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CHAPTER 20

Design, maintain and operate movable storm surge barriers for flood risk reduction

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Introduction

After the flood disaster of 1953 in the Netherlands, it was clear that a new form of coastal defense was urgently needed. The Dutch chose to shorten the coastline, whereby part of the coastal inlet was completely closed off with dams and another part was provided with movable storm surge barriers. The so-called Delta Works were implemented, and in a period of about 45 years, six movable barriers were constructed. They were all the first of their kind prototypes of which by now various features have been applied in some form or another in several places around the globe (a.o. Daniel & Paulus, 2019). At multiple locations, possibilities for building a barrier or upgrading an existing barrier are currently being considered to protect coastal areas against storms, sea-level rise, and possible future consequences of climate change. For example, in Rotterdam, the Maeslant barrier faces a range of challenges caused by potential sea-level rise (Deltares, 2019). Similarly, in the Houston Galveston Bay region, shortening of the coastline by means of a Coastal Spine is being considered following Hurricane Ike (2008), and a movable storm surge barrier in the Houston Ship Channel has been included in the preliminary design (USACE & TGLO, 2020).

Over the years, storm surge barriers have proven to incorporate a number of very specific characteristics that have a significant impact on their management, maintenance, and operations (MMO). In the process, many lessons have been learned worldwide about the use of several types of barriers similar to those in the Delta Works, and a number of new designs have also been developed. Sharing these valuable lessons amongst barriers, worldwide, is one of the main aims of the I-STORM* network (I-STORM, 2020).

* I-STORM is the international knowledge-sharing network for all those working in the storm surge barrier profession. See also www.i-storm.org.

When designing a new barrier or modifying existing barriers, incorporating these lessons can be of great advantage for both practitioners and policymakers. By including the (consequences of) specific characteristics of a storm surge barrier in the design and design requirements, a number of undesirable MMO implications can be avoided. Here we first sketch the basics of movable storm surge barriers and provide a general typology. By exploring some of the specific characteristics of these barriers, the implications for MMO are highlighted, offering insights into how they might be addressed in the design along with examples.

Movable storm surge barriers

A storm surge barrier is a movable construction in an estuary or river branch that can be closed temporarily (Mooyaart & Jonkman, 2017). It is designed to protect against extreme water levels caused by storm surges. Its main function during surges is to reduce or prevent the rise of water level behind the barrier and thereby protecting the area at flood risk from inundation. A storm surge barrier is usually part of a more extensive flood protection system (Kuhn, Henao-Fernandez, Batchelor, & Morris, 2020; Walraven & Noguiera, 2018). The barrier takes the first impact of a storm, which ensures that the system behind the construction is less heavily burdened. This minimizes the required standards for flood risk protection measures in the hinterland and thus enables lowering their impact on landscape and environment. During normal daily weather conditions, movable storm surge barriers provide an open connection with the sea to enable shipping traffic to transit, for ecological reasons, and/or to allow river discharge or a gradual spillway to be uninterrupted.

In the process of transition from structural safety to intelligent safety, the variety and types of barriers have become increasingly sophisticated. Increased technological knowledge and possibilities combined with changing contextual requirements have led from human-operated constructions that mainly focused on safely controlling the surge tide, to barriers with all sorts of opening features, often operated with high-tech systems. Fig. 1 shows some exemplary storm surge barriers, with their main typology explained in Table 1 based on:

- *The movement direction:* Barriers can operate either in a horizontal or vertical direction. Horizontal movement, for example, allows a passageway for shipping that is not restricted in height. Vertical movement usually creates less stress on the bank connection; the barrier can be lowered from above the water, or rise from the waterbed.
- *The nature of the hydraulic gates:* A variety of gate types and the way they are in use, and sometimes different concepts are combined within one barrier system. Most frequently used are the vertical lift gate, vertical rising gate, segment gate, rotary segment gate, sector gate, inflatable barrier, flap gate, barge gate, and rolling gate (Dijk & Van der Ziel, 2010; Mooyaart & Jonkman, 2017).



Fig. 1 Overview of exemplary movable Storm Surge Barriers, see typology explained in [Table 1](#). From left to right, top to bottom: 1.01 Haringvliet Barrier, 1.02 Eastern Scheldt Barrier, 1.03 Seabrook Floodgate Complex, 1.04 Moses Lake Floodgate, 1.05 Hartel Barrier, 1.06 Maeslant Barrier, 1.07 Ramspol Barrier, 1.08 Thames Barrier, 1.09 MOSE Barrier, 1.10 Hollandsche IJssel Barrier, 1.11 Barking Creek Barrier, 1.12 Emsspierwerk, 1.13 Singapore Marina Barrage, 1.14 Colne Barrier, 1.15 St. Petersburg Barrier, 1.16 Lake Borgne Surge Barrier. (Image credits: 1.01 Rijkswaterstaat/Joop van Houdt, 1.02 [123RF.com/Andreas Basler](#), 1.03 US Army Corps of Engineers/Patrick M. Quigley, 1.04 Raven Drones/Al Barboza, 1.05 De Fotovlieger/Hans Elbers, 1.06 Rijkswaterstaat, 1.07 [i4photos.nl/Paul Kaandorp](#), 1.08 Environment Agency, 1.09 Consorzio Venezia Nuova/Giorgio Marcoldi, 1.10 Rijkswaterstaat/Joop van Houdt, 1.11 Environment Agency, 1.12 [Bin im Garten](#), CC BY-SA 3.0, 1.13 [123RF.com/Richard Whitcombe](#), 1.14 Steve Brading, 1.15 [AlamyStock Photo/Anton Vaganov](#), 1.16 US Army Corps of Engineers/Patrick M. Quigley.)

Table 1 Movable storm surge barriers typology based on direction of movement and gate type.

Movable storm surge barriers typology—Based on gate type

Direction of movement	Nature of hydraulic gate	Ref. to Fig. 1	Barrier name	Location (country)	Commenced Operation	Maximum sill level (based on local ordinance datum)	Total width of barrier	Number of gates^a
Horizontal	Segment gate	1.06	Maeslant Barrier	Rotterdam region, Netherlands	1997	−56 ft. (−17 m)	1181 ft. (360 m)	2
		1.15	St. Petersburg Barrier (S1)	St. Petersburg, Russia	2011	−52 ft. (−16 m)	656 ft. (200 m)	2
	Segment gate + Barge gate	1.16	Lake Borgne Surge Barrier	New Orleans, USA	2014	−16 ft. (−5 m)	676 ft. (206 m)	3
Vertical	Vertical lift gate	1.02	Eastern Scheldt Barrier	Province of Zeeland, Netherlands	1986	−36 ft. (−11 m)	10,171 ft. (3100 m)	62
		1.05	Hartel Barrier	Rotterdam region, Netherlands	1997	−21 ft. (−6.5 m)	591 ft. (180 m)	2
		1.04	Moses Lake Floodgate	Texas City, USA	1967	−13.4 ft. (−4.1 m)	97.4 ft. (29.7 m)	1
		1.11	Barking Creek Barrier	London, England	1983	−11.8 ft. (−3.6 m)	245 ft. (74.6 m)	4
		1.10	Hollandsche IJssel Barrier	Rotterdam region, Netherlands	1958 + 1975	−21 ft. (−6.5 m)	262 ft. (80 m)	2

Combined	Vertical, moving down + Vertical, moving up Horizontal + Vertical, moving down Horizontal + Vertical, moving down	Radial lift gate	1.01	Haringvliet Barrier	Rotterdam region, Netherlands	1971	−18 ft. (−5.5 m)	3445 ft. (1050 m)	17
		Inflatable dam	1.07	Ramspol Barrier	Lake IJssel region, Netherlands	2002	−15 ft. (−4.7 m)	1148 ft. (350 m)	3
		Rising sector gate	1.08	Thames Barrier	London, England	1982	−40 ft. (−11.3 m)	1706 ft. (520 m)	10
		Flap gate	1.09	MOSE Barrier	Venice, Italy	2020	−46 ft. (−14 m)	5.446 ft. (1660 m)	78
			1.13	Singapore Marina Barrage	Singapore	2008	−8.2 ft. (−2.5 m)	1148 ft. (350 m)	9
			1.12	Emssperrwerk	Gandersum, Germany	2002	−29.6 ft. (−9 m)	1562 ft. (476 m)	5 + 2
			1.03	Seabrook Floodgate Complex	New Orleans, USA	2013	−18 ft. (−5.5 m)	361 ft. (110 m)	2 + 2
			1.14	Colne Barrier	Wivenhoe, England	1993	−7.9 ft. (−2.4 m)	24.6 ft. (max 7.5 m)	2 + 13
				Sluice				427 ft. (130 m)	

^aGates in adjacent ship locks not included (often mitre gates).

Specific characteristics and their implications

One of the most important things to take into account when building or rebuilding movable storm surge barriers is their specific characteristics, as these have a major impact on the MMO of the barrier during its usually intended lifetime. Recognizing and incorporating this aspect could, for example, substantially reduce future maintenance budgets and increase safety and reliability. Nevertheless, awareness of these specific characteristics is often low, as storm surge barriers are managed by organizations that mainly manage standard structures and are set up accordingly. Unique structures, such as barriers, are not part of the standard systems and their specific characteristics then become easily overlooked (Walraven, 2020). Exploring some of the most important characteristics and highlighting their implications for MMO, can increase recognition of this important aspect.

Every storm surge barrier is a prototype

Broadly speaking, each major movable storm surge barrier can be considered a prototype, a unique structure. On the one hand, this is because every barrier system as a whole is unique when looking at the combination of the specific physical environment, specific requirements, and the specific type of barrier. On the other hand, it's because of the unique application of parts: either the use of parts which are custom made—and thus unique per definition—or/and standard parts being used in a nonstandard way—and thus unique in application.

For MMO, the uniqueness of the components and system firstly creates a need for very specific expert knowledge, a high-quality document management system, and an elaborate training program.

Secondly, incorporating unique components in the design means that in MMO many different spare parts have to be available since these parts cannot be bought 'off the shelf.' Thirdly, when 'off the shelf' parts are used differently from what they were designed for, it can cause issues. Water pumps are a common example. They are designed for continuous submerged use, but at barriers, they are mostly used infrequently in an alternating wet and mostly dry environment. This will affect their reliability and maintenance requirements as against what they were originally designed for. Fourth, political decisions on infrastructure usually do not take into account the uniqueness of storm surge barriers; they are focused on the generic situation of common infrastructure such as locks and bridges which occur in much greater numbers than storm surge barriers. Finally, the fact that barriers contain unique components has an impact on the relationship between the designer—often a market party—and the commissioner—often a government agency. These projects are often not very lucrative projects for the market, as design, construction, and MMO cannot rely on cost-saving and knowledge acquired from repetitive production.

Low occurrence of intended functioning under extremely high-reliability requirements

The combination of these two aspects is a specific characteristic for storm surge barriers, with major effects for MMO.

Extreme storm conditions are not regular occurrences. This means that many movable storm surge barriers are not often deployed regularly: usually a few times a year or in some cases, only once every few years. For example, the Ramspol Barrier closes on average 1–3 times per year, whereas the Maeslant Barrier has only operated twice in more than 20 years. The limited use has multiple effects for MMO. Firstly, the low deployment ratio limits the opportunities to gain technical and organizational experience with the barrier. In order to be sufficiently prepared, expertise must thus be obtained through simulated testing and training—also in the event of a malfunction—and by learning from experiences at other barriers. Secondly, the low deployment frequency limits possibilities to find out about unique and specific maintenance problems and the effects of maintenance on specific parts. Finally, the low frequency of intended functioning means that testing the barrier in an integrated manner is limited. When the design offers possibilities to facilitate partial tests and inspections, this can be overcome to some extent.

The reliability of a barrier must comply with legal and policy requirements throughout its entire lifecycle. The extremely high-reliability requirements have to be met in the design phase. However, MMO has to support continued compliance with these initial and/or future requirements. Firstly, a fault-tree analysis is often performed to show that the reliability requirements are met. However, it is often only used in the design and construction phase. Adjusting this approach so that it can also be used in the MMO phase is necessary because in practice you may not be able to ‘measure’ that the requirements are met if you have a low deployment frequency. A fault-tree analysis for MMO would make it possible to check whether requirements are being met during the entire lifecycle of the barrier. Secondly, more redundancy measures can support MMO to maintain resilient systems which provide high reliability. Design can support this, for example, by not allowing ‘Single Points of Failure’ or introducing some over dimensioning.

However, the reliable functioning of the barrier not only depends on its technical function reliability but also on the reliability of the operational team. This team must have appropriate knowledge and experience in order to monitor and manage (and if necessary: intervene in) the closure process in a storm call. This human factor should also be implemented in the fault-tree analysis. Usually, this kind of analysis only considers technical failure aspects; yet, humans can on the one hand correct technical failure (which adds to system reliability) but can on the other hand also make mistakes in maintenance or in operation (which makes the system less reliable).

Maintenance windows are limited

In the Netherlands, the maintenance cycle of a barrier must be adjusted accordingly to the storm season, placing high demands and constraints on maintenance planning. The availability of so-called ‘safe weather windows’ strongly affects MMO.

Firstly, under the impact of changing climate, the number of closures will rise and during those operations, no (major) maintenance is allowed for the Dutch barriers. Where historically the maintenance cycle was mostly related to the storm seasons, MMO is currently also looking into shorter predictable ‘safe weather windows’ in the storm season to be used for maintenance work. Secondly, maintenance that is not or difficult to divide into parts, requires a continuous and often long maintenance period. This might mean that including multiple smaller gates in a design could prevail over implementing one or two large gates. Thirdly, maintenance could be made more independent from the weather, for instance, by applying the ‘push-through principle’: replace a part, maintain extracted part, use it to replace next one, then maintain it, etc. This needs to be facilitated by design using interchangeable elements. In the Eastern Scheldt barrier, for example, this kind of maintenance is impossible because almost every lift gate has a different dimension/size; in the design of the MOSE barrier in Venice, it has been an extensive point of attention. Fourthly, enabling maintenance within a shorter time frame could be achieved by facilitating easier maintenance by design.

Static structure in a dynamic environment

Changes in the environment of a storm surge barrier strongly impact MMO. Based on empirical evidence, five categories of changes create a workable base for an inventory of these implications (Walraven, 2020) (see Table 2):

- Politics, policy, law, and regulation changes
- Organizational and process changes
- Technological changes and innovation
- Knowledge and craftsmanship changes
- Physical environment changes

Major movable storm surge barriers in the Netherlands are designed and built for a life span of about 100 years. During this period many changes take place in the organization, technique, law, society, physical environment, safety, etc. Barriers are mostly not, or only to a very limited extent, designed to adapt to these dynamics, which often involve multiple future implications for MMO. A changing organizational context, for example, more stringent environmental impact rules and regulations, means that maintenance asks for situational adjustment, and additional work is required due to the need to renew (maintenance) equipment that is still good in itself. However, by creating flexibility and adaptability in both construction and organizational design, a workable degree of agility could be obtained. In the sphere of changing political and societal demands, an

Table 2 Dynamic environment of storm surge barriers.

Type of dynamic environment	Example of dynamics
Politics, policy, law and regulation changes	<ul style="list-style-type: none"> • Shift from mainly focus on managing flood risk to also include attention to environmental aspects. • Awareness of the need for flood safety measures decreases the longer no flood disasters occur; this leads to paradoxical feature: high flood safety level because of high flood risk means less attention and thus (political) support for flood risk reduction measures.
Organizational and process changes	<ul style="list-style-type: none"> • Changing relationship between market and government. Shift from ‘all technical knowledge in-house at government level’ to ‘obtaining technical knowledge from market parties’ to ‘part of the technical knowledge in-house and partly from the market’.
Technological changes and innovation	<ul style="list-style-type: none"> • Application of new types of materials and new design processes. For example, hydraulic laboratories used to be built and operated manually (e.g., the Mississippi River Model in Vicksburg; and Waterloopkundig Laboratory in Flevopolder) and are now built and operated mainly by computerized systems (e.g., the Lower Mississippi River Physical Model at LSU Baton Rouge, LA; and the Delta Flume at Deltares in Delft). • Shift from structural safety (on construction and material knowledge basis) to intelligent safety (including probabilistic knowledge), driven by the development of ICT technology. • New potential threats and needs for security: e.g., cyber security.
Knowledge and craftsmanship changes	<ul style="list-style-type: none"> • Additional requirements, for example resulting from the demand for multifunctionality, require additional and different types of knowledge. • In the Netherlands, many barriers were built after the 1953 disaster, a strong new knowledge impulse. The level of safety became so high, that for decades no new barriers have been built: knowledge and (human) knowledge carriers become obsolete or even disappear.
Physical environment changes	<ul style="list-style-type: none"> • Sea level rise, climate change, higher/lower levels of river discharge • Increasing amount of shipping, for example resulting in a higher chance of colliding with a storm surge barrier.

increasing amount of (potential) additional functions is becoming relevant, mostly related to creating economic, recreational, ecological, or sustainable energy benefits. Think of additional design to enable fish migration (e.g., at the Haringvliet Barrier) or to incorporate turbines to generate energy from tidal motion (e.g., at the Eastern Scheldt Barrier). For MMO, this means for the first case monitoring and maintaining an extra opening in

the barrier and in the second case dependency on a third party that builds and operates the turbines. Regarding changes in knowledge and craftsmanship, it is important to secure existing knowledge. Therefore, a 'Knowledge strategy for storm surge barriers' was developed, sparking renewed focus on mastering and maintaining design knowledge and knowledge of basic principles, which is crucial for carrying out improvements or replacements.

How reasoned design could enable more efficient MMO: Three cases

The specific characteristics of storm surge barriers and their implications for MMO, could (partly) be met in reasoned design. Three cases are presented as indicative examples. We thus intend to show the relevance of design based on the specific characteristics of movable storm surge barriers and their MMO and the importance of further developing this knowledge field.

Maeslant Barrier: Replacing compression blocks

The Maeslant Barrier is the barrier with the biggest sector gate in the world, protecting the port and city of Rotterdam and its hinterland. Many components of a storm surge barrier need to be replaced sometime during their 100-year service life. These are often significant and complicated projects that (partly) could have been avoided by design. At the Maeslant barrier, the compression blocks under the gate are a good example (Figs. 2 and 3).

In the dock, the barrier rests on a structure providing some elasticity because some deformation has to be handled: rubber packages with steel plates resting on a very large concrete pole. These spring packages will need to be replaced in the coming years, yet they are under the gate and, in normal circumstances, underwater. In terms of design and construction, that was easy: build the poles, put the rubber on top, and put the gate on top. But now the rubber has to be replaced, there is a gate on top of it. And, if one concrete upstand with its spring package is removed, the gate will probably deform as a result of the excess load. However, when the barrier was designed and built, it could have been taken into account to add one extra pole. Then one pole could always be removed, upgraded, or renewed, and put back, without damaging the gate.

The maintenance complications of the compression blocks also have to do with a limited maintenance window. Maintenance of all compression blocks at once is such a major activity that it can hardly be done over one summer season. However, the design of the barrier was optimized for construction and not for MMO within a predictable safe weather window. If barrier design is considered a structure that enables splitting maintenance jobs in smaller portions of a maximum of 2–3 weeks, this kind of major maintenance could be executed, both within and outside of the storm season.



Fig. 2 Compression blocks under the gate at Maeslant Barrier. (Image: Courtesy of Rijkswaterstaat.)



Fig. 3 Maintenance work at Maeslant Barrier. (Image: Courtesy of Rijkswaterstaat.)

Ramspol Barrier: A corroded nut

The Ramspol Barrier is an inflatable flexible membrane dam or ‘rubber dam’ in the IJssel River system in the east of the Netherlands. During the storm season, after running a test function, one of the large water inlet valves did not open. This is part of the primary system to fill the rubber tube, without an open valve gate there is no functioning barrier. A costly, complicated procedure was followed to find out what was wrong. The 900+ kg valve had to be removed and disassembled; this involved a large, over 24-h underwater operation involving divers, expanding the valve casing, and installing extra pumps in case of leakage (Fig. 4). After disassembly, it appeared that the nut that attached the valve blade to the spindle was severely corroded. This caused a rupture, causing the blade to jam and stay shut. A new nut was not “on the shelf” because of its irregular size, and had to be custom made. The corrosion was most likely caused by the alternating wet/dry environment while the valve (a standard element from the drinking water industry) was designed for underwater use in a continuously filled pipe.



Fig. 4 Expanding the valve casing at Ramspol Barrier. (Image: Courtesy of Rijkswaterstaat, Tycho Busnach.)



Fig. 5 Corroded and broken nut at Ramspol Barrier. (Image: Courtesy of Rijkswaterstaat, Tycho Busnach.)

- This case highlights a few examples of some MMO issues in the context of design:
 - Why use a valve that shuts in case of a problem? This turned out to be the standard construction. However, for this barrier function and reliability, it would have been better to choose a valve that opens as standard.
 - The design includes two tubes with a diameter of D800. Standard is D600, therefore this valve was not easily available. Why not design three tubes of D600, so replacement pipes and valves are available off the shelf?
 - Ramspol has six of these valves, of which most showed severe stages of the corrosion process (e.g., Fig. 4). All nuts had to be replaced and an inspection strategy needed to be developed. A huge extra MMO cost in man-hours and material: valve inspections alone cost €20,000 at a time, and the extra material costs more than a quarter of the usual annual maintenance budget.
- A clear example of two characteristics: at a barrier, many components are not used in a standard fashion and the need for a reasoned choice between unique or custom-made components. None of this is a problem in the construction process, it shows only later during MMO (Fig. 5).

Bolivar Roads barrier: Preliminary design

In the Houston Galveston Region, the Coastal Texas Study, a plan to protect the Texas Coast from flooding, is currently underway (www.coastalstudy.texas.gov). One of the elements of the plan is the construction of a so-called ‘coastal spine’ along Galveston Bay (see also chapters by Merrell and by Jonkman; this volume). A storm surge barrier in the Bolivar Roads is an essential part of this spine, and it presents a major design challenge to meet the many design and environmental requirements. USACE Galveston held the world’s first international design session under the umbrella of I-STORM to gather input for the preliminary design of this storm surge barrier in the Bolivar Roads. This exercise is the ultimate example of a modern approach: a wide spectrum of facets is taken

into account from the outset, of course, the technical and hydraulic for the construction phase, but also their possible effects on MMO. The workshop identified several aspects that (might) have an impact on future MMO, which now are taken into account by introducing them as early as this design phase:

- Redundancy in the design in order to increase reliability;
- Collision risks;
- Accessibility of various locations on and around the storm surge barrier in case of unforeseen circumstances during the closure process, but also for management and maintenance activities;
- The type of organization that needs to be prepared and trained, and to build up knowledge and experience to perform the reliable maintenance and increase the likelihood of successful closure.

Interestingly enough, the effort also yields new knowledge for other parties working in the practice of design and MMO of flood defenses. For example, a design issue about bed protection for the proposed barrier at Bolivar Roads led to a request to Rijkswaterstaat for input as they had many years of this system working in practice. An internal design session was organized locally in the Netherlands, during which Rijkswaterstaat shared their knowledge and operational experience of bed protection and MMO strategies of their own Dutch storm surge barriers. This information exchange, reviewing the proposed potential design strategies for the barrier in Galveston, greatly assisted the designers in the United States.

Preparing feedback on the preliminary design for the Bolivar Roads barrier also led to the securing of original design knowledge within RWS that had become somewhat ‘out of sight’ because no designs have been made for more than 20 years and many experienced designers have retired. One of the designers of the Maeslant Barrier still works at RWS, so the original designs of the Maeslant Barrier were found, and his tacit and personal knowledge about them was shared before comparing this with the draft designs of the Bolivar Roads barrier. This provided new opportunities for design and MMO not only for Galveston but also for the Netherlands: the requests for knowledge from Galveston allowed Rijkswaterstaat to dust off ‘old’ knowledge, actively share it, and secure it more broadly which benefited their own organization.

Conclusions

It is important to keep in mind when it comes to the design or redesign of movable storm surge barriers many design choices will have a major impact on MMO. Reasoning from the specific characteristics of these flood defenses, and based on the lessons learned from existing barriers, these implications and potential negative impact can be (partly) anticipated, reduced, and often even prevented.

However, both awareness of these characteristics and knowledge of their impact are currently limited. Most recent publications and research related to the design of storm surge barriers have either a technological character or a financial-economic approach (a.o. Dijk & Van der Ziel, 2010; Aerts, Bowman, Botzen, & de Moel, 2013a, 2013b; Mooyaart, Jonkman, De Vries, Van der Toorn, & Van Ledden, 2014; Mooyaart & Jonkman, 2017; Walraven & Noguiera, 2018; Davlasheridze et al., 2019; Daniel & Paulus, 2019; Kluijver, Dols, Jonkman, & Mooyaart, 2019). Although technological knowledge and financial-economic insights are essential for the design and adaptation of storm surge barriers, practitioners insist that knowledge of MMO aspects is at least equally as vital in this respect. Acknowledging that the most important asset in an asset management system such as a storm surge barrier is the people working on it (Kuhn et al., 2020), we recommend further research for expanding knowledge based on retrieval of empirical findings worldwide. Retrieving and translating these experiences into lessons learned to be implemented in new designs or when modifying current flood defenses, can be done in the global context of I-STORM, collaborating with various government agencies, contractors, and universities. Apart from further expanding on the specific characteristics of movable storm surge barriers, some relevant research topics to consider are

- Automated versus manual: The role of humans in the fulfillment of requirements for storm surge barriers, what is the optimum ratio ‘human/automated’ MMO, and how to achieve this?
- Maintenance by design: How to give maintenance and asset management of storm surge barriers the most effective and efficient place in the design and planning process?
- Innovation versus proven technology: Incorporating innovative components and processes, which are lessons learned for storm surge barrier design and MMO? How can the market be incentivized to invest beyond proven technology for one-time-only designs?
- Organizational stability in a changing environment: How to guarantee the continuity and steadiness of MMO of a storm surge barrier in changing circumstances?
- Knowledge and expertise: How to ensure that design principles and technical decisions are transferred over time as a basis for future adjustments and updates?

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