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Knowledge Continuity Aspects in Designs and Contracts of Dutch Storm Surge Barriers

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Abstract: The infrastructure we build is increasingly complicated and automated. After it is designed and constructed, it needs to be maintained and updated to sustain its functioning for far longer than the careers of its designers and builders. Continuity of engineering knowledge is necessary to make future updates and adapt to changing demands, conditions and technology in a safe and reliable manner. The Dutch storm surge barriers protect the low-lying hinterlands from flooding during extreme weather events. Each of the six barriers managed by the Directorate General of Public Works (Rijkswaterstaat) was designed at a different time, to different requirements, and using different types of contracts. This has resulted in six unique structures, some of which use systems and components found nowhere else. In 1997, the Maeslant Storm Surge Barrier was completed, pioneering the use of Design and Construct contracts for major hydraulic structures. Experience with maintaining this hallmark structure through its first decades of operation provides a valuable opportunity to reflect on the effect of contracting- and design choices. Little work has been done to evaluate different contract types on the basis of delivering long-term maintainability and reducing the knowledge continuity challenge. This study views the Maeslant Barrier in the context of the earlier storm surge barriers with regard to facilitating knowledge continuity through design. It was found that the interdependent behaviour of subsystems in a high-reliability structure results in a notable increase in engineering complexity, especially in the control systems, increasing the challenge of achieving knowledge continuity. Examining the knowledge flows in a design-and-construct contract shows several advantages, but also that it does not naturally facilitate attention to important but less obvious aspects of maintainability, such as those related to knowledge continuity.

Keywords: Knowledge Continuity, Continuity Management, Maintainability, Storm Surge Barrier, Obsolescence, Life-Cycle Engineering

1. Introduction

Hydraulic structures such as locks, weirs, and storm surge barriers play a critical role in managing water levels in river delta waterways. These structures are major investments, and it is crucial that their functionality and reliability are sustained for the intended service life, typically about 100 years (Walraven, Vrolijk, and Kotshuis, 2022). Storm surge barriers are also unique structures, which are operated only when necessitated by external conditions, yet as critical infrastructure their reliability and availability must be guaranteed throughout the life-cycle (Kharoubi, 2023).

During these structures' long service life, many changes occur in their environment. These may include changes in laws on water regulation, advancements in technology, shifts in environmental- and safety regulations, and the impact of climate change, including altered water levels and storm intensities (Walraven, Vrolijk and Kotshuis, 2022). The Directorate-General of Public Works in the Netherlands, Rijkswaterstaat (RWS), has a rich history of designing, building, and managing major hydraulic structures. This paper will focus on the Dutch storm surge barriers, the oldest of which has been continuously operational since 1958 and remains of vital importance to flood safety to this day. The long experience managing storm surge barriers has shown that the changing environment of these engineering structures has caused many cases of partial or subsystem obsolescence. (Walraven, Vrolijk and Kotshuis, 2022). A major source of obsolescence at the barriers is the control system. Electronics and operating systems need to be replaced when they are no longer supported by industry. Efforts to replace barrier control systems have proven to be challenging.

In the 1990s, RWS started outsourcing more of its (re)design work, and has since continued this policy (Brink, 2009). The outsourcing policy has reduced the number of knowledgeable engineers directly employed by RWS. RWS still requires procurement process and engineering knowledge to be an effective principal (Vinke, 2013; Walraven, Vrolijk and Kotshuis, 2022). In 2018 a program was started specifically for managing key engineering and operational knowledge of RWS's storm surge barriers.

2. Literature

Managing knowledge for complex, long lived assets has received considerable scholarly attention, especially in the nuclear energy sector, where there are scientific journals dedicated specifically to the subject. The impact of decisions in the design and procurement phase on the knowledge continuity challenge during the life-cycle of the asset has received little attention. The majority of papers take the engineering knowledge to be managed as a given. Boy and Barnard (2019) briefly touch on design choices in their study on knowledge management for safety-critical systems. Reducing knowledge continuity challenges through early design and contracting decisions remains an understudied topic.

Unique and complex storm surge barriers are found challenging to maintain long term (Walraven, Vrolijk, and Kotshuis, 2022). The science of maintainability aims to cover all design aspects affecting maintenance during the life-cycle. Dhillon (1999) offers design principles contributing to maintainability. In Section 5, we examine if these principles contribute to or oppose knowledge continuity.

Ivory, Thwaites and Vaughan (2001) studied the process of designing for maintainability in multiple cases. They found that for good results, the design process must be conceptualized from the beginning to integrate maintainability. Design for maintainability should be supported by data and practical maintenance experience (Dhillon, 1999). This knowledge is generally outside the core competence of the primary contractor and engineering consultant of a project delivery organization, forcing buyers to rethink and adjust their contracting strategy to better facilitate maintainability (Ivory, Thwaites and Vaughan, 2001). In Section 6, we examine key knowledge contributions and flows between partners in two contracting strategies used for storm surge barriers.

3. Method

The research is situated at RWS, in the research group on asset management of storm surge barriers. Work is also physically located in the asset management office for four of the six storm surge barriers. Research data collection is primarily based on interviews with current and former storm surge barrier professionals. Other data sources are public writings on the storm surge barriers and confidential policy- and consultancy documents. For this paper, only public sources are referenced, while the available confidential reports were used for validation through triangulation. Ten initial interviews were held. Participants include storm surge barrier engineering and asset management professionals, an external engineering consultant, a reliability expert and a barrier manager. The participants were selected to cover teams from multiple storm surge barriers, multiple roles, and include both current and retired professionals. The aim was to cover the distinct perspectives. Interview questions centered on current knowledge management practice, knowledge management history and experience with knowledge management challenges. During the interviews, the topic of barrier complexity recurred almost exclusively in relationship to the Maeslant Barrier. To explore this further, an ongoing series of adaptive interviews was conducted focusing specifically on barrier design choices and their effects on barrier complexity. In these complementary interviews, the main topics were complexity in barrier engineering, complexity of barrier control systems, trade-offs in complexity versus simplicity, and the process and history of how these (design) decisions were made. Interviews were recorded by audio recording and transcription or by taking minutes, depending on the preference of the participant. Transcriptions or minutes were then sent to the participant for review and approval.

Interview analyses of both initial and follow-up interviews were done using the Thematic Analysis method (Braun and Clarke, 2021). Atlas.ti was used to code the interviews, and also to facilitate the review of public and confidential reports. Because of the immersive character of the research, any apparent contradictions between interviews or between interviews and documents could be quickly resolved by additional questions to participants or their colleagues at the barrier's office.

4. Controlling the Maeslant Storm Surge Barrier

A storm surge barrier is a very large gate, or set of gates, that can open or close a waterway depending on what hydraulic conditions require. This function by itself does not require a very complex structure. The most common type of storm surge barrier is the lifting gate (Mooyaart and Jonkman, 2017). Lifting gates, as well as the second most common design, segment gates, are 'passive' gates. When open, the gates are above the water and lowered into it to close the waterway. A passive barrier can be closed without an external power source. Lifting gates and segment gates can be closed by force of gravity if electric power fails. The potential to close by force of gravity contributes to the reliability of a storm surge barrier. Although the structures may be very large, expensive, and take a long time to build, the engineering and control systems involved are not overly complicated. All the Dutch storm surge barriers preceding the Maeslant Barrier are of the lifting gate and segment gate types. Ponsioen and Nederend (2023) provide a description of all six RWS storm surge barriers.

The design requirements of the Maeslant Barrier called for a normally open storm surge barrier that posed no height restrictions on shipping, and introduced no obstacles in the shipping lane. Because of these requirements, the Maeslant Barrier needed to be of a different type than the earlier barriers. A design and construct contract was tendered, resulting in the design of the Maeslant Barrier. It is a barrier of the floating sector-gate type, and was chosen from five proposals and a reference design (sliding gates). The working principle of all six designs is depicted in Figure 1. RWS (2012) provides a more detailed description of the Maeslant Barrier's working, engineering, and procurement process.

Because of the importance of the Maeslant Barrier for flood safety, a high reliability target was set. To avoid the possibility of operational mistakes, the barrier was designed to be fully automatic. The design and construct contract featured a maintenance period of five years, starting after completion of its construction in 1997. While RWS was preparing to take over maintenance and design responsibilities of the barrier, it became clear that the automatic closure reliability of the barrier (software reliability) could not yet be accurately assessed. It was also noticed that knowledge continuity of its complex software was going to be a major challenge. The Maeslant Barrier was the first barrier where RWS was not directly participating in the design. Because of this, RWS staff was not immediately familiar with the finer details of the hardware and software. A major improvement effort was started in 2001 to address these issues. A full barrier reliability analysis showed that the probability of failure of the automated control system was a major contributor to not meeting reliability targets for the barrier, but also that it could not be accurately determined (Nieuwenhuizen Wijbenga, 2019). To meet reliability requirements and to bypass potential software failure, a backup procedure of human intervention was instated. Also, a first knowledge management program was started as part of the improvement effort. This involved hiring knowledgeable engineers from the building combination into RWS and establishing a digital knowledge management system. These efforts led to the barrier passing audits in 2007.

Even though it has been established that primary automatic control with a highly trained operational backup team present is sufficient to meet reliability targets, accurately assessing the reliability of automated control of the Maeslant Barrier has remained elusive. To prepare the barrier for the rest of its service life, a new control system was required, but the first two attempts at its development were halted before completion (Nieuwenhuizen Wijbenga, 2019; Osch and Amerongen, 2023). The new control system must have proven reliability, modernized security features, and be more hardware-independent. Being able to provide a direct proof of a new system's reliability is very important. Because the existing system has been proven in use, a new system must be proven at least as reliable without the need for additional maritime-traffic disrupting live-tests. Efforts thus far could not prove reliability improvement beyond doubt.

Difficulties and delays in proving reliability of software systems for hypothetical adverse situations have been common in the Netherlands for other infrastructure as well, and are described for tunnels in Ruland et al. (2012). The long-term maintenance of complex legacy software systems remains a major challenge, and is largely due to inevitable attrition of knowledge during the life cycle (Anquetil et al., 2007). Experience managing its various complex assets has lead RWS to investigate whether some of the software complexity can be avoided through early design choices. Traditionally, early design focusses on the civil and hydraulic engineering aspects of the design, as these influence construction costs the most. Lately however, this view is shifting towards an early involvement of software and control, at both RWS and the major Dutch infrastructure contractors (Rijkswaterstaat, 2019).

5. A Knowledge Continuity View on Storm Surge Barrier Design

Within RWS, many of the challenges with sustaining the control systems and other complex systems in storm surge barriers are attributed to the inability to achieve continuity of designer-level engineering knowledge. The timeframes between initial- and re-design are typically twenty to thirty-five years. During this time, knowledge loss from attrition will affect RWS, as well as the companies that designed and built the structure.

Challenges to knowledge continuity can potentially become a serious impediment to long-term sustainment. Designing systems in such a way that knowledge continuity challenges are reduced, can therefore make a meaningful contribution to the long-term maintainability of a barrier. Major contributors to the challenge of achieving knowledge continuity are the complexity of engineering, the uniqueness of some of the systems and components, long redesign cycles of systems, and high-reliability requirements. With the exclusion of the long redesign cycles, these challenge-driving characteristics can be recognized as being almost direct opposites to the established maintainability principles of simplicity, modularity, standardization, and testability (Dhillon, 1999). Complexity is the opposite of simplicity and modularity. Uniqueness is the opposite of standardization, and reliability requirements preclude most live-testing at the barriers. The long redesign cycles constitute a significant challenge to knowledge continuity, but given the cost of redesigning and updating a barrier, long cycles are desirable from a maintainability perspective.

The effect of simplicity on knowledge continuity is largely self-evident. If a design is easy to understand, less engineering knowledge needs to be passed down through generations of engineers. A modular design has a loose-coupling and clear interfaces between the modules. Therefore any module can be redesigned without having to worry about unforeseen knock-on effects on other parts. This avoids the requirement of a deep understanding of the integral workings of the whole barrier to redesign one module. Standardization means that there are many identical or very similar systems used elsewhere, increasing availability of knowledge. In a testable system, modifications and improvements can be verified before they need to be relied upon.

The Dutch storm surge barriers show significant differences in the knowledge continuity challenge over their life-cycle. The differences in knowledge continuity challenge can be related to the variations in the basic design of the barriers. The following paragraphs will show that when a storm surge barrier features a redundancy at the gate level, a favorable knowledge continuity profile is created. This will be explained in the following paragraphs using the principles of simplicity, standardization, modularity and testability.

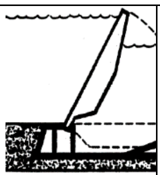
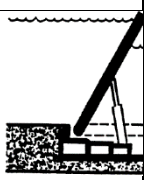
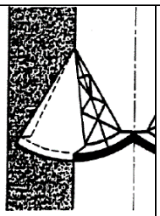
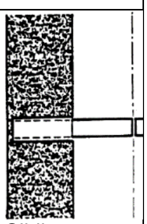
Three of the Dutch storm surge barriers feature redundancy at the gate level. The Eastern Scheldt Barrier has 62 parallel gates. The Haringvliet sluice features 17 parallel openings. The Dutch IJssel Barrier has two gates in series, each fully capable of closing the waterway. Redundancy at the gate level is very beneficial to achieve simplicity of the operating system of the barrier. When one gate fails in a barrier with gate-level redundancy, the other barriers can close in the same way as always. The control system therefore does not need to feature separate provisions for every combination of working and non-working gates. This keeps the control program short and simple.

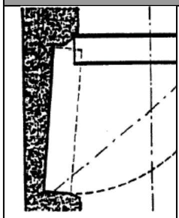
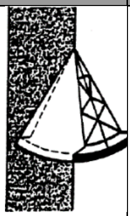
The control system of the Maeslant Barrier has proven to be the most challenging system to sustain in the face of obsolescence. The case of barrier control, where all systems work as intended, is referred to as the ‘happy flow’. Most of the complexity comes from what engineers involved with the barrier call ‘the unhappy flow’ of barrier control, in which the control system has to allow for one or more failed components. The Maeslant Barrier has no redundancy at the gate level, as both gates must close for the barrier to be effective against a storm surge . The barrier does have redundancy at the level of its pumps and valves. This creates a large number of possible partially failed but still operational states to account for in the control system. Allowing operation for a multitude of cases of component failure increases the reliability of the barrier, but also the complexity of the controls. The unhappy flow makes up roughly three quarters of the control program of the Maeslant Barrier. Rewriting the control system to avoid technical obsolescence requires highly case-specific and detailed knowledge of the set of built-in ‘unhappy flows’. It is very challenging to credibly and verifiably prove the reliability of this complex system with limited testability.

When a barrier has redundancy at the gate level, the failure to close one gate does not create a large enough opening to cause flooding. Redundancy of gates creates internal modularity, standardization, and testability. Having multiple identical gates to maintain increases internal opportunities for learning and intergenerational transfer of knowledge during maintenance. This internally re-creates the benefits of standardization, even if the technology used becomes obsolete by outside standards. A barrier with multiple (almost) identical gates is also inherently modular. Each gate is a module, when its operation is independent of the other gates. When one gate fails during a storm closure, the other gates can close the same way as otherwise. Testability is guaranteed because any modification or upgrade can be tested on one gate, and only be applied at the other gates after thorough verification.

As the Maeslant Barrier was the first storm surge barrier that does not feature redundancy at the gate level. It therefore has a less favorable profile for the knowledge continuity-aspect of maintainability. In the selection of the design, general maintainability was nonetheless a major concern. Figure 1 divides the six barrier types of which designs were developed for the Maeslant Barrier into three groups. The basic designs of group 1 offer a simple, modular design with a high number of identical 'valves' or partial gates. Failure of one 'valve' or partial gate does not cause the whole storm closure to fail, providing redundancy at the gate-level. Group 2 offers fixed paths of movement, so relatively simple controls, but no gate-level redundancy. The third group has floating gates which require more complex controls, and also no redundancy. Hydraulic aspects of maintainability are however most favorable for the third group, as these designs are relatively insensitive to silting-up and require little underwater maintenance. The first group is both sensitive to silting and requires underwater maintenance, and the second group once again takes the middle position. It can be seen that avoiding complexity of controls through basic design choices is feasible for the design requirements of the Maeslant Barreir, but comes with important trade-offs in other aspects of maintainability. Participating senior engineers consider simplicity an important concern, but still secondary to other design aspects. Since all height-restriction free barrier types shown in Figure 1 are in use somewhere in the world, there is an important opportunity to record and share sustainment challenges and performance, so all relevant actors can learn more about the development of the relative importance of aspects of maintainability and knowledge continuity. The I-storm network of storm surge barrier managers is a good platform for this.

Table 1:Adapted from (Riteco, 2017)

Design & schematics		Simplicity	Standardization, Modularity & Testability	Other maintainability
Group1: Tumble gates / flap gates.		- Fixed path of movement and independent valves will result in a simple operating system	- Reliable parallel systems (14 and 24 independent gates) - Modifications can be tested on one gate before the others are renovated - Best for standardization, modularity and testability	- Silting up of valves - Underwater maintenance
 Pneumatic tumble gate	 Hydraulic tumble gate			
Group 2: Rolling and sliding gates		- Fixed path of movement and independent valves will result in a simple operating system	- No gate-level redundancy - Modifications need to be applied to the whole barrier at once	- Gates need to plough through sediment deposits
 Rolling sector gate	 Sliding gate			
Group 3: Floating gates		- Process control of gate closure		

Design & schematics		Simplicity	Standardization, Modularity & Testability	Other maintainability
 Barge gate	 Floating sector gate	not easy, especially for barge gate	- No gate-level redundancy - Modifications need to be applied to the whole barrier at once	- Insensitive to silting up - Ease of physical maintenance

6. An Inter-Organization Knowledge-Transfer View on Storm Surge Barrier Design

General knowledge management theory has established that knowledge exchange between departments or organizations working together can be slow and ineffective, see for example Szulanski (1996). Given that knowledge transfers best when people work together, it is possible to consider the effects of different setups for promoting or impeding the flow of knowledge. Figure 2 identifies five knowledge flows related to building a new structure. From 2a to 2b, it is shown which knowledge flows are improved or impeded, switching from a traditional Bid & Build procedure where RWS designed its barriers itself, to the Design & Construct (D&C) contract used for the Maeslant Barrier.

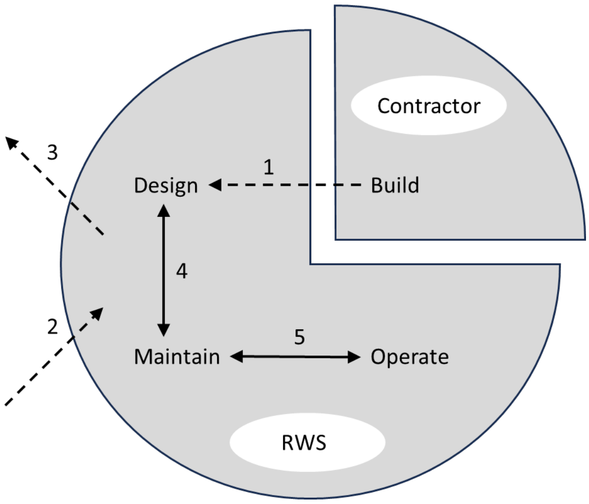


Figure 1: Dutch IJssel Barrier and Haringvliet Sluices (Bid & Build, self-designed and initially self-maintained)

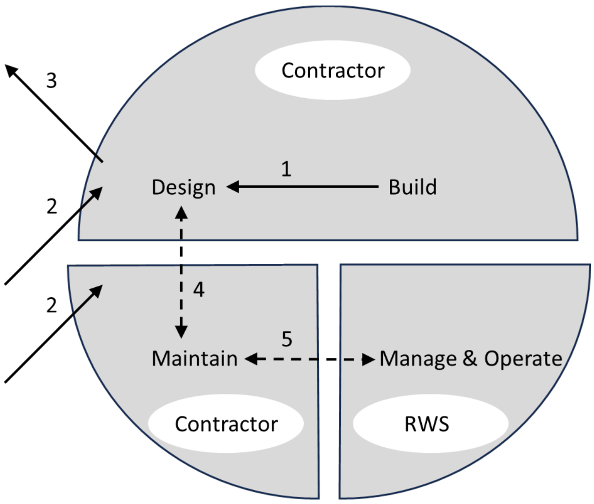


Figure 2: Maeslant Barrier (D&C, outsourced maintenance)

The dashed arrows in Figure 2 represent relatively more difficult, and the solid arrows relatively more effective flows of knowledge. The traditional Bid & Build, self-maintained model in Figure 2a has three dashed arrows. Since RWS designed, maintained, and operated the barriers by itself, there was less room to benefit from knowledge and innovation available from construction companies (Rijkswaterstaat, 2004). This is represented by arrow 1. Private engineering firms had less opportunity to input the latest design knowledge (arrow 2), and there was also less opportunity for re-use of design experience by the market (arrow 3).

Figure 2b represents a D&C contract with an outsourced maintenance model. Design services are provided by market parties (arrow 2). Re-use opportunity of design experience in the market (arrow 3) has arguably improved. Dutch firms that regularly work for RWS also consult for major hydraulic projects around the world, see e.g. Zwaan (2018). For the design of the Maeslant Barrier, RWS was specifically not to interfere with the engineering. This left little room to input its own knowledge regarding barrier maintainability to the design, leaving decades of experience managing the earlier barriers unused (arrow 4). Responding former design engineers and consulting engineers consider limited attention to maintainability in the Maeslant Barrier design as a result of the D&C contract. The contractor had a five-year maintenance obligation, and no further maintainability clauses were part of the D&C requirements. This gave the contractor little incentive to consider the impact of design choices on knowledge continuity as a factor in long-term maintainability. RWS not insisting on having a say in maintainability is also illustrative of a limited focus on maintainability from RWS during its early transition years from leading designer to professional principal. Herd and Pirretti (2022) identify a lessons learned program as a key function of knowledge management in an organization driven by a succession of major engineering projects. It is important for the transition at RWS to continue the development of internal knowledge on maintainability and design for knowledge continuity.

Finally, arrow 5 deals with the knowledge exchange between asset management and the maintenance contractor. Professionals report that detailed access to maintenance information indicating the state of the asset is less accessible compared to when internal technical services provided maintenance to the barriers. As more experience is gained with the new outsourced setup, procedures are being improved, resulting in a better flow of knowledge.

In summary, when developing truly new solutions through a D&C contract, there is a vulnerability to insufficient attention to maintainability, because a D&C contract does not create a shared work environment for those with experiential knowledge of maintainability, and those in charge of the design. The use of integrated contracts for design, therefore, requires extra attention to maintainability in general and those parameters that are crucial to knowledge continuity in particular.

7. Discussion

The benefits of producing goods in high numbers is so well-known nearly everyone has become familiar with the expression 'economics of scale'. Flyvbjerg and Gardner (2023) note that projects in sectors with a high degree of repetition and modularity like solar and windfarms are far less likely to experience considerable cost-overruns. This study sees the benefits of standardization and modularity also applying to the long-term knowledge continuity management of complex assets. What is perhaps most surprising is that these benefits start from very small numbers. Participants from the Dutch IJssel Barrier report few issues, despite it being the oldest barrier. The paper offers an explanation to differences between respondents from different barriers in knowledge continuity challenges reported. The benefits of simplicity, standardization, modularity and testability which are present in the design of the older barriers explain the why less challenges are reported there. When making a design they must however be carefully weighed against other factors. As was seen in the discussion of Figure 1, the designs for the Maeslant Barrier that most allign with the principles of simplicity, standardization, maintainability and testability, had major drawbacks on other aspects of maintainability.

This paper has shown that with regards to knowledge continuity, even within a specific domain like storm surge barrier design and contracting, not all design and contracting methods are created equal, and it is well possible to analyze these for their knowledge continuity profile. This does however not necessarily offer a method for selecting a better design outright, as there are other major factors to consider as well. Its value is in showing how knowledge continuity can be made a key topic from the earliest discussion of design and contracting options.

8. Conclusion

It was shown that engineering complexity in the design and control of a storm surge barrier is a feature that emerges through design choices, but does not result from the design requirements as an absolute necessity. It was also shown that designs featuring redundancy at the gate level, either through parallel partitioning in a relatively large number of gates, or by putting gates in series, create favorable conditions for long-term maintainability and sustainment of function. The design principles are simplicity, modularity, standardization and testability. Achieving a high degree of simplicity requires a favorable 'unhappy flow' of control. Finally, while there are currently a multitude of commissioning or procurement contract types available, none of these are specifically geared toward the long-term sustainment and knowledge continuity of assets. It is, therefore, of vital importance to internally collect experiential knowledge on these topics and make it a consideration in future (re)designs.

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