Flood Risk And Economically Optimal Safety Targets For Coastal Flood Defense Systems

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ABSTRACT: A front defense can improve the reliability of a rear defense in a coastal flood defense system. The influence of this interdependency on the accompanying economically optimal safety targets of both front and rear defense is investigated. The results preliminary suggest that the optimal safety level of a coastal flood defense system can only be improved with a combination of front and rear defense if for a similar risk reduction, the front defense investment is cheaper than the rear defense. If a case needs a more complex risk and economic optimization model, the simplified approach is no longer applicable and a computational framework is recommended. Nevertheless, the simplified approach offers a fast, first order assessment of the economically optimal safety targets for coastal flood defense systems.

1. INTRODUCTION

Coastal flood defense systems can consist of a combination of defenses, sometimes even with multiple lines of defense. A typical combination, often found in estuaries, is that of a barrier separating a large water body (front defense) and levees surrounding the large water body (rear defense). Examples of this type of coastal flood defense system can be found in Lake IJssel and the Eastern Scheldt in the Netherlands, and in Neva Bay, close to Saint Petersburg in Russia.

A common type of interdependence is that the reliability of the rear defense depends on the reliability of the front defense. For example, a working front defense can reduce surge levels at the rear defense, leading to an improved reliability of the rear defense. Because flood risk is tightly coupled to the economic optimization, this leads to possibly differing optimal safety targets. Therefore, interdependence can be an important factor (a) in analyzing the flood risk of the protected area and (b) in establishing optimal safety targets for newly built flood defenses in such systems.

To the best of our knowledge, a generic method that describes the effect of interdependencies on economic optimal safety targets for coastal flood defense systems has not yet been presented. A promising case study using detailed numeric computations was done in Zwaneveld and Verweij (2014a). However, Zwaneveld and Verweij (2014a) focused on results for the Lake IJssel case: it is unclear if the methods used by Zwaneveld and Verweij (2014a) are generically applicable. On the other hand, simplified cases with multiple layers of defense are described in Vrijling (2013), but these focus on the ‘multi-layer safety’ concept and do not cover our definition of a coastal flood defense system.

The aim of this study is to assess the influence of interdependencies in a coastal flood defense system on the accompanying economically optimal safety targets. A simplified coastal system, similar to the characteristic cases in Vrijling (2013), is used to describe the characteristics of this system. These characteristics are then used to provide the contours of the optimal solution.
Furthermore, the Galveston Bay near Houston is contemplated as input for an example application. The Galveston Bay area has millions of people living in the region and represents a large economic value. It does not yet have an integral flood defense system, but the feasibility of such a system is being investigated because it is situated in a hurricane prone area (e.g. see Bedient and Blackburn (2012)).

Finally, the limits of the simplified approach for more complex case studies is discussed. To that end, we contemplate a more comprehensive numeric probabilistic risk analysis and optimization framework in the spirit of Courage et al. (2013); Zwaneveld and Verweij (2014a), which is able to cope with a more detailed model than the previous simplified coastal system.

2. OPTIMIZATION OF A SIMPLIFIED COASTAL FLOOD DEFENSE SYSTEM

The effect of reliability interdependency between front and rear defense on the flood risk and economically optimal safety targets is investigated by means of simplified model (Figure 1).

![Figure 1: Simplified cross section of a front defense (B) and rear defense (A).](image)

2.1. Risk and annual costs

Assuming that the two flood defenses in Figure 1 have two states each (failure or non-failure), a total of four \(2^2\) system states are possible. In Vrouwenvelder (2014), a mathematical representation of Figure 1 is given. The main assumption in this representation is that flooding of the hinterland can only occur if the rear defense fails, which means that the system states where the rear defense does not fail can be ignored as contributions to the flood risk. This means that the annual system failure probability \(P_{sys}\) is a summation of the two remaining system states:

\[
P_{sys} = P_{A \cap B} + P_{A' \cap B'}
\]

where \(P_{A \cap B}\) is the state where both the front and rear defenses fail, and \(P_{A' \cap B'}\) where just the rear defense fails.\(^1\)

Reformulating Eq. 1 in terms of conditional probabilities instead of intersections results in Eq. 2. This notation is favorable as all terms can be related to physical states of the system.

\[
P_{sys} = P_B P_{A|B} + P_{B'} P_{A|B'}
\]

2.2. Economic optimization characteristics

The optimal safety level is determined by minimizing the total costs in Eq. 4 (analogue to e.g. van Dantzig (1956); Eijgenraam (2006); Vrijling (2013)). Effectively, the optimal point on the total cost curve denotes that a further increase in safety level is more expensive than the reduction in risk costs.

\[
C_{risk} = P_B P_{A|B} D_{A \cap B} + P_{B'} P_{A|B'} D_{A' \cap B'}
\]

\[
TC = C_A + C_B + PV(C_{risk})
\]

2.2.1. Optimization principles and assumptions

For this paper, the flood damage in Eq. 3 will be solely based on economic damages, excluding loss of life and accompanying concepts such as individual risk and societal risk. In a complete risk evaluation these concepts should be included, as done in for example Jongejan et al. (2013), but are considered out of scope for this paper. An overview of

\(^1\)The used notation of annual failure probabilities was chosen for brevity. A more correct notation of, for example, \(P_{A \cap B}\) would be \(P(F_A \cap F_B)\).
risk acceptance measures can be found for example in Jonkman et al. (2003).

The determination of both repeated investments (their size and the duration between investments) and the timing of the initial investment is left out in this paper. The timing of the investments could also be a part of the optimization process, for example see Eijgenraam (2006), but are left out by excluding time dependent processes such as sea level rise or economic growth. It is assumed that the initial investment is done immediately at the start of the strengthening project, and only the size of that initial investment is determined. These assumptions simplify the present value calculations, as only the annual flood risk needs to be discounted. The present value of a annual flood risk \( P_{sys} \) with a discount rate \( r \) (positive and larger than zero) over an infinite time horizon is a geometric sequence, which converges to \( P_{sys} D \); see also for example van Dantzig (1956).

### 2.2.2. Investment, failure probability and damage

The investment, failure probability and damage relations in Eq. 3 & 4 need to be specified in order to make a non-trivial optimization of the system described in Figure 1.

First, the annual failure probabilities in Eq. 2 are simplified from annual probability of exceedance of safety level to annual exceedance of crest level \( h_i \), making the simplifying assumption that overflow/overtopping is the dominant failure mechanism (analogue to van Dantzig (1956); Eijgenraam (2006) and specifically Vrijling (2013)). Furthermore, we assume the annual extreme water level to follow an exponential distribution with parameters \( \alpha_j \geq 0 \) and \( \beta_j > 0 \):

\[
P_j = 1 - F(h_i) = e^{-\frac{h_i - \alpha_j}{\beta_j}},
\]

where subscript \( i \) is either \( A \) or \( B \), which is the flood defense in question. Subscript \( j \) belongs to the physical system state; this relates to a specific annual failure probability distribution. Specifically, flood defense \( A \) can be associated with the system states \( A \) (rear defense with no front defense), \( A \cap B \) (rear defense with functioning front defense), or \( A \cap \bar{B} \) (rear defense with functioning front defense). Contrary to this, flood defense \( B \) can only be associated with system state \( B \).

Second, the investment relations (\( C_A \) and \( C_B \)) are also chosen similarly to for example van Dantzig (1956); Vrijling (2013) and assumed to be a linear function dependent of the crest level:

\[
C_i = C_{f,i} + C_{v,i} h_i \tag{6}
\]

where subscript \( i \) is either \( A \) or \( B \), which relates to the flood defense in question. Furthermore, \( C_{f,i} \) and \( C_{v,i} \) (both assumed \( > 0 \)) are consecutively the fixed and variable cost necessary to strengthen flood defense \( i \) to height \( h_i \).

By rewriting Eq. 5 in terms of \( h_i \), Eq. 5 can be substituted in Eq. 6. However, this is only straightforward in case the subscripts \( i \) and \( j \) match, which is only true for flood defense \( B \). Substituting these investment costs definitions in Eq. 4, leads to the following expanded total cost definition:

\[
TC = C_{f,A} + C_{v,A} h_A + C_{f,B} + C_{v,B} (\alpha_B - \beta_B \ln(P_B)) + PV(C_{risk}) \tag{7}
\]

What remains are definitions for the flood damages \( D_{B \cap A} \) and \( D_{B \cap \bar{A}} \) of Eq. 3. These are assumed to be constant and equal for each outcome, i.e. \( D_{B \cap A} = D_{B \cap \bar{A}} = D \). These assumptions, and including discount rate \( r \) as mentioned in Section 2.2.1, lead to an updated definition of the total risk costs:

\[
PV(C_{risk}) = (P_B P_{A|B} + P_{\bar{B}} P_{A|\bar{B}}) \frac{D}{r} \tag{8}
\]

### 2.3. Interdependency front and rear defense

Eq. 7 & 8 contain conditional probabilities, which represent the interdependencies between the front and rear defense. The front defense is assumed to have a positive influence on the unconditional failure probability distribution of the rear defense (\( P_A \)). Conceptually, the extent of this positive influence is assumed to be a function dependent on the front defense reliability. Using the conditional annual failure probability \( P_{A|\bar{B}} \) as an example, this can be written down as

\[
P_{A|\bar{B}} = f_{rel}(P_B) \cdot P_A, \tag{9}
\]
where the upper limit of a conditional failure probability would then be its unconditional failure probability \( f_{\text{red}}(P_B) = 1 \). In theory, the lower limit of \( f_{\text{red}}(P_B) \) is zero, which also implies \( P_{A|B} = 0 \). However, that would practically lead to no water (threat) between the two defenses in Figure 1. Therefore, it is assumed that the failure probability of the rear defense cannot be reduced to zero; instead, the maximum reduction is assumed to be \( n \). An example of such a conceptual relation describing \( f_{\text{red}}(P_B) \) could be a polynomial such as \( n + (1 - n)P_B^2 \). For small values of \( P_B \), \( f_{\text{red}}(P_B) \) can be approximated with the constant lower bound reduction \( n \).

### 2.3.1. Risk reduction rear defense for a non-failing front defense

A conservative assumption would be to assume that only in the case of a non-failing front defense, the performance of the rear defense can improve. Using the assumption of a constant reduction factor \( n \), and only applying it to the conditional failure probability \( P_{A|B} \), changes Eq. 8 to Eq. 10. Eq. 10 is rewritten into Eq. 11 using \( P_B = 1 - P_B \).

\[
PV(C_{\text{risk}}) = (P_B P_A + P_B n P_A) \frac{D}{r} \quad (10)
\]

\[
PV(C_{\text{risk}}) = (P_B P_A + (1 - P_B) n P_A) \frac{D}{r} \quad (11)
\]

The reduction factor \( n \) has a lower limit of zero and an upper limit of one. For the upper limit of one, Eq. 11 reduces to \( \sum C_{\text{risk}} = P_A \frac{D}{r} \). Since the upper limit of one implies no reduction even with a working front defense, the front defense does not contribute to flood protection and falls out of the equation. This also has implications for the optimization: because if the front defense has no effect, the optimization reduces to an optimization of a single layer of defense.

The (theoretical) lower limit of zero indicates that with a working front defense, the rear defense has a failure probability of zero. This effectively reduces the risk equation to only contain the system state where both front and rear defenses fail. This case was investigated in Vrijling (2013) as ‘a two layer system’, and the optimal solution was found to only invest in the defense that has the lowest variable cost.

### 2.3.2. Risk reduction rear defense for both a failing and non-failing front defense

It is conceivable that even if a front defense fails, the remnants of the front defense might still have a positive influence. This reduction can be added in the same way as in the previous section, and is called \( m \). However, we assume that a failed front defense is less effective at reducing failure probabilities than a non-failing front defense; this implies that reduction \( m \) has to be greater than \( n \). The upper bound is of \( m \) is one, just like \( n \). This expands Eq. 11 to:

\[
PV(C_{\text{risk}}) = (P_B m P_A + (1 - P_B) n P_A) \frac{D}{r} \quad (12)
\]

### 2.4. Economic optimization

The total costs of Eq. 7 with the \( PV(C_{\text{risk}}) \) definition of Eq. 12, has three variables that need to be optimized: \( P_B \), \( P_A \) and \( h_A \). Eq. 5 is used to substitute \( P_A \), which reduces the number of optimization variables to \( P_B \) and \( h_A \). The optimum of Eq. 7 can be found by finding the partial derivatives \( \frac{\partial}{\partial h_A} TC \) and \( \frac{\partial}{\partial P_B} TC \). Equating these partial derivatives to zero leads to two expressions for optimal values of \( h_A \) and \( P_B \). The formulation for \( P_B \) is shown in Eq. 13.

\[
\frac{\partial}{\partial h_A} TC = 0 \rightarrow \hat{h}_A = \frac{C_{v,B} \beta_B r}{e^{-\frac{h_A - \alpha_A}{h_A}} D (m-n)} \quad (13)
\]

Because the constant reductions \( m \) and \( n \) both use the unaltered distribution parameters of \( P_A \), optimal height \( \hat{h}_A \) can immediately be substituted in Eq. 5, resulting in an optimal annual system failure probability \( \hat{p}_{\text{sys}} \), as shown in Eq. 14.

\[
\frac{\partial}{\partial h_A} TC = 0 \rightarrow \hat{h}_A \rightarrow \hat{p}_{\text{sys}} = e^{-\frac{\hat{h}_A - \alpha_A}{h_A}} \frac{C_{v,A} \beta_A r}{D (\hat{P}_B (m-n) + n)} \quad (14)
\]

The optimal solution for a single layer of defense, as mentioned in for example Vrijling (2013), is \( \hat{P}_{A,\text{single}} = \frac{C_{v,A} \beta_A r}{D} \). Eq. 14 reduces to \( \hat{P}_{A,\text{single}} \) in case \( m = n = 1 \); this agrees with the earlier statement made in Section 2.3.1.
Eq. 13 & 14 are dependent on each other. It is possible to remove this dependency by substituting Eq. 13 in Eq. 14 and vice versa:

\[ \hat{P}_B = \frac{1}{(m - n - 1) \left( \frac{\beta_A C_{v,A}}{B_{Cv,B}} - 1 \right)} \]

\[ \hat{P}_{sys} = \frac{(\beta_A C_{v,A} - \beta_B C_{v,B}) r}{nD} \tag{16} \]

2.5. Limits of the optimal safety targets

Because of the substitutions made in Eq. 15 & 16, additional bounds are in effect. The first bound follows directly from Eq. 15 & 16: \( \hat{P}_B \) and \( \hat{P}_{sys} \) both need to larger than zero, which implies that \( \beta_A C_{v,A} > \beta_B C_{v,B} \). This can be explained as requiring that, for a similar risk reduction, the front defense investment needs to be cheaper than the rear defense. Failing to fulfill this requirement indicates that the combination of front and rear defense is less effective than a single rear flood defense.

A second requirement can be found in Eq. 13 by stating that \( \hat{P}_{sys} \leq 1 \). Rewriting this leads a requirement for \( \hat{P}_B \): \( \hat{P}_B \geq \frac{\hat{P}_{A\text{-single}} - n}{m - n} \). This lower limit for \( \hat{P}_B \) can be used in setting both the upper and lower limits of Eq. 15. The found lower limit is combined with an upper limit of 1, and can be rewritten into an upper and lower limit for \( n \):

\[ \hat{P}_{A\text{-single}} \left( 1 - \frac{C_B \beta_B}{C_A \beta_A} \right) \leq n \leq m \left( 1 - \frac{C_B \beta_B}{C_A \beta_A} \right) \tag{17} \]

Substituting consecutively the lower and upper bound of Eq. 17 back in Eq. 16 for \( n \), leads to \( \hat{P}_{sys} = 1 \) and \( \hat{P}_{sys} = \frac{1}{m} \hat{P}_{A\text{-single}} \). The former is a trivial consequence of the lower limit for \( \hat{P}_B \), which was found by setting the upper limit of \( \hat{P}_{sys} \) to one. The latter is again a confirmation that when \( \hat{P}_B = 1 \), \( \hat{P}_{sys} \) reduces to \( \hat{P}_{A\text{-single}} \), even though \( m \) is still in the equation, in this case \( m \) is most likely equal to one.

Finally, another upper limit for \( \hat{P}_B \) originates from choosing constant reduction factors, instead of reductions dependent on the reliability of the front defense. As mentioned in Section 2.3, this means the formulations in Eq. 15 & 16 are only accurate when the reduction relation is approximately constant.

2.6. Behavior of the optimal safety targets

The optimal value \( \hat{P}_B \) in Eq. 15 is only dependent on the fractions \( \frac{m}{n} \) and \( \frac{\beta_A C_{v,A}}{\beta_B C_{v,B}} \). If the value of \( \beta_A C_{v,A} \) and/or \( \frac{m}{n} \) increases, \( \hat{P}_B \) will become smaller and \( \hat{P}_{sys} \) will be larger.

A smaller value for \( \frac{\beta_A C_{v,A}}{\beta_B C_{v,B}} \) implies a larger \( \hat{P}_B \) and a smaller \( \hat{P}_{sys} \). However, although a small value for \( \frac{m}{n} \) does imply a large value for \( \hat{P}_B \), it does not give information regarding the response of \( \hat{P}_{sys} \): a small value of \( \frac{m}{n} \) can be obtained as long as \( m \) and \( n \) are approximately in the same order. This means \( n \) can be either small or large, which consecutively leads to \( \hat{P}_{sys} \) becoming either larger or smaller.

3. CASE STUDY: HOUSTON, TEXAS

In this section, an application is shown of the simple approach in Section 2. The input will be provided by work from a real, ongoing case study in Houston, Texas. However, the fundamental schematization in Section 2 is over-simplified for this case study; therefore the results found in this section are purely for illustration purposes.

3.1. Area of interest

The area of interest is the Galveston Bay area near Houston, Texas, which consists of a large bay with barrier islands; see also Figure 2. The Galveston Bay area has millions of people living in the region and represents a large economic value. It does not yet have an integral flood defense system, but the feasibility is being investigated because it is situated in a hurricane prone area (e.g., see Bedient and Blackburn (2012)).

In order to apply the model in Section 2, fictive defenses are placed in line with the barrier island (front defense) and near Eagles Point in Figure 2 (rear defense). This rear defense will protect an economic value which protects a first order approximation of the entire bay area economic value. Even though the economic value on the barrier islands is significant, it is ignored in this application.

3.2. Risk modeling

Of primary interest is the response of the water levels inside the bay, with respect to the fictional front defense. For this purpose, the bay area uses the
conceptual hydraulic model as proposed in Stoeten (2013). This hydraulic model simulates the hurricane surge and wind setup inside the bay. A front defense can influence the surge by reducing the inflow into the bay. In case of a failing front defense, no reduction is applied ($m = 1$).

In addition to the surge and wind setup calculated by the model of Stoeten (2013), significant wave heights at key points inside the bay are calculated according to Breugem and Holthuijsen (2007). Finally, the surge levels and wave heights inside the bay are combined into annual water level exceedance probabilities, assuming earthen levees with a 1:6 front slope for the rear defense (only accounting for overflow/overtopping), and calculated by means of Monte Carlo simulations.

Figure 3 shows results for Monte Carlo simulations with each $5 \times 10^4$ runs. In this figure are four graphs, and shows the outside water level and three situations inside the bay: no barrier ($P_B = 1$), a barrier with a height of +1.5 m MSL (‘Barrier 1’, $P_B \approx 0.7$), and a barrier at +2.5 m MSL (‘Barrier 2’, $P_B \approx 0.3$). Preliminary tests with higher front barriers indicate no further significant reduction in failure probabilities. This figure also shows that there is not a constant reduction, but some dependency on the front defense reliability; otherwise the barrier configurations would have overlapped each other in Figure 3.

The reductions $n$ for the three barrier schematizations can be determined by finding the relative difference in annual failure probability with respect to the ‘No barrier’ situation. Using the failure probabilities around a water level of 4.6 meter (i.e. large markers in Figure 3), reduction $n$ for ‘No barrier’, ‘Barrier 1’ and ‘Barrier 2’ is consecutively 1, 0.2 and 0.05.

However, contrary to the description of the conceptual reduction relations in Section 2.3, different water levels lead to significantly different reduction factors. This means that the reductions in this case are also dependent on the annual failure probabilities inside the bay, and that the conceptual reduction relation in Section 2.3 does not accurately capture the actual reduction relation in this case. This could be improved by applying separate reduction relations that modify the distribution parameters of the unconditional probability, instead of applying the reduction relation to the unconditional probability itself. On the other hand, this would also imply that the probabilities would need to have the same distribution (e.g. exponential distribution).

3.3. Economic optimization

The previously mentioned dependency of the reduction on the water levels inside the bay is considered out of scope for this paper, and ignored in any
further calculation. Furthermore, because the maximum reduction already occurs at a relative high $P_B$ (0.3), the formulations in Eq. 13 & 14 are used with a constant reduction $n = 0.05$. As mentioned earlier, no reduction will be applied in case of a failing front defense ($m = 1$).

Values regarding investment costs and flood damage are loosely based on Stoeten (2013): $C_f = 2$ billion, $C_{vA} = 1.2$ billion, $D = 160$ billion and $C_{vB} = 0.5$ billion. Furthermore, the discount ratio is set to 0.04.

Lastly, the exponential distribution parameters for front and rear defense were gained by fitting exponential distributions on the ‘Outside’ and ‘No barrier’ curve in Figure 3; these parameters are rough estimates and estimated to be $\alpha_B = 2.6m$, $\beta_B = 0.51m$, $\alpha_A = 4.6m$ and $\beta_A = 1.0m$.

Using these values in Eq. 15 & 16 leads to the optimal values $\bar{P}_B = 1.4 \cdot 10^{-2}$ and $\bar{P}_{sys} = 4.7 \cdot 10^{-3}$. In comparison, the optimal value for a single line of defense is $\bar{P}_{A,single} = 3.0 \cdot 10^{-4}$.

However, this does not necessarily tell which of the two defense strategies is the optimal choice yet, because the fixed costs and displacement parameters ($\alpha$’s) do not influence Eq. 15 & 16, but do influence the total costs (e.g. see Eq. 7). Therefore, a final check which compares the total cost of a front and rear defense with the total cost a single defense needs to be done. The total cost of a single line of defense is $C_{f,A} + C_{vA}\hat{h}_{A,single} + \bar{P}_{A,single}D$, and amounts to $C_{f,A} + 16.5$ billion. The total cost of a front and rear defense with the found optimal values is $C_{f,A} + C_{f,B} + 15.5$ billion.

In conclusion, for the previously mentioned values and depending on the extra fixed cost for a front defense, the combination of front and rear defense preliminary appears to be cheaper and thus the optimal choice.

4. OUTLOOK

The simplified approach in the previous section provides valuable insight into the mechanisms driving the schematization of Figure 1 and the resulting optimization. However, for a practical application, the simplified approach has its limits. These limits can be found both in the implicit and explicit assumptions/simplifications made in Section 2:

- Economic optimization assumptions regarding the frequency and timing of investments (only once and immediately), and the exclusion of time dependent processes
- Potential damage $D$ is assumed to be constant. In some cases this might be a good model, but depending on the geography of the hinterland and the intensity of the flooding, a different, smaller damage might occur.
- The used schematization where only the rear defense protects against potential damage $D$: more complex flood defense systems can exist, with each system having its own distinct flood damage.

For a single layer of defense, concepts such as sea level rise, economic growth, (initial) waiting period and repeated investments have been discussed for analytical solutions by for example Vrijling and van Beurden (1990); Eijgenraam (2006). However, especially when all items mentioned above need to be considered, a computational framework becomes a more attractive option.

For example, in Zwaneveld and Verweij (2014a) and Zwaneveld and Verweij (2014b) such a numerical approach is discussed. Inspired by this work, a high level overview of the steps involved in both the risk and economic models is shown in Figure 4. In this figure, the risk steps (schematization, physical model & probabilistic estimation) are purposefully displayed inside the economic optimization. The economic optimization calls various sources and parameters which can be delivered either by the outcome of the sequence of risk steps (i.e. failure probabilities), or by the intermediate steps. For instance, the heights of the flood defense are relevant both for physical model (determine risk), as well as the economic optimization (investment costs). If the risk model is coupled to damage models as well, risk costs can be obtained directly and can also be used in Zwaneveld and Verweij (2014b). These can be obtained using a computational framework in the spirit of for example Courage et al. (2013).

5. CONCLUSIONS

The work in this paper was done to understand characteristics of the economic optimization of coastal flood defenses, as shown in Figure 1. This was
done by deriving formulations based on a simplified economic optimization of a simplified coastal defense system. The formulas indicate that the optimal safety level of the system can only be improved with a combination of front and rear defense if for a similar risk reduction, the front defense investment is cheaper than the rear defense.

The case study showed that the formulations describing the optimal values can give answers with relatively little effort. However, the application also showed that the proposed conceptual reduction relation only partially describes the case study’s reduction relation between front and rear defense. This and other issues regarding the model need to be addressed in future work, for example by extending the simplified model. However, for more complex cases (either in number of flood defenses, risk modeling, damage modeling, or number and type of economic optimization variables) a computational framework is a better choice.

Nevertheless, this study captures the interdependency of a front defense being capable of improving the reliability of the rear defense in a set of transparent economic optimization formulations. These can be used as a first order estimate in finding out if what the optimal safety targets of a coastal flood defense system are, and whether or not such a system could be the economic optimal choice.

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7. REFERENCES


