals in the later stages of the research process.

Qualitative research aims for saturation of the model or theory of the explored, where data collection stops yielding new insights or experiences (Creswell and Poth, 2017). As the Maeslant Barrier is already more than 25 years old, only a few initial barrier's design and construction engineers were available to interview. Saturation of the initial interviews could therefore not be achieved in this small group. However, RWS is a large organization with people knowledgeable in a great variety of technical domains and processes. In a way akin to discriminant sampling, over a six-month period after the analysis of the initial interviews, the various topics mentioned in the initial interviews were explored further. Initial findings and

	Theme	Codes	Illustrative quote
	Obsolescence	Do not let the need to redesign surface during replacement!	The archives themselves are mostly fine. It is society that evolved. What you need now is not what was documented in '97. Back then cybersecurity wasn't a priority. It is now.
		Functional obsolescence - changing demands	
		Improving the original design	
		Obsolescence of software	
		Technical obsolescence, parts unavailable	
		Obsolete archives, changing areas of interest	
	Barrier characteristics	Unique structure built from common components	Civil engineering knowledge about foundations and concrete is used the least and is disappearing. Industrial Automation gives most issues forcing us to work on it. Knowledge loss here is not as bad.
		Knowledge cycles that span over decades	
		Manage the asset as High Reliability Organization	
		Limited knowledge outside of managing organization	
		Older documentation: Names keep changing	
		Older documentation: Understanding old assumptions	
	Outsourced knowledge	Asset knowledge inaccessible from outside	We are an organization that orders engineering work to be done. This sets limits to the level of knowledge we can achieve. You do not really learn it unless you do it yourself.
		Boundaries between parties hard to cross	
		Centralized or decentralized knowledge?	
		Outsourcing: knowledge lost after project	
		Outsourcing: less in-house learning	
Challenges	Expert engineers: critically important	A non-technical manager will not prioritize technical uncertainties	He knows how the system behaves and how the software should react. That is why he could spot the mistakes the company made. Someone else might have missed it.
		An outsourced project still requires technical knowledge to buy it right	
		It takes an expert to notice what goes wrong and ask the right questions	
	Expert engineers: difficult to train a new generation	The learning process of the design and build period cannot be replicated	
		Knowing how it all works together is essential but so hard to transfer in detail	
		There is no more safe space for making mistakes	
		Master-apprentice does not work for knowledge which is not in use	
Solutions	Improving continuity	Simulators and twins can help with learning and experiencing	We should invest in a good simulator. It should run scenarios real-time, so you can experience what happens. Keeping the simulator up-to-date does add a new challenge.
		Improving knowledge transfer from contractors	
		Research as knowledge management tool	
		There are so many learning opportunities we do not use in apprenticeships	

Source(s): Table by authors

Table 2.
Code table

the topics raised in the initial interviews were discussed in 16 additional meetings, of which extensive notes were taken. Four of these meetings were informal and serendipitous, but still very valuable. Around 12 follow-up meetings were organized by appointment and took roughly an hour each. These meetings delved into the respondent's relevant expertise about topics raised in the original interviews. For example, in the original interviews, changes in health and safety regulations are mentioned as a contributor to challenges in replacing and updating barrier systems. Being able to discuss this later with a professional currently involved with compliance with these regulations helped with understanding the background and significance of the initial recorded remarks. Other topics about which additional background information was sought and found during the development, from initial analysis to reporting on this research, are systems acceptance procedures, record keeping and document storage, the current training and mentoring program, the division of engineering knowledge between RWS and its partners, digital twins, working with old barrier drawings from the 1950s and a few more. After six months, all topics from the initial interviews that appeared valuable to understand better and know more about had been discussed at length at least once with a professional specifically knowledgeable about the topic. This resulted in only minor edits to the initially developed narrative, but it did provide the background and confidence to write about it and remain true to the lived experience of RWS professionals. It was determined that sufficient saturation had been achieved.

Validation was achieved by utilizing multiple means. Prolonged observation and interactions with professionals within the barrier asset management organization provided the first part of the validation. Three data sources were used, providing validation through the triangulation of research findings. Policy and consultancy works were re-read to check for inconsistencies with the themes and narrative. The narrative recorded from senior engineers participating in the study was corroborated by the records in the body of consultancy works from the relevant period. All the major events, challenges and policy developments described could be confirmed. Comparing interview records with current and obsolete policy documents, however, showed not all knowledge management programs and policies feature in the interview records. Some of these, as well as policies and tools found in the literature relating to the situation, were discussed with professionals over the six-month period after the initial analysis of interview records. Based on the feedback, the mapping of knowledge continuity challenges to specific knowledge management tools was decided against. Professionals are not especially attached to any particular knowledge management tool, although the knowledge strategy and the training and mentoring program are highly valued. The scope was slightly adjusted, which resulted in Section 5 of this paper. This section describes how RWS professionals deal in practice with barrier maintenance projects that are challenging from a knowledge management perspective. Section 4 presents the findings derived from the thematic analysis outlined in Section 3, highlighting the critical challenges and implications for engineering knowledge continuity, while Section 5 describes how these challenges are approached in practice.

4. Thematic analysis

The central knowledge continuity challenge at the storm surge barriers was found to be the inability to replace the barriers' most senior retired engineers (hence called "expert engineers") with someone equally skilled. Table 2 contains the main themes, subthemes, codes and an illustrative quote from each theme in the analysis. The subsequent paragraphs explain the themes and reflect on the findings in the context of practice and with reference to the literature.

4.1 Obsolescence

All complicated assets with long service lives will experience obsolescence, especially if these assets contain electronic components (Classi *et al.*, 2021; Gravier and Schwartz, 2009). When obsolescence issues with subsystems threaten the performance of the asset, these subsystems must be redesigned and replaced (Classi *et al.*, 2021; Sols *et al.*, 2013). Two main types of obsolescence are technical obsolescence and functional obsolescence (Hertogh *et al.*, 2018; Sols *et al.*, 2013). A component becomes technically obsolete when it is no longer available for purchase. Functional obsolescence happens when the component no longer meets the latest requirements. Both types of obsolescence can be observed at the storm surge barriers. An example of an obsolescence-driven subsystem redesign is the control system of the Maeslant Barrier. The original hardware and operating systems on which the control software was running are no longer available or supported; thus, they are technically obsolete. Not all obsolescence issues at the barriers are related to electronics or software. At the Eastern Scheldt Barrier, occupational safety regulations made the outer staircases functionally obsolete, and environmental regulations made the hydraulic oil of its main cylinders technically obsolete, necessitating further hydraulic system modifications.

Redesigning and rebuilding parts of a complicated existing system can be very difficult. New requirements must be met while connecting new systems to unalterable and obsolete interfaces with the rest of the system (Anquetil *et al.*, 2007). Interactions within a system are often neither obvious nor explicitly documented. One retired engineer explained the interaction between the operating system and the structural engineering of the Maeslant Barrier. The operating system was designed with consideration for the load-bearing capacity of the structure and its foundations. The sequencing and speed of operation of pumps, valves and motors have a direct impact on the forces acting on the structure. Therefore, modifications cannot be safely made without understanding the barrier's structural engineering. Another example from the Maeslant Barrier is the installation of synthetic pads in the outer shell of the ball joint. This required cutting out recesses in the steel outer shell at high precision in a very small space, which was never intended for such work.

Obsolescence can also affect the documentation of barrier systems. A changing context can cause an unforeseeable need for information. The necessity for an in-depth understanding of the design assumptions of the Maeslant Barrier to re-evaluate it for sea-level rise was not anticipated. A more current example is the ongoing evaluation of the cyber security of the barriers. Since the barriers were built before cyber security became a major concern, archives do not hold the related functional information. When the knowledge contained in the barriers' documentation no longer fits current sustainment needs, the documentation also suffers from functional obsolescence.

4.2 Barrier characteristics

Three characteristics significantly affect the knowledge management effort required to sustain the barriers' functions. These characteristics are uniqueness, long replacement cycles and high reliability requirements. The storm surge barriers are unique structures built in different periods, under different local circumstances and with different requirements. The barriers feature a few truly unique components. Examples are the ball joints of the Maeslant Barrier, the reinforced rubber of the inflatable rubber weir (bellows weir) type Ramspol Barrier and the emergency closing system of the Eastern Scheldt Barrier. Detailed engineering knowledge of these unique systems is limited to one or very few companies, and knowledge loss at the partner company for a unique component is the first major vulnerability of engineering knowledge continuity at a barrier. A strategy to deal with this vulnerability is entering into long-term partnership agreements with knowledge-carrying parties. This incentivizes partners to invest in continuity and update their knowledge to maintain the partnership and related workflow.

Mostly, however, the barriers are made up of common materials and components. Therefore, the second important vulnerability is what one expert engineer described as "deep systems knowledge" of the barrier, or the understanding of how it all works together and how the individual systems influence one another. As explained in the Obsolescence section, such knowledge is necessary, for example, to safely update barrier control systems. Since the barriers are one-offs, such whole-system knowledge can be unavailable from engineering firms and must, therefore, be preserved by RWS (Vrolijk and Walraven, 2018).

While the uniqueness of the barriers makes specific engineering knowledge more vulnerable, the length of the replacement cycles makes transferring knowledge between different generations of engineers in charge of a (re)design cycle more difficult. Barrier control software and hardware have a nominal service life of ten to fifteen years. Mechanical and hydraulic systems have replacement cycles of 25 to 35 years. When systems are due for replacement, depending on technical and functional obsolescence, these may need to be redesigned. The current average engineer's career span at a barrier is about seven years. This means the current engineers preparing and overseeing the partial replacements work multiple career spans apart from the former design engineers, precluding full interpersonal knowledge transfer. Storing documentation over such time periods is not in itself a problem, but as discussed in the section about obsolescence, codified knowledge is nonetheless vulnerable. Shortcomings in documentation will go unnoticed until a new replacement effort gets underway, so their possibility must always be considered.

High reliability requirements and infrequent use of the barriers influence the possibilities for local knowledge creation. The reliability requirements give rise to conflicting demands on knowledge creation (Milosevic *et al.*, 2018). To meet reliability requirements, solutions to engineering challenges must be proven, but new potential solutions cannot be readily tested as the testing could affect reliability. Because of infrequent use, components wear out differently than similar components in industry, making the barriers unique not just in design but also in component behavior (Walraven *et al.*, 2022). With few operations and infrequent breakdowns, opportunities for collecting data, learning about component behavior, practicing design and problem-solving are rare.

4.3 Outsourced knowledge

Since the 1990s, RWS has outsourced more of its engineering. The RWS business plan of 2004 elevated outsourcing to an important agency policy and introduced the principle of "market unless" (Rijkswaterstaat, 2004; Brink, 2009). In the current policy, the barriers' engineering knowledge is assured by "shared knowledge" (Vrolijk and Walraven, 2018). This means that the required knowledge for sustaining the barriers' functions during their service life is divided among contractors, engineering firms, research institutes and RWS itself. Knowledge is considered sufficiently assured when it resides with multiple reliable partners. Outsourcing design and maintenance to market parties allowed RWS to focus on its core competence of managing the main road and water networks, their asset management and operation. Most participants, however, believe the current level of outsourcing is contributing to the challenges of ensuring knowledge continuity. Several responding barrier professionals would prefer a situation where the ability and knowledge for any task are available in-house and outsourcing is used to obtain additional capacity rather than capability. The three identified main causes for knowledge continuity challenges at the barriers (obsolescence of systems, barrier characteristics and outsourcing of knowledge) underlie the observed key challenge for knowledge continuity, which will be elaborated on in the following section.

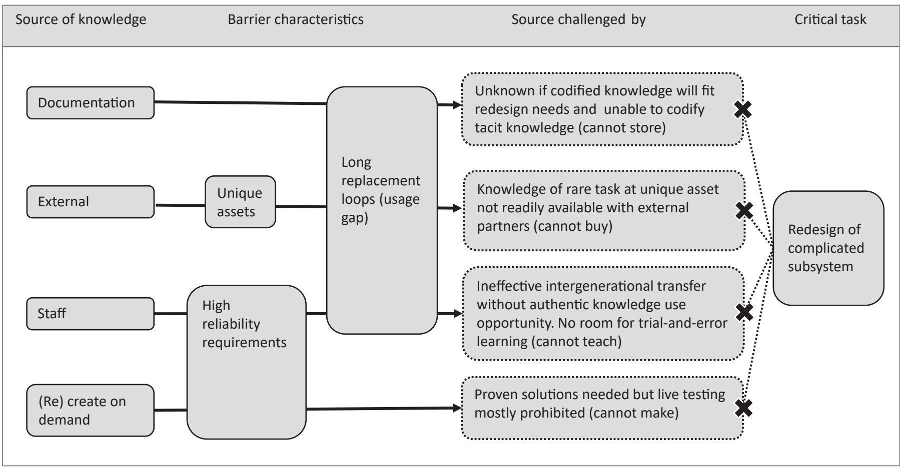
4.4 Expert engineers: critically important but very difficult to train a new generation

The main source of personified barrier engineering knowledge has been former designers and construction managers. At the Eastern Scheldt Barrier, these experts remained in employment after construction. At the privately constructed Maeslant Barrier, the engineering experts were hired back when the first technical challenges occurred. The expert engineers have been invaluable to the barriers through contributions such as scoping redesign projects, setting paths and targets for reliability improvement, evaluating redesign proposals, explaining anomalies and assisting with solving engineering issues. It is essential for the sustainment of the barriers to maintain access to deep whole-system barrier engineering knowledge.

Barrier asset management teams spend a lot of time on training and use many instruments for knowledge risk identification and continuity. This ensures well-trained professional teams for operation and maintenance. With regard to expert-level engineering knowledge, research participants unanimously share the view that current asset management engineering advisors do not have the same level of knowledge as retired experts. Engineering judgment, such as estimating whether a desired project demarcation or timeframe will work or if issues are to be expected with interfacing systems, are, to a large degree, tacit skills. As remarked in the literature section, tacit skills transfer best through mentored performance of authentic tasks. The barriers' asset management teams have facilitated multiple apprenticeships with the goal of transferring tacit engineering knowledge to a new generation of engineers. These efforts have faced twofold challenges. Most engineers of the first generation of completed apprenticeships left the barrier teams for management positions and other employment elsewhere. The recently completed apprenticeships show that engineering knowledge improved but did not yet reach the mastery of former designers. Participants explained that during the period of the apprenticeship, most of the barrier's engineering knowledge was never experienced in action. This is inevitable due to the characteristics of the barriers, where many engineering challenges only come around once in about thirty years. The retired engineers participating in the research believe that the people they have mentored have forgotten a lot after years-long gaps in knowledge use. Considering also the research by Beane (2019) and Walker (2018) discussed in the literature section, training and mentoring programs will not transfer the full depth of expert knowledge in the absence of authentic knowledge demand.

4.5 An integrated view of causes and challenges

The identified knowledge continuity challenges and their origins have been elaborated on in the previous paragraphs. Figure 1 visualizes how the barrier characteristics challenge knowledge continuity. On the left side of the figure, four distinct sources of engineering knowledge are displayed. The barrier characteristics challenge all conventional ways to assure knowledge availability for redesign projects. The use-discontinuity during long partial replacement cycles devaluates the knowledge obtained from documentation. It also prohibits the intergenerational transfer of knowledge, both between RWS staff and external partners. Because of the barriers' uniqueness, partners can leverage work for other clients for



Source(s): Figure by authors

Figure 1.
Challenges to knowledge continuity at the barriers

knowledge continuity in their professional discipline, but not for a deep systemic understanding of the barriers. Without effective intergenerational knowledge transfer, long-term knowledge continuity cannot be fully assured. The high reliability requirements of the barriers hamper experimentation and testing. This also limits intergenerational knowledge transfer, as there is little room for new hires to learn by trial, error and feedback. This inability for authentic testing also precludes re-creating lost knowledge, exacerbating the dependence on pre-existing proven knowledge. The knowledge continuity challenges can be summarized as: cannot store, cannot buy, cannot teach and cannot make. The next section will explore how professionals cope with these challenges in practice.

5. Coping in practice

A shortage of qualified engineers has contributed to several cases of maintenance being deferred to a later date. Nonetheless, since the inauguration of the first barrier in 1958, no closure has failed. In the context of this study, it is important to understand how this achievement in asset management has been realized.

5.1 The multi-firm team approach

Most of the recent major engineering projects were staffed by teams brought together from multiple organizations. Three examples of this are (1) the development of one-time measures and an adjusted maintenance schedule to deal with scour pits at the Eastern Scheldt Barrier in 2015, (2) redesigning "lubrication" for the ball-joint of the Maeslant Barrier in 2003 and (3) updating the reliability assessment of the Eastern Scheldt Barrier in 2023. In each case, the team comprised of engineers from RWS and external partners. These teams have completed all three projects to the satisfaction of those involved and the client. The continued need to have in-house expert engineers does, therefore, not primarily concern the ability to solve the most challenging problems but rather to avoid delays and mistakes while preparing the projects.

To achieve knowledge continuity, the engineering knowledge from a finished project should be stored in an accessible, documented and personified form. In the current approach, the majority of the engineers involved in a project have no continued involvement with the barriers. Vrolijk and Walraven (2018) state about the scour pit example: "after solving the problem (. . .) the group fell apart, and the developed knowledge was not put to further use." While some engineers can probably be hired again if needed, the current environment does not support the engineers in transferring what they have learned to the next generation.

5.2 Knowledge continuity for four groups of sustainment tasks

Although there is no single strategy that can solve the continuity challenges at the barriers, as was shown in Section 4.5 and Figure 1, there is much that can be done to improve knowledge continuity. Main efforts to improve knowledge continuity are:

(1) Develop new engineering talent

(2) Document redesigns systematically

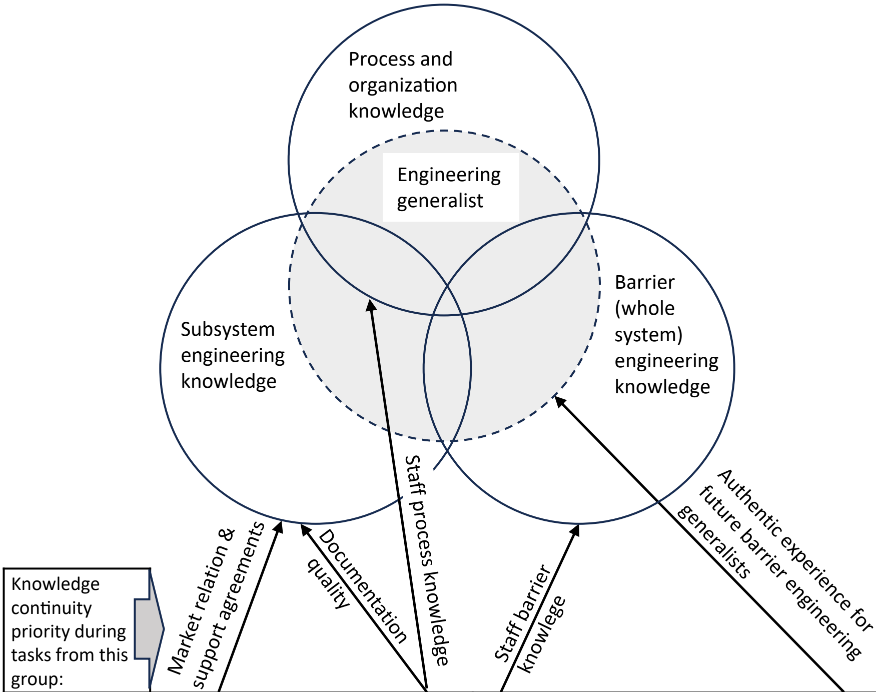
(3) Reduce the knowledge-use gap

(4) Design and buy for maintainability

(5) Learn from redesign projects

Efforts 1 to 3 can reduce the loss of knowledge over time, while effort 4 can avoid starting to rely on difficult to continuate knowledge in the first place and effort 5 can improve how effective the available knowledge is utilized. In this section, tasks for the general sustainment of the barriers are arranged into four groups. It is then shown that tasks from each group provide specific opportunities for the knowledge continuity effort. In Section 4, cycle length and knowledge requirements were shown to be key determinants of continuity challenges. Tasks are therefore grouped based on cycle length and knowledge requirements. This is shown in the task-characteristics row in Figure 2. The two main groups are arranged from tasks focused on subsystem engineering knowledge on the left to tasks requiring understanding of an entire barrier's engineering and the barrier behavior (the interaction between subsystems). Both groups encompass short- and long-cycle engineering tasks.

For subsystem engineering tasks with short life cycles (mostly left in Figure 2), RWS has transitioned from one-time supply contracts maximizing economic competition between suppliers to long-term contracts that emphasize partnership, shared learning and continuity of support for delivered subsystems. Continuity effort number 4 from the list above, design and buy for maintainability, is prioritized here. For the group of subsystem engineering tasks in Figure 2, where the cycles are much longer, documentation is key. Modifications to long-



	Subsystem engineering		Barrier (whole-system) engineering	
Task characteristics	Short cycle	Long cycle	Short cycle	Long cycle
Example cases	Electronic hardware replacement	Ball-hinge renovations Rubber tube replacements	Operating the barriers Data analysis Digital twin training	Updating barrier control system Digital twin development

Source(s): Figure by authors

Figure 2.
Connecting task characteristics to knowledge continuity

lasting, unique systems are carefully documented while paying attention to assumptions and design choices. Given that such projects involve bringing in knowledge from multiple firms, they present valuable opportunities to improve staff knowledge about organizing these complex redesign projects. Efforts 2 and 5 are most important here. For the group whole-system engineering tasks with short cycles, knowledge continuity is served by data emerging from regular operation and maintenance of the Maeslant Barrier, including testing. Steps are taken to improve and internalize the processing and use of this data. Collecting and analyzing operational data with regards to engineering behavior contributes to all aspects of efforts 1 to 3.

The most challenging group of tasks can be found on the right side of Figure 2: whole-system engineering tasks with long cycles. These tasks require a broad working knowledge of the barriers' engineering after a long gap of use. These tasks also present talented new engineers with the best opportunity for authentic learning. The RWS knowledge strategy (Vrolijk and Walraven, 2018) specifically states the importance of staff with a general and broad understanding of both the barriers' engineering and the organizational processes of barrier sustainment. Every challenging new project provides an opportunity for staff to learn about the new system, its relation to the general engineering of the barrier and the processes in the organization and thus to become the generalists shown in the center of Figure 2. Maximizing use of this learning opportunity should become as central to approaching the project as delivering on time and on budget. Not all participating engineers will remain involved with the barriers long-term, so it is advisable to make the most valuable learning opportunities available to more people than strictly necessary for project delivery.

5.3 Knowledge continuity initiatives outside of primary sustainment tasks

Aside from utilizing learning opportunities in the primary sustainment tasks, there are specific initiatives to reduce gaps in knowledge use (Effort 3). One initiative is the establishment of a new RWS design team. The team specifically aims to provide young RWS-employed engineers access to the experience of doing challenging engineering assignments in a multidisciplinary team. Another is the formation of three research groups on sustainment-related topics. Research and development of digital twins that simulate barriers' operation and behavior offers a unique opportunity for the knowledge continuity of the barriers. A digital twin can be understood as a virtual simulation that mirrors the real-world barrier. A digital twin can contribute to knowledge management in three ways. First, it acts as a structured and well-navigable storage of explicit knowledge. Additional documented knowledge can be attached through links to make it easier to find. A suitable digital twin can also be used to train various (emergency) scenarios in a realistic way (Ponsioen and Nederend, 2023) and finally building and updating the digital twin requires in-depth knowledge of the barrier's engineering. These activities can help to bridge the periods in which critical engineering knowledge is not in use in the primary process.

6. Discussion

The continuity of engineering knowledge is a vital prerequisite for effectively scoping, planning and executing partial redesigns of complicated and long-lived infrastructure assets. This study shows how the storm surge barriers' characteristics of uniqueness, high reliability requirements and long redesign cycles limit the effectiveness of conventional knowledge continuity management, as summarized by Figure 1. Apprenticeships necessitate feedback and guided reflection on the apprentice's execution of authentic tasks, making it imperative that such tasks are readily accessible (Beane, 2019; Leonard-Barton *et al.*, 2015). For competitive results, firms should focus on their core competences (Grant, 1996; Nonaka and Takeuchi, 1995), yet adjacent to their core competence, the "requisite redundancy" or knowledge overlap with partner firms, is required. The focus of knowledge continuity literature is currently on the transfer of core competence from incumbent to starting professionals (Leonard-Barton *et al.*, 2015). At the barriers, it was found that intergenerational transfer in the requisite redundancy domain is actually more difficult, as here the use of critical knowledge is more discontinuous. Neither of the two most pertinent continuity management theories explicitly considers continuity of knowledge use as a specific parameter to manage. The knowledge-based view of the firm (Grant, 1996) assumes knowledge processes as continuous and does not discuss use-discontinuity. Knowledge continuity management (Beazley *et al.*, 2003) considers retirements as discrete events of knowledge loss. Economic theory adheres to the principle that supply aligns with demand, and the research by Walker (2018), discussed earlier, underscores that the availability of knowledge diminishes during prolonged periods of low demand. Knowledge continuity theory should be expanded to include the impact of gaps in knowledge utilization and tools to deal with these gaps. Figure 2 groups sustainment tasks by required knowledge and length of the gap and shows how continuity is promoted for each of the groups. The group of tasks requiring whole-barrier knowledge should be supported by reducing the gap itself. Taking the knowledge-based view of the firm perspective, the demarcation of the organization can be altered to reduce gaps in knowledge use. Switching specific engineering tasks with a high potential for knowledge transfer from outsourced to in-house improves vertical demarcation. Tasks demanding engineering knowledge of unique components or systemic knowledge of the whole system facilitate the use of critical knowledge and are therefore vital opportunities to improve the continuity of critical knowledge. Horizontal demarcation can also be expanded to include activities like research and digital twinning, which have recently taken off at the barriers.

7. Conclusion

This study investigated the underlying causes of the challenges with the continuity of engineering knowledge at the Dutch storm surge barriers. It was found that the characteristics of the barriers, in combination with obsolescence, of systems and outsourcing policies, impact knowledge continuity. The barrier characteristics of uniqueness, long life cycles and high reliability requirements challenge conventional approaches to engineering knowledge continuity. Neither theory nor current policy pays much attention to the continuity of knowledge demand and opportunities for filling long discontinuities. Currently, a retirement wave of first-generation barrier engineering experts is underway. Challenging sustainment projects requiring understanding of the engineering behavior of the barrier as a whole are the best environment for a new generation of engineers to acquire whole-system engineering knowledge. It is important to utilize upcoming sustainment tasks to this end. Reviewing the outsourcing strategy of a barrier and returning some activities with a high potential for the transfer of critical knowledge to in-house is shown to be valuable. In addition, current efforts to encourage the use of dormant knowledge include participating in research programs, facilitating (inter)national knowledge exchange and developing digital twins of the barriers. It is recommended to recognize these new efforts as knowledge management strategies for complex, long-lived assets.

References

Abbas, Y., Martinetti, A., Rajabalinejad, M., Schuberth, F. and Van Dongen, L.A.M. (2022), "Facilitating digital collaboration through knowledge management: a case study", *Knowledge Management Research and Practice*, Vol. 20 No. 6, pp. 797-813, doi: 10.1080/14778238.2022.2029597.

Anquetil, N., de Oliveira, K.M., de Sousa, K.D. and Batista Dias, M.G. (2007), "Software maintenance seen as a knowledge management issue", *Information and Software Technology*, Vol. 49 No. 5, pp. 515-529, doi: 10.1016/j.infsof.2006.07.007.

Beane, M. (2019), "Shadow learning: building robotic surgical skill when Approved means fail", *Administrative Science Quarterly*, Vol. 64 No. 1, pp. 87-123, doi: 10.1177/0001839217751692.

Beazley, H., Boenisch, J. and Harden, D. (2003), "Knowledge continuity: the new management function", *Journal of Organizational Excellence*, Vol. 22 No. 3, pp. 65-81, doi: 10.1002/npr.10080.

Boyles, J.E., Kirschnick, F., Kosilov, A., Yanev, Y. and Mazour, T. (2009), "Risk management of knowledge loss in nuclear industry organisations", *International Journal of Nuclear Knowledge Management*, Vol. 3 No. 2, pp. 125-136, doi: 10.1504/IJNKM.2009.02656.

Braun, V. and Clarke, V. (2021), *Thematic Analysis: A Practical Guide*, SAGE Publications, London.

Brink, M. A.v. d. (2009), *Rijkswaterstaat on the Horns of a Dilemma*, Eburon, Netherlands.

Classi, C.C., Nowicki, D.R., Dickens, J.M. and Glassburner, A.V. (2021), "A redesign decision model for large-scale complex sustainment-dominated systems", *IEEE Transactions on Engineering Management*, Vol. 70 No. 10, pp. 1-11, doi: 10.1109/TEM.2021.3092962.

Cresswell, J.W. and Poth, C.N. (2017), *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed., SAGE Publications, Thousand Oaks, California.

Dalkir, K. (2017), *Knowledge Management in Theory and Practice*, The MIT Press, Cambridge, MA.

Delany, A. and O'Donnell, D. (2005), "Perceptions of continuity management in an Irish semi-state organisation", *Electronic Journal of Knowledge Management*, Vol. 2 No. 1, pp. 1-12.

Ericsson, A. and Pool, R. (2016), *Peak: Secrets from the New Science of Expertise*, Penquin Random House UK, London.

Grant, R.M. (1996), "Toward a knowledge-based theory of the firm", *Strategic Management Journal*, Vol. 17 Winter Special Issue, pp. 109-122, 1986-1998, doi: 10.1002/smj.4250171110.

Grant, K.A. (2007), "Tacit knowledge revisited – we can still learn from Polanyi", *Electronic Journal of Knowledge Management*, Vol. 5 No. 2, pp. 173-180.

Gravier, M.J. and Swartz, S.M. (2009), "The dark side of innovation: exploring obsolescence and supply chain evolution for sustainment-dominated systems", *The Journal of High Technology Management Research*, Vol. 20 No. 2, pp. 87-102, doi: 10.1016/j.hitech.2009.09.001.

Herd, A. and Piretti, F. (2022), "Lessons Learned process case study: an unintended enabler of upstream and downstream knowledge management capabilities at the European Space Agency", *European Conference on Knowledge Management*, Vol. 23 No. 1, pp. 510-518, doi: 10.34190/eckm.23.1.675.

Hertogh, M., Bakker, J., Vlist, M. and Barneveld, A. (2018), "Life cycle management in upgrade and renewal of civil infrastructures", *Organization, Technology and Management in Construction: An International Journal*, Vol. 10 No. 1, pp. 1735-1746, doi: 10.2478/otmcj-2018-0005.

Iracane, D. and Di Trapani, A. (2019), "Knowledge management and the sustainability of the nuclear sector", *NEA News*, Vol. 37 No. 1, pp. 19-20.

Jensen, G., van Egmond, T., Örtenwall, P., Peralta, R., Aboutanos, M.B. and Galante, J. (2020), "Military civilian partnerships: International proposals for bridging the Walker Dip", *Journal of Trauma and Acute Care Surgery*, Vol. 89 No. 2S, pp. S4-S7, doi: 10.1097/TA.0000000000002785.

Joe, C., Yoong, P. and Patel, K. (2013), "Knowledge loss when older experts leave knowledge-intensive organisations", *Journal of Knowledge Management*, Vol. 17 No. 6, pp. 913-927, doi: 10.1108/JKM-04-2013-0137.

Kirschbaum, J.W. (2020), *Defense Nuclear Enterprise: Systems Face Sustainment Challenges, and Actions Are Needed to Effectively Monitor Efforts to Improve the Enterprise*, United States Government Accountability Office, Washington.

Kharoubi, Y., van den Boomen, M., Hertogh, M.J.C.M. and van den Bogaard, J. (2023), "Foundation for risk-based asset management for storm surge barriers: IALCCE 2023", in Biondini, F. and Frangopol, D.M. (Eds), *Life-Cycle of Structures and Infrastructure Systems*, pp. 3214-3221, doi: 10.1201/9781003323020-392.

Leonard-Barton, D., Swap, W.C. and Barton, G. (2015), *Critical Knowledge Transfer: Tools for Managing Your Company's Deep Smarts*, Harvard Business Review Press, Boston, Massachusetts.

Massingham, P. (2010), "Knowledge risk management: a framework", *Journal of Knowledge Management*, Vol. 14 No. 3, pp. 464-485, doi: 10.1108/13673271011050166.

Milosevic, I., Bass, A.E. and Combs, G.M. (2018), "The paradox of knowledge creation in a high-reliability organization: a case study", *Journal of Management*, Vol. 44 No. 3, pp. 1174-1201, doi: 10.1177/0149206315599215.

Mooyaart, L.F. and Jonkman, S.N. (2017), "Overview and design considerations of storm surge barriers", *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol. 143 No. 4, 06017001, doi: 10.1061/(ASCE)WW.1943-5460.0000383.

Nonaka, I. and Takeuchi, H. (1995), *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*, Oxford University Press, New York, NY.

Ponsioen, L.A. and Nederend, J.M. (2023), "Investigation and development of a digital twin for the Maeslant barrier: exploring the application of digital twins in the maintenance and operation of storm surge barriers", Delft University of Technology, available at: https://research.tudelft.nl/en/publications/investigation-and-development-of-a-digital-twin-for-the-maeslant-

Rijkswaterstaat (2004), "Ondernemingsplan: Een nieuw perspectief voor Rijkswaterstaat: doorpakken, wel degelijk", Directoraat-Generaal Rijkswaterstaat, Den Haag, available at: https://open.rijkswaterstaat.nl/zoeken/@29231/ondernemingsplan-nieuw-perspectief/#highlight=ondernemingsplan%202004

Sols, A., Romero, J. and Fernández, I. (2013), "A technology refreshment methodology-maintaining system's relative performance quasi-constant over time", *Engineering Management Journal: EMJ*, Vol. 25 No. 3, pp. 51-62, doi: 10.1080/10429247.2013.11431982.

Vrolijk, K. and Walraven, M. (2018), *Kennisstrategie Stormvloedkeringen*, Rijkswaterstaat, Utrecht.

Walker, A. (2018), "The 'Walker dip'", *Journal of The Royal Naval Medical Service*, Vol. 104 No. 3, pp. 173-176, doi: 10.1136/jrnms-104-173.

Walraven, M., Vrolijk, K. and Kothuis, B.B. (2022), "Chapter 20 – design, maintain and operate movable storm surge barriers for flood risk reduction", in Brody, S., Lee, Y. and Kothuis, B.B. (Eds), *Coastal Flood Risk Reduction*, Elsevier, pp. 271-286, doi: 10.1016/B978-0-323-85251-7.00020-2.

Corresponding author
Merlijn Kamps can be contacted at: m.kamps@tudelft.nl