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designing and retrofitting infrastructure systems under structural uncertainty

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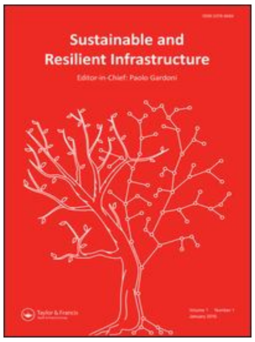

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Polder pumping-station for the future: designing and retrofitting infrastructure systems under structural uncertainty

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ABSTRACT

In designing and retrofitting infrastructure systems, engineers are increasingly confronted by uncertainties about the future operating conditions of these systems, stemming from climate change or rapid socio-economic development. Particularly for long-lived capital-intensive infrastructure components like pumping stations, current engineering practices need to be complemented by structured approaches for designing infrastructures whose performance is robust to a wide range of possible future operating conditions. This paper presents multi-objective robust simulation as a viable approach. We investigate its applicability in a case study of the re-design of a polder pumping-station in The Netherlands. The research demonstrates the added value of multi-objective robust simulation in establishing robust design alternatives. The approach generates additional decision relevant insights into the performance of the pumping-station under uncertain future conditions while supplying decision-makers with the information required to make informed trade-offs amongst key design choices.

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Climate adaptation; infrastructure; pumping station; deep uncertainty; robust decision making

1. Introduction

In designing and retrofitting infrastructure systems, increasing uncertainties regarding their future operating conditions challenges engineers. Besides climate change, engineers are confronted with the onset of a transition in the energy system from fossil to renewables and, in the rapidly developing economies in the global South, unprecedented urbanisation and socio-economic change. How these developments will unfold over the coming decades is deeply uncertain (Lempert et al., 2006). Translated to the infrastructure engineering domain, deep uncertainty is the condition in which engineers do not know or cannot agree upon (1) the appropriate models to describe interactions among an infrastructure system's variables and its interaction with its operating environment, (2) the probability distributions to represent uncertainty about key parameters in these infrastructures systems, or (3) how to value the desirability of alternative designs (adapted from Lempert et al., 2006).

Hitherto, engineering theory and practise have focussed on the development of probabilistic design methods for developing optimal designs (Doorn & Hansson, 2011; Madanat et al., 1997; Vrijling, 2001). These methods are now fruitfully geared to include the new probabilistic reality by for example downscaling hydro-meteorological data for urban drainage design (Cook et al., 2017). However, the optimality of the design critically depends on the assumed probabilistic characterization. Under deep uncertainty, such characterizations are themselves uncertain. Ignoring this can result in decision myopia where the optimal design fails to account properly for the uncertainties that will affect its performance. Under such conditions, robustness of the performance of the infrastructure system under diverging future conditions is preferable to statistical optimality as a criterion for evaluating designs (Herman et al., 2015; Maier et al., 2016; McInerney et al., 2012).

The problem of supporting planning and design in the presence of deep uncertainty has been receiving quite some attention in the planning literature (Walker et al., 2013). Methods such as Assumption-Based Planning (Dewar, 2002), (Many Objective) Robust Decision Making (Groves & Lempert, 2007; Kasprzyk et al., 2013), Adaptive Policy-Making (Hamarat et al., 2013; Kwakkel et al., 2010; Walker et al., 2001), Adaptation Options (Wilby & Dessai, 2010), Adaptation Tipping Points and Adaptation Pathways (Haasnoot et al., 2012; Wise et al., 2014), Adaptive Policy Pathways (Haasnoot et al., 2012), among others are now more and more applied in planning and policy

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practice. This article seeks to apply the approach and methods underlying planning and policy design under deep uncertainty to the domain of infrastructure design.

From an analytical perspective, all model-based approaches for supporting design under deep uncertainty are rooted in the idea of exploratory modelling (Bankes, 1993; Kwakkel, 2017; Walker et al., 2013). Traditionally, model-based decision support is based on a predictive use of models. Simulation models are used to predict future consequences, and designs are optimized with respect to these predictions. Under deep uncertainty, this predictive use of models is highly misleading. Instead, models should be used in an exploratory fashion, for what-if scenario generation, for learning about system behaviour, and for the identification of critical combinations of assumptions that make a difference for design (Weaver et al., 2013). In this exploratory approach, the single optimal design resulting from predictive approaches gives way to an approach that results in a robust design that performs satisfactorily in many plausible futures.

In this paper, we present a general framework for the design of infrastructure systems under deep uncertainty. The framework is inspired by methods developed in the policy sciences and illustrated by designing a polder pumping-station. In the section Robust Design of a polder pumping station: a framework, we first introduce robustness as an alternative to optimality as a design criterion under conditions of deep uncertainty and then present the framework for applying multi-objective robust simulation to the design of infrastructures. In the section Robust Design of a polder pumping station: application of the framework we apply this framework to the design of a polder pumping station in The Netherlands. The final section, results, presents and discusses our conclusions.

2. Robust design of a polder pumping station: a framework

2.1. Robustness in engineering design

Under conditions of deep uncertainty, robustness of the functioning of the infrastructure under diverging future conditions is a preferred decision criterion (Maier et al., 2016; Metz et al., 2001; Rosenhead et al., 1972). However, the notion of robustness is ambiguous and can overlap with related concepts such as resilience, reliability, flexibility (Anderies et al., 2013; de Haan et al., 2011) and phasing of construction (Creaco et al., 2015).

Cook et al. (2017), following Faturechi and Miller-Hooks (2014), distinguish between infrastructure reliability which is the ability of systems to remain functional during a disaster, and resiliency which is the ability to resist, absorb, and adapt to disruptions. Walker et al. (2013) distinguish four planning approaches that may yield a fruitful conceptualisation for the application of a robustness criterion in infrastructure design:

1. Resistance: design for the worst possible case or future situation. This comes at high costs and the potential of substantial overinvestments.
2. Resilience: whatever happens in the future, make sure that the design can quickly recover.
3. Static robustness: a design that performs satisfactorily under a wide variety of future conditions.
4. Dynamic robustness: a design that leaves options open and can be adapted to changing future conditions such that the design continues to perform satisfactorily.

Reliability in the definition of Faturechi and Miller-Hooks (2014) is akin to the definition of resistance according to Walker et al. (2013), while resiliency according to Faturechi and Miller-Hooks (2014) is akin to a mixture of the dynamic robustness and resiliency definitions in (Walker et al., 2013). Phasing of construction (Creaco et al., 2014) realizes dynamic robustness in water distribution network design but, however, assumes that costs, discount rate, and demands are known with certainty, which is not the case under conditions of deep uncertainty. An alternative perspective on robustness is offered by Kwakkel et al. (2016), who distinguish between two robustness definitions:

- Reducing the uncertainty about the expected consequences of a given policy. So, no matter how the future plays out, the policy performance falls in a narrow bandwidth.
- Minimizing the undesirable outcomes. So, no matter how the future unfolds, policy performance will be satisfactory.

The first definition is focused on ensuring that the performance of a design falls within a narrow bandwidth, while the second definition only focuses on whether a design can guarantee a minimum performance threshold. For instance, a water management organization retrofitting a polder pumping-station would not want an energy bill that is higher than expected, but they do not mind if the energy bill is lower than expected. In the first definition of robustness good and bad deviations from the expected outcome are treated equally, while in the second definition only the bad deviations are considered.

Identifying an appropriate robustness criterion for infrastructure system design is contingent on case specific considerations. For example, for large scale, long lived, complicated infrastructure systems in mobility, flood protection, and other engineering domains, resilience in accordance with the above definition from Walker et al. (2013), might be preferred. Or, for the pumping-station, a structural design of the pumphouse allowing for the installation of additional pumps and engines on the longer term might be a strong argument to apply dynamic robustness as the design criterion. The operationalisation of the robustness criterion for our case study is discussed under 3.2.3. Performance Metrics (M).

2.2. *Method*

The XLRM framework (Lempert et al., 2003) was designed to structure decision problems under deep uncertainty and has successfully been applied to water allocation problems (Murray et al., 2012) and water quality management (Fischbach et al., 2017). In this contribution, we adopt the XLRM framework (Figure 1) for structuring the engineering design of water infrastructure, more specifically a pumping station. The framework distinguishes four types of factors: external factors (X), policy levers (L), relationships within the system (R), and performance Metrics (M). External factors are factors outside the control of decision-makers that may nonetheless prove important in determining the success of a design. In our application to infrastructure design, external forces represent the uncertainties relevant for the future performance of the pumping station. Policy levers are actions that, in various combinations, comprise the alternative designs decision-makers are considering. In this context, policy levers are the design choices for the pumping station. Relationships within the system describe the ways in which the various factors relate to one another. They thus determine how the future functioning of the infrastructure will evolve based on the decision-makers' choices of policy levers and the manifestation of the external factors. Performance metrics are indicators that decision-makers and stakeholders would use to decide on the desirability of the various alternative designs. For a pumping station, these are metrics such as water level exceedance causing crop losses and damage to homes and properties, and investments cost. In this research, the relationships (R) between uncertainties (X), policy levers (L) and performance metrics (M) are linked together in the Pumping Station Simulation and Testing model (PSST-model) developed for this research.

Vulnerability analysis aims at identifying the relative influence of the various uncertain factors on the robustness of a policy or infrastructure design (Herman et al., 2015). The first step is to simulate the performance of one or more alternative designs of the pumping station under a range of scenarios. Next, one can investigate how performance is affected by the various uncertainties and design choices. This can be done through factor prioritization based approaches as found in the sensitivity analysis literature (Saltelli et al., 2000) and scenario discovery (Bryant & Lempert, 2010; Kwakkel & Jaxa-Rozen, 2016). In our case study, we apply feature scoring, which is a machine learning alternative to traditional global as well as a regional sensitivity analysis techniques (Jaxa-Rozen & Kwakkel, 2018; Spear & Hornberger, 1980; Young et al., 1978). The PSST-model developed for this research (Figure 3) is structured in accordance with the XLRM (Figure 1) model, integrates a rainfall-runoff model and a functional model of the pumping station including power supply, energy use and alternative design options.

The PSST-model was used to simulate the effect of design choices and exogenous uncertainties on the performance of the pumping station. We considered eight climate scenarios and six energy scenarios, leading to 48 plausible future states of the world. Out of the eight design levers, the mix of solar to wind is a continuous range between 0% and 100%, while the other seven design choices are each characterized by a set of alternatives. Five choices are binary, while fish safe solution has three options, and pump control six options. These design choices lead to $2^5 \times 3 \text{ x } 6 = 576$ design alternatives. The remaining choice of mix solar wind has an infinite number of options, making the total number of design alternatives also infinite. To get a sense of the possible outcomes Latin Hypercube sampling was used to choose 500 design alternatives to simulate. Combining the 48 future states of the

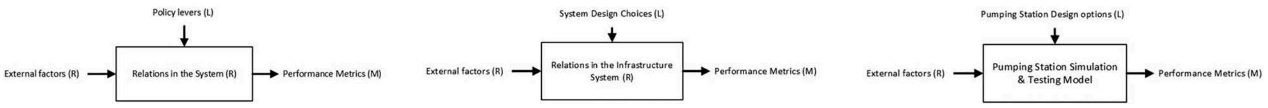

Figure 1. The XLRM framework for policy, infrastructure system and pumping station design.

world and the 500 design alternatives sampled results in a set of 24,000 simulations. The results of the simulations express the performance of a candidate design for the pumping station using the performance metrics measuring functional, energy, ecological, and costs performance. The resulting spread in performance of a design over the 48 scenarios is used to quantify robustness. The sensitivity of the performance metrics to design choices and scenarios was analysed using extra trees feature scoring (Geurts et al., 2006; Jaxa-Rozen & Kwakkel, 2018). Extra-trees feature scoring provides insight into the sensitivity of an outcome of interest to variations in both policy levers and exogenous uncertainties by producing a sensitivity ranking. In addition, we used visual analytic approaches combining composite Gaussian kernel density estimates, scatter plots and parallel coordinate plots. Gaussian kernel density estimation is a non-parametric way to estimate the probability density function of a random variable, in our case performance of a pumping station, and is basically a data smoothing technic (Parzen, 1962; Rosenblatt, 1956). The entire analysis is implemented with the help of the exploratory modelling and analysis workbench (Kwakkel, 2017).

3. Robust design of a polder pumping station: application of the framework

3.1. Pumping station Vissering

Pumping station Vissering is situated in the Noordoostpolder near the former island of Urk in The Netherlands (Figure 2). It is designed to discharge excess water from the polder into the IJsselmeer. The Noordoostpolder is part of the Zuyder Sea works that turned the Zuyder Sea into a fresh water lake, the IJsselmeer, and reclaimed large polder areas from the former Zuyder Sea. The Noordoostpolder was reclaimed between 1937 and 1942 and has a total area of 48,000 hectares. The Noordoostpolder avails of a water management system for water supply and drainage of the agricultural land and is protected from the 4 m higher water levels of the bordering Ijsselmeer by dikes. From the central city of Emmeloord, the main channels go to east, west and north with a pumping station at the end of each main channel. The Water Board Zuiderzeeland is responsible for water management in the polder and consequently the construction, operation, and maintenance of the three pumping stations. The Noordoostpolder has only a small wet area (about 1%) available for storage of excess precipitation and regularly experiences water level exceedance. The Water Board Zuiderzeeland has managed to increase the water storage capacity over the past decade to limit water level exceedances. However, climate change, land subsidence, and a possible rising of the water level of the IJsselmeer pose new challenges for water management in the Noordoostpolder.

Pumping station Vissering opened in 1940. The pumping station has three vertical centrifugal pumps in a concrete volute casing. Two pumps have a capacity of 800 m^3/min each, and the third pump has a capacity of 720 m^3/min. The head (lifting capacity) is 5.5 m. The last major renovation included the replacement of the two oldest diesel engines by gas engines. When there is no need to discharge, the gas engines can drive a generator for producing electricity that is fed into the grid. Pumping station Vissering will be re-designed and renovated in 2021. The aim of the renovation is to make Vissering the most sustainable pumping station of the Netherlands.

3.2. Structuring the design challenge

3.2.1. External factors (X)

In our case study, the External factors (X) relevant for the design of a pumping station are future electricity prices and climate change. To include these uncertainties in the evaluation of the performance of alternative designs, we included several generally used and accepted scenarios for climate change and energy supply generated by dedicated institutions in our simulation model. We used scenarios for electricity prices on the Amsterdam Power Exchange (DNV GL, 2015) summarized as price duration curves on the Amsterdam Power Exchange (APX) for 5 scenarios, business as usual, high CO2 price, sustainable, vision 3 and vision 4. The reference dataset consists of historical prices from 2011 to 2015 (APX, 2016). We were forced to limit the number of years to 5 because these scenarios are commercially developed by DNV and are therefore not available as complete data sets. This limits the value of our substantive conclusions but not the illustration of the approach. An important, but debatable, assumption in this dataset is curtailment when prices threaten to become negative.

As a reference scenario for the current climate, we used hourly precipitation and daily potential transpiration data for the period 2011–2015 of station Marknesse, geographically close to pumping station Vissering (KNMI, 2016) and applied an area reduction factor to compensate for point to area scaling (Wolters et al., 2015).

For future climate, we used a total of eight hourly datasets (Wolters et al., 2015) representing the KNMI 2030 and 2050 climate scenarios (Klein Tank et al., 2014) obtained from meteobase.nl (Wolters et al.,

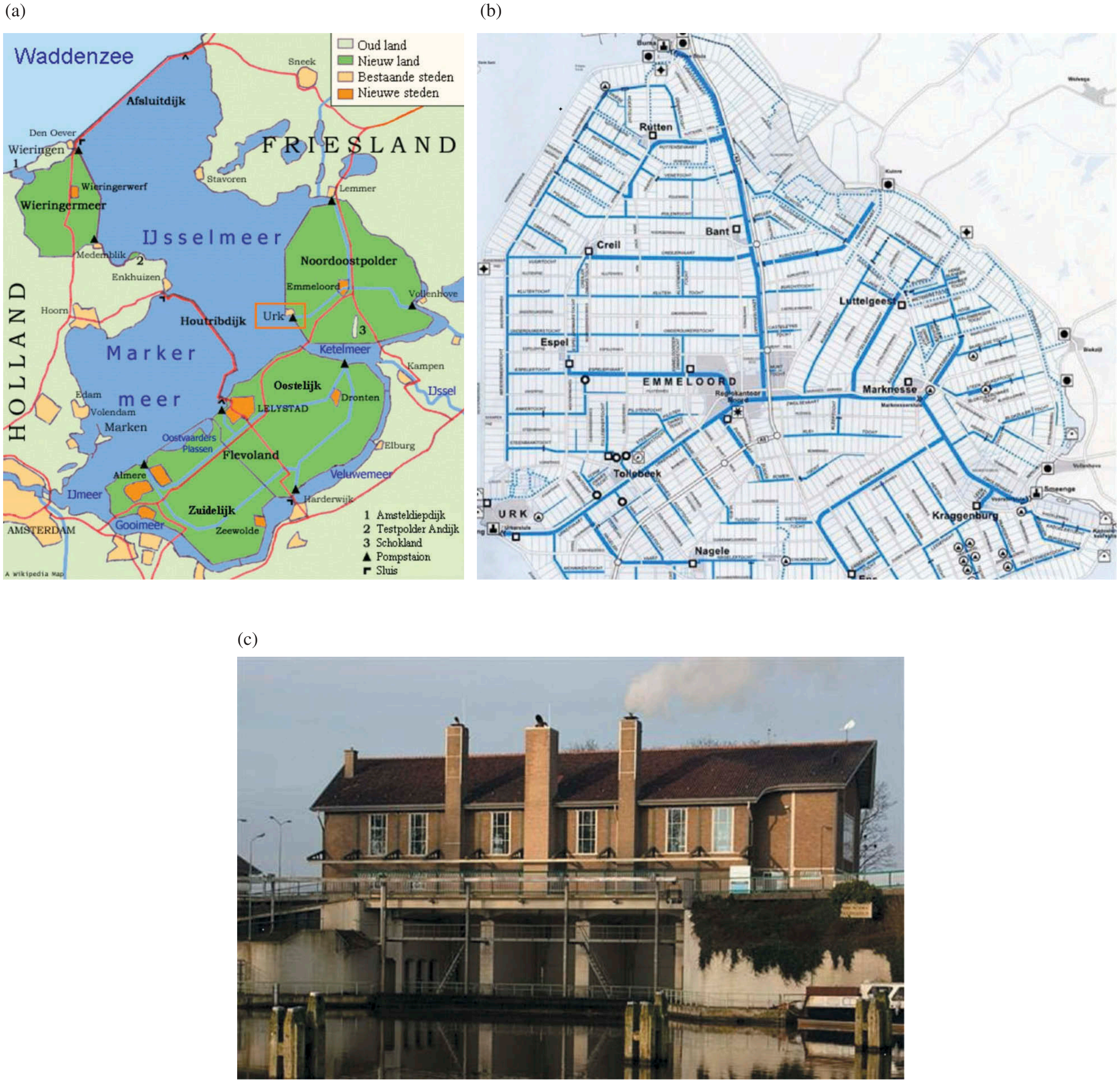

Figure 2. Maps of the Zuyder sea works (a) (Delta Works Online Founfdation, 2004. Published with permission) and the Noordoostpolder (b) (Waterschap Zuiderzeeland, 2004. Published with permission) and a picture of pumping station Vissering (c) (Waterschap Zuiderzeeland, 2018. Published with permission.). The red arrow indicates the location of the pumping station.

2015). These eight scenarios represent a stationary climate. Only the last 5 years of the dataset were used in our model, to have the same length as the available energy scenarios. The 2030 and 2050 scenarios both contained a single dataset for potential transpiration.

3.2.2. Policy levers (L)

In the general case of infrastructure design, the policy levers are combinations of design options. In our case, the design of a pumping station, a design is a combination of pumps, pump inflow, motor type, pump control, and possibly an innovation in, for example, the electricity supply. To generate design options, focussed and structured interviews were conducted with professionals and researchers in domains relevant for the design of a polder pumping station. A total of 16 specialists from the field of decision support systems, aquifer thermal energy storage, control systems, energy supply, hydrology, pumping stations, and energy markets were consulted. Each interview specifically focussed on the expertise of the interviewee in relation to the design of pumping stations. The respondents were recruited from water boards, consultancies, universities, knowledge

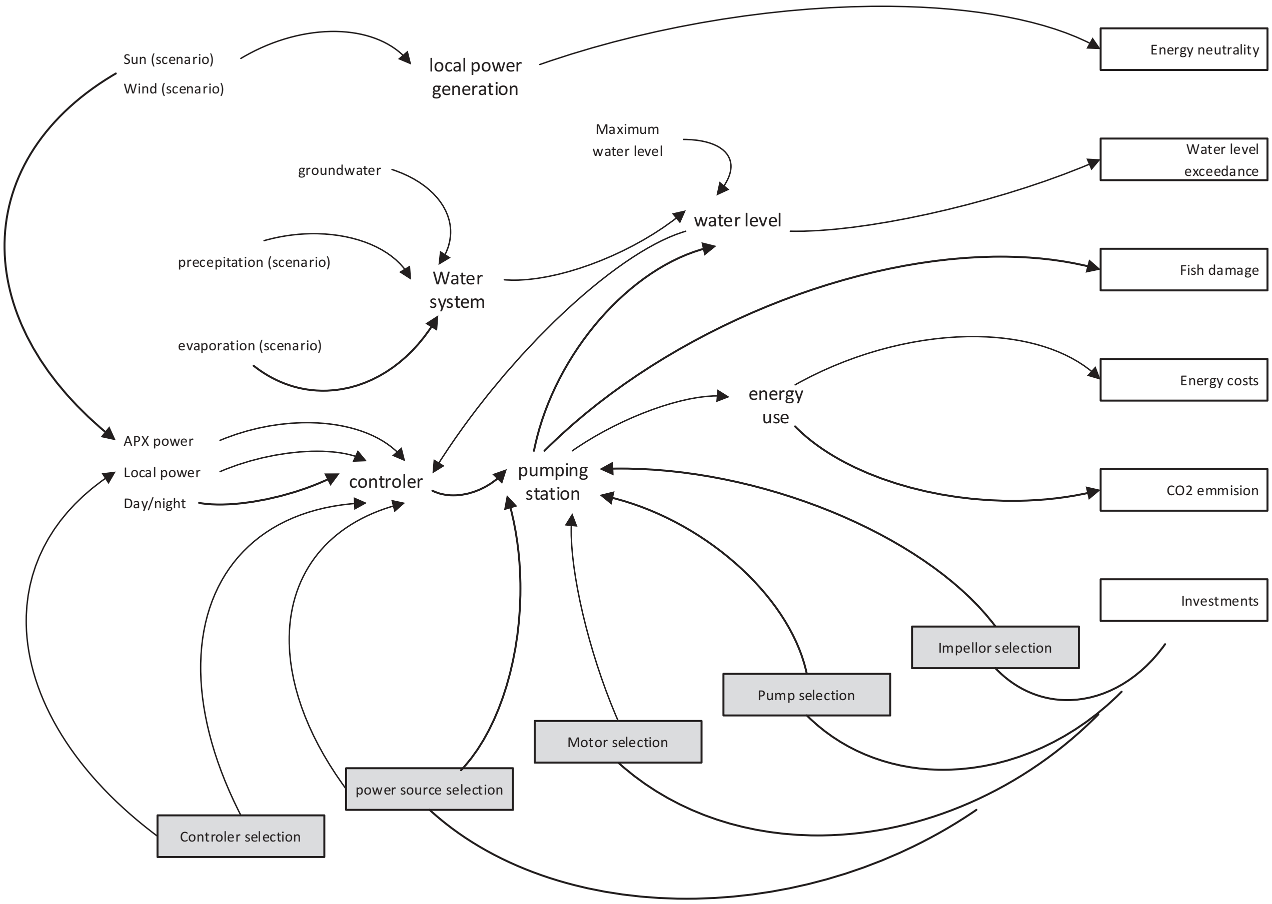

Figure 3. Causal model of the pumping station simulation and testing model with design choices in grey and performance indicators in white boxes.

institutes, and businesses. The interviews yielded a rich set of design choices including innovative options that are currently discussed among pumping station specialists and within the water boards. Next, these generic design options were adapted to the specific situation at pumping station Vissering, resulting in the following design levers:

- **Number of pumps**: number of pumps to install
- **Pump type**: standard pumps or fish safe pumps, standard impellors or fish safe impellors
- **Pump Inflow**: standard inflow or improved inflow
- **Motor type**: induction or permanent magnet
- **Pump control**: weather alarm, water level, day night, APX power, local power
- **Electricity supply**: grid, solar, wind, solar/wind mix

The number of pumps represents the design choice between two larger pumps or three smaller pumps. Pumps can be equipped with improved inflow to decrease energy use with 1.5% and with impellors that are fish safe but reduce energy efficiency with 2%. Permanent magnet motors improve the energy efficiency with around 1% to 96% as compared to 95% for the newest induction motors. CAPEX and OPEX of permanent magnet motors are lower, but their performance over a period of 20 years or more is still uncertain. The pump controller optimizes pump activation and normally applies an optimisation algorithm given a utility function. The weather alarm uses radar-based rainfall predictions to start pumping well before the actual rainfall arrives. For a pumping station, a range of utility functions can be applied, depending on contingent factors. For the redesign of pumping station Vissering, controllers based on water levels, differences in day and night electricity prices, electricity prices on the Amsterdam Power Exchange, local power production, and their combinations are of interest.

3.2.3. *Performance metrics (M)*

A robust design will deliver a pumping station that shows robust performance under a wide range of future conditions and that is neither too expensive, nor results in extensive damages in case of severe rainfall. For retrofitting pumping station Vissering static robustness is the preferred criterion because the lifetime of the electro-mechanical parts does not warrant a dynamic approach. Kwakkel et al. (2016) distinguish 3 families of robustness metrics. Regret-based metrics compare the performance of a design in a state of the world (i.e., scenario) with either the best possible design for that state of the world, or the performance of a baseline design for that state of the world. Satisficing metrics focus on the number of future scenarios for which a design meets a performance threshold. In this research, we use robustness metrics based on descriptive statistic, averages and variances, because they do not need additional assumptions on the baseline or threshold and are easy to communicate and discuss as averages and variances and can be visually communicated and assessed from a graph. Kwakkel et al. (2016) present five robustness metrics based on descriptive statistics of the distribution of the performance over the set of scenarios. The most transparent among these five expresses robustness as a combination of a good average performance (μ) and a narrow variance (σ) will be used in this research.

For the evaluation of the performance of the pumping station, we used four categories of performance metrics measuring functional, energy, ecological, and cost performance. The main water management function of a polder pumping station is regulating water levels to account for water shortages in dry periods and water excess in wet periods with the objective to facilitate water-related land use. The main land use of the command area of pumping station Vissering is agricultural production. In agricultural areas, regulating water levels boils down to maintaining pre-specified water levels under both dry and wet conditions. Water demand, however, is hardly causing a problem in the Noordoostpolder because water intake under gravity is possible from the IJsselmeer. The most relevant task of the pumping station is thus to prevent exceedance of the maximum water level to avoid damage to crops and to allow farmers to work their fields with heavy equipment. At pumping station Vissering the maximum allowed water level is −5.50 m NAP. For our case study, we used the cumulative water level exceedance [mm·hr] as a performance measure for the pumping station.

Climate change has put CO_2 emission of their operations and assets on the agenda of the Dutch water boards. In 2017, the Union of Water Boards signed the Green Deal Energy. This entails a commitment to 40% self-generated renewable energy supply by 2020, and the ambition to ultimately become energy neutral (UvW, STOWA, & Rijk, 2016). Water Board Zuiderzeeland is currently investigating how to operationalize the Green Deal Energy for its operations. In our model, we included two energy system related performance metrics: CO_2 emissions and energy neutrality. CO_2 emission is expressed in ton and an average CO_2 intensity of power generation of 0.355 ton/MWh (co2emissiefactoren.nl, 2016). The energy neutrality performance indicator is expressed as the percentage of the total energy use of the pumping station that is locally produced by a mix of solar- and wind-generated power.

From an ecological perspective, fish are the only species known to be directly impacted by pumping stations. Kunst et al. (2010) showed that many pumping stations are not fish save. Esch and Rommens (2010) developed a fish collision model that calculates a fish safety factor on the basis of pump specifications. We applied the fish safety factor as a performance metric in our model but did not implement the full fish collision model in this phase of the design process. As an approximation, we instead adopted the fish safety assessment of pumping station Krimpenerwaard (Nieuwkamer & Klinge, 2016).

We included cost-related performance metrics for investment, operational, and energy costs. A pumping station renovation requires investments. From a financial perspective, the idea is that the components are improved thereby reducing the operational costs with the aim to obtain an acceptable return on investments and pay-back period. Table 1 gives a summary of all the performance metrics included in the simulation model and used for the evaluation of the performance of the alternative pumping station designs.

3.2.4. Relationships in system (R)

Relationships in System (R) describe the ways in which X, L and M relate to one another and so governs how the future may evolve over time, based on the decision-makers' choices of levers and the manifestation of the external factor (R. Lempert et al., 2003). In our Pumping Station Simulation and Testing model (PSST-model), a pumping station and its operational, hydrological, financial, and energy environment, are integrated. The PSST-model consists of three sub-models:

- A rainfall run-off sub-model of the polder system
- A sub-model of alternative pumping station controllers
- An electrical and mechanical sub-model of the operation of the pumping station

The three sub-models constitute a complete model of the functioning of the polder system and the pumping station (Figure 3). In the model, the design choices components act as switches that implement an alternative pumping station design, for example by selecting

Table 1. Overview of performance indicators and their sensitivity for design choices.

Category	Proxy	Unit	Relevant uncertainties	Relevant design choices
Functional	Water level exceedance	(mm*hr)	• Climate scenarios	• Number of pumps • Weather alarm • Pump control
Energy	CO2 emission Realized energy neutrality	MWh %	• Climate scenarios • Energy scenarios • Energy scenarios	• Pump control • Percentage energy neutral • Percentage energy neutral
Ecological	Fish damage	kg		• Fish safe solutions
Cost	Investments	€	• Energy scenarios	• Number of pumps • Fish safe solutions • Motor choice
	Operational	€	• Energy scenarios	• Energy scenarios
	Indirect Electricity	€ €	• Energy scenarios • Climate scenarios	• Solar/wind mix

a specific type of pump or an energy source. The performance metric components translate and aggregate model output into the selected performance indicators.

The model was developed using the System Dynamics (Forrester, 1994) approach and implemented in Vensim (Ventana Systems, 2016). As integration method, we used Euler with a time step of 0.03125 hours (112.5 sec.). Best practices of the System Dynamics Society advise a time step of one eight of the time resolution of the model parameter with the smallest resolution, which is 1 h for the discharge data and the rainfall. Sensitivity analysis revealed that the suggested time-step of 0.125 h still caused an error of circa 2% on water level exceedance performance. The time-step of 0.03125 hours (112.5 seconds) used reduces this error to an acceptable 0.2%.

The hydrological and hydraulic sub-model including the operation of the pumping station were calibrated on historical measurements and simulation results of an existing more detailed SOBEK rainfall-runoff model (Deltares, 2018) and showed sufficiently good performance as can be seen in Figure 4. The figure compares the discharge of pumping station Vissering calculated with the PSST model to measured discharges and discharges simulated by a dedicated rainfall runoff model. The rainfall data set includes some more extreme rainfall events of around 20 mm per day.

4. Results

4.1. Initial design and performance

Extra trees feature scoring generates a ranking of the sensitivity of the performance indicators for all design choice and scenarios. Figure 5 presents these sensitivities for the most sensitive performance indicators, design choice and scenarios on a parallel coordinate plot. Each vertical axis expresses the sensitivity of the performance criteria for scenarios and design choices on a normalized scale between 0 and 1.

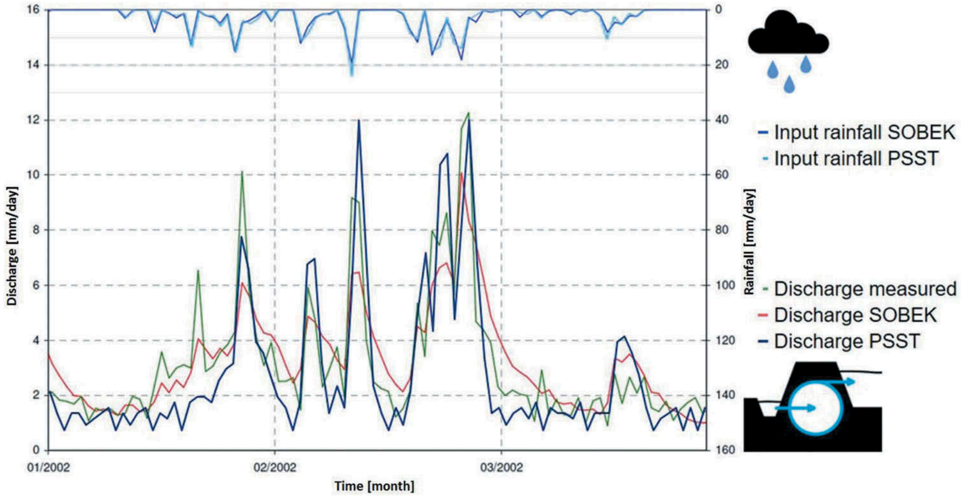

Figure 4. Rainfall run-off calibration comparing measured and detailed SOBEK discharges with the output of our integrated PSST model.

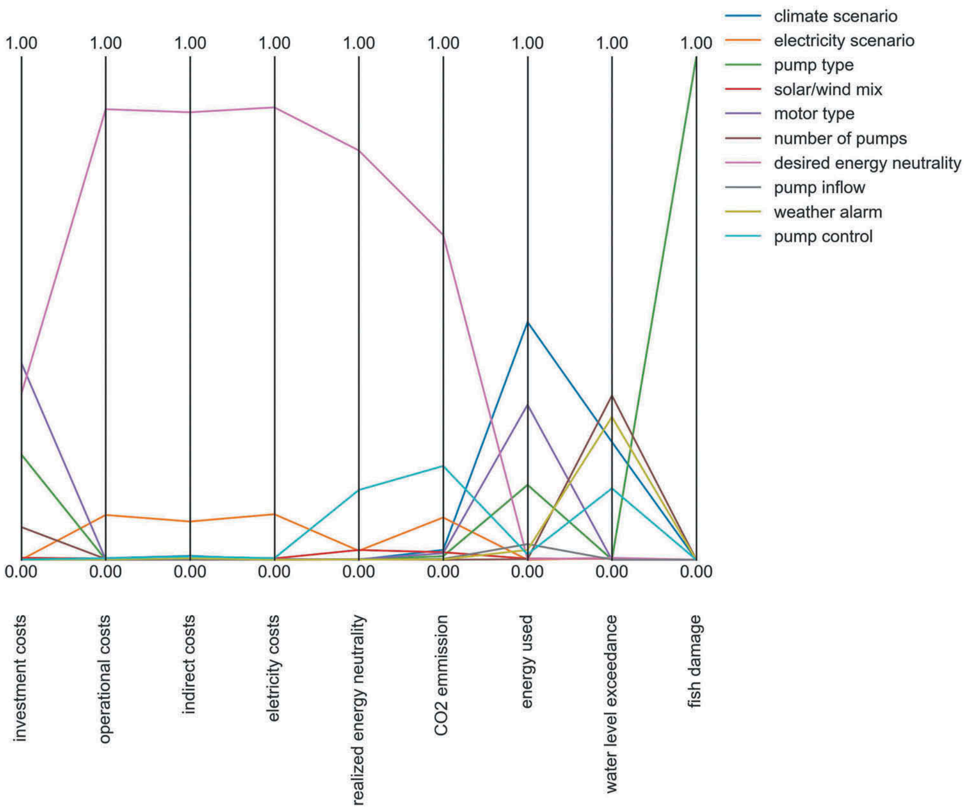

Figure 5. Feature scoring for the entire design space.

From Figure 5 we learn that most of the performance indicators are sensitive to (i) the desired energy neutrality of the pumping station design, and (ii) that climate scenarios have a large impact on energy use. Investment costs are depending on motor choice, pump type, and the number of pumps that will be installed. Table 1 summarises the results of the feature scoring presented in Figure 5 for all performance indicators, their units, their relevant uncertainties and relevant design choices. Performance measures are cumulated over the simulation period of 5 years, expressed in the units indicated. Next, we will develop and discuss an initial design based on these results.

4.1.1. Functional performance

Functional performance is evaluated based on water level exceedance. The feature scoring identifies that water level exceedance is influenced by the number of pumps, the weather alarm, pump control, and is sensitive to the climate scenarios. Figure 6, further analyses this sensitivity for the number of pumps and the weather alarm. Figure 6 presents the spread of the water level exceedance performance over the 24,000 simulations for these factors, color coded by the number of pumps, weather alarm on/off, and the eight climate scenarios in, respectively, Figure 6(a–c). When the number of pumps is 2, there is quite some water level exceedance as appears from the spread of the red line. A third pump can completely prevent water level exceedance, as evidenced by the blue spike at a water level exceedance of 0 in Figure 6(a). However, the simulation results reveal that this pump is used only 1.3% of the year. Not installing this additional third pump, but instead maintaining one of the currently already installed gas engines seems an attractive and cheap option to reduce water level exceedance to zero.

Figure 6(b) shows that the weather alarm can significantly reduce water level exceedance to no more than 50,000 mm*hr in 5 years and contributes considerably to the robustness of the design with an average water level exceedance around zero and very small variance.

The impact of the climate scenarios is shown in Figure 6(c). The highest observed water level exceedance for the 2030 scenarios is slightly higher than that of the historical rainfall data (pink) at about 75,000 mm*hr. However, in scenarios 2050 WL (green) and 2050 WH (red) this doubles to 150,000 mm*hr. Fortunately, using three pumps in combination with the weather alarm can reduce water level exceedance to near zero for these high end climate change scenarios. Installing two new pumps and maintaining one of the installed gas engines combined with

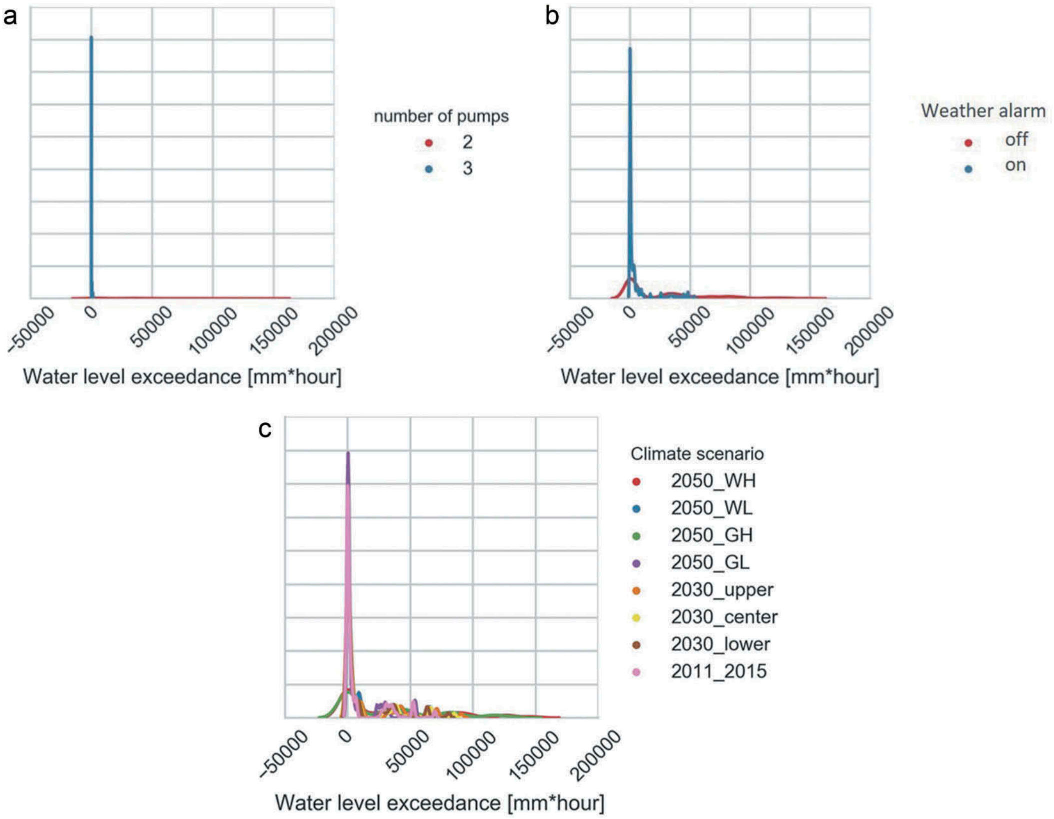

Figure 6. Sensitivity of water level exceedance to number of pumps (a), weather alarm (b), and climate scenarios (c).

implementing the weather alarm results in a robust design for water level exceedance for these two design choices.

For the pump control, we cannot derive a robust solution based on the available set of simulation and the feature scoring because the effect of pump control on performance is closely linked to the choice for energy neutrality: while pump control based on APX prices is expected to be robust for a pumping station with a low percentage of energy neutrality and consequently a high dependence on the APX, a controller that maximises the use of local power can be expected to perform better in case of a highly energy neutral design of the pumping station. To further analyse this design choice, we performed an additional simulation experiment, in which the percentage energy neutral was fixed at 100% and the solar/wind mix was set to 50% and the number of pumps was set to 2, based on the design choices discussed above. For this experiment only the five remaining design choices, pump inflow (2 alternatives), motor type (2 alternatives), weather alarm (2 alternatives), pump type (3 alternatives) and pump control (5 alternatives) were considered, resulting in $2^3 \times 3 \times 5 = 120$ design alternatives. We ran a full factorial sampling of all 120 designs in all 48 future states of the world resulting in 48 × 120 = 5760 simulations. Again, feature scoring was applied to analyse the results. From this additional analysis, we conclude that pump control has some influence on the water level exceedance and operational costs, but that energy-related considerations are indeed more relevant. We therefore further discuss the design choice for the pump control under energy and cost performance below.

4.1.2. Energy performance

The energy performance of the alternative pumping station designs is evaluated on CO_2 emissions and energy neutrality. The energy neutrality is depending on the mix of locally generated solar and wind power. Figure 7 shows a maximum in the use of locally generated energy around a mix of 50% solar and 50% wind in the power supply, where about 55% of the locally generated sustainable energy is used directly in the pumping station (see also SD Figure 1).

As concluded under functional performance, arriving at a design choice for pump control requires a more detailed analysis of the energy performance of the

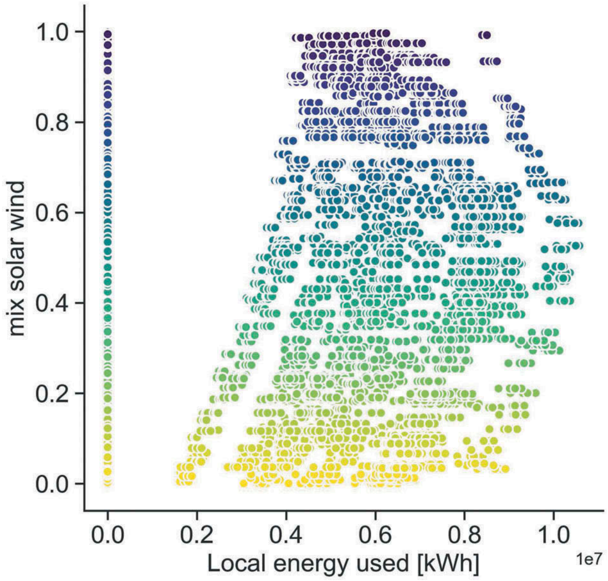

Figure 7. Local energy used versus solar wind mix.

reduced design space where the percentage energy neutrality is set to 100%, the solar/wind mix to 50%, and the number of pumps to 2. The plots in Figure 8 show the relation between energy bill, local energy used, and CO_2 emissions for all possible types of pump controls for this reduced design space, using both Gaussian kernel density estimates and scatter plots. The Gaussian kernel density plots show one bell-shaped peak for each scenario for the energy bill, while in CO2 emitted and local energy used three peaks appear for every scenario.

From the feature scoring on the full design space as presented in Figure 5 and summarized in Table 1 we already concluded that pump control has a large impact on both CO_2 emissions and local energy used under all climate and energy scenarios. Thus, we conclude that the three peaks observed in Figure 8 are caused by pump control. For the energy neutral alternative of the reduced design space we then conclude from Figure 8 middle that local control is the option with the highest average percentage of local energy used, albeit with a lower robustness as compared to APX and day night control that have a narrow bandwidth (σ) but are not energy neutral. In summary, from an energy perspective, the most robust design is a solar-wind mix of 50% combined with local control.

4.1.3. Ecological performance

The ecological performance of the pumping station design is evaluated in terms of fish safety, which is influence by the installation of fish safe impellors or fish safe pumps. The pump layouts not only influenced fish safety, but also impact energy use and investment cost. The design choice for ecological performance thus becomes a trade-off between investments cost and energy use of fish safe impellors versus fish safe pumps. The theory on fish safety of Esch and Rommens (2010) suggests that additional investments in fish safety at pumping station Vissering are relatively ineffective as compared to other pumping station, because the station is already quite fish safe because of its big pumps and large impellors. New fish save pumps have very high investment cost compared to maintaining the existing pumps and only changing the impellers. In addition, fish safe impellers and fish safe pump decrease the pump efficiency by, respectively, 2% and 4% and consequently increase in energy use. Shifting to a fish safe design thus creates a trade-off between cost, energy, and ecological performance. We used a scatter plot (SD Figure 2) and Gaussian kernel density plots similar to the plots of Figure 9 to gain insight into this potential trade-off by looking at the spread in performance outcomes. This analysis leads to the conclusions that although both changing impellers and new fish safe

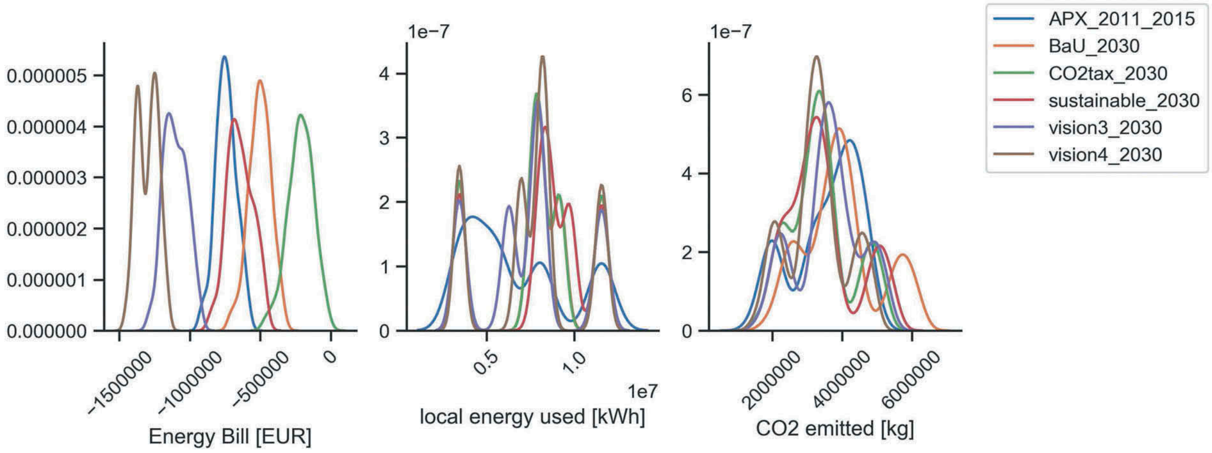

Figure 8. Energy bill, local energy used, and CO2 emitted grouped by pump control for the reduced design space.

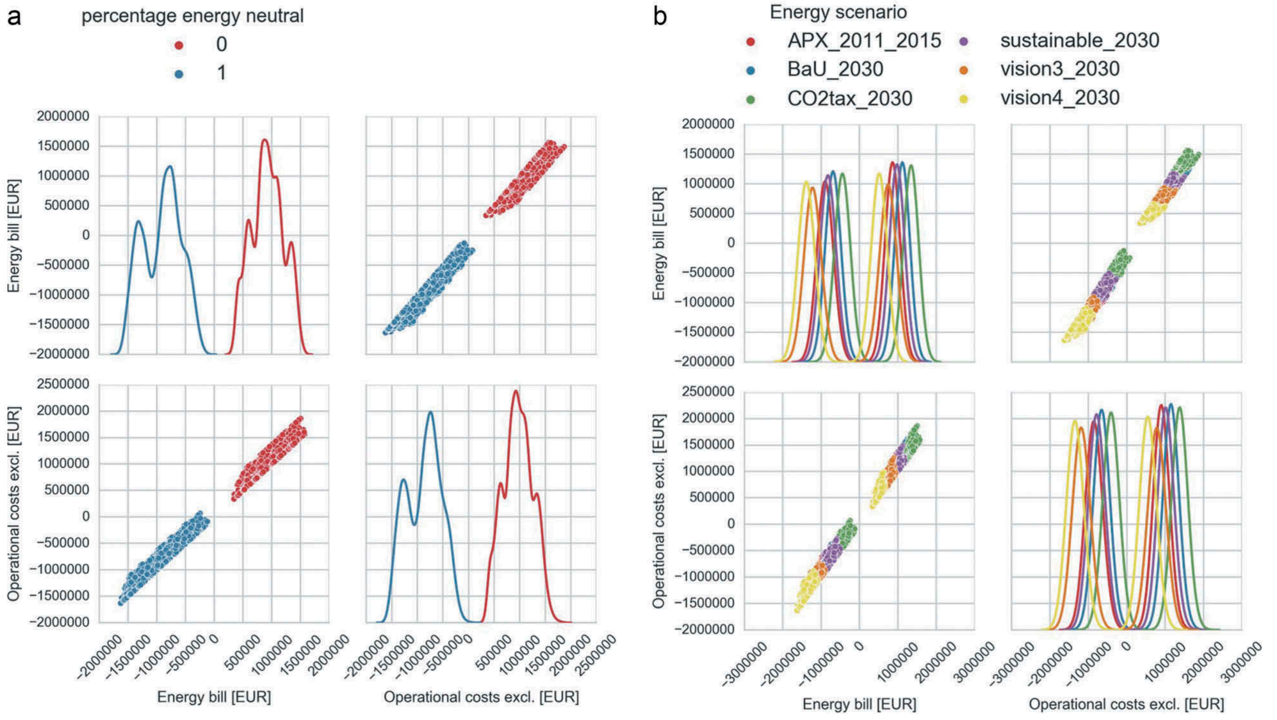

Figure 9. Operational cost and energy bill for energy neutral and non-energy neutral designs grouped by energy neutrality (Figure 9(a)) and scenarios (Figure 9(b)).

pumps reduce fish damage at pumping station Vissering, its ecological impact remains limited because the pumping station is already fairly fish-safe. Changing the impellers thus seems to provide the most balanced trade-off between energy and investments costs and ecological performance. This conclusion is however subject to the discussion and opinions of the decision makers of the water board.

4.1.4. Cost performance

Evaluation of cost performance is based on investments, operational, indirect, and electricity costs. According to the feature scoring of Figure 5, investment costs are sensitive to the number of pumps, pump type in relation to fish safety, and motor choice, while operational costs are sensitive to the energy scenarios and electricity costs are determined primarily by the solar/wind mix. For number of pumps and fish safe solutions, we already concluded under functional performance and ecological performance that installing two pumps while maintaining the existing gas engine and pump, and installing fish safe impellers results in the most robust design. Currently, the more efficient permanent magnet motors are cheaper than the often-installed induction motors. Moreover, permanent magnet motors are smaller, lighter, have a broader efficient working range and require less maintenance and thus have lower operational costs than induction motors. Based on these advantages permanent magnet motors are advised for pumping station Vissering. Furthermore, from the perspective of cost performance, the investment costs of improved pump inflow are so minor as compared to their benefit in improving energy efficiency that they should be, like permanent magnet motors, be included in all designs and are robust under all scenarios.

This leaves the cost trade-off for the energy neutrality as a crucial design choice for the water board. The relevant information to inform this decision is summarized in Figure 9. These figures present the operational cost and energy bill for an energy neutral design with a fifty-fifty solar/wind mix and a non-energy neutral design for all scenarios, grouped by energy neutrality (Figure 9(a)) and scenarios (Figure 9(b)). The scatter plots show the distribution of the simulation results on the dimensions relevant for the design choice for energy neutrality: energy bill and operational costs. The clear separation of the simulation outcomes makes clear that both energy neutrality and scenarios have a large and consistent impact on the operational costs and energy bill. The scatter plot of Figure 9(a) also indicates that both the operational costs and energy bill for an energy neutral design are significantly smaller. The Gaussian kernel density plots represent the same date and, in addition to the scatter plots, give a clear representation of the robustness of the two design alternatives. From the average, μ, of the Gaussian kernel density plots we conclude that the energy neutral design has both lower operational costs, and a lower energy bill for all scenarios. The bandwidth, σ, for the energy bill and operational costs is larger for the energy-neutral design as compared to the non-energy neutral design for all scenarios (Figure 9(b)), indicating that the energy-neutral design is less robust for uncertainties that the non-energy neutral design. However, the better average performance of the energy neutral design, even turning it into an energy producer and money maker, makes the energy neutral design a very attractive alternative. It is however up to the water board to trade-off the additional investment costs against the lower energy bill and their energy ambition as declared in the Green Deal Energy of the Union of Water Boards.

4.2. Performance of the final design

Based on the foregoing analysis we arrived at a robust design for the pumping station. The final design and the motivation of the design choices are summarized in Table 2.

To compare the performance and robustness of the final design and the efficacy of the multi-objective robust simulation approach to infrastructure design presented, we plotted the performance of the final design against the average performance of all 500 simulated design alternatives (Figure 10(a)) and the performance of the final design for all scenarios for all design criteria. The blue lines in Figure 10 show the average performance of all 500 design alternatives. The orange line(s) show the average performance of the final design and its performance for all scenarios. For the final design, the performance improved as compared to most available designs, except for its investment cost. For the electricity costs and closely related operational cost, the bandwidth is still quite large, and thus its robustness low, due to the large irreducible uncertainty of future electricity prices. Fortunately, on average the costs are negative because of the choice for a 100% energy neutral design that turns the pumping station into an energy producer. The choice for local control results in robust performance on local energy use and CO_2 emissions. The final pumping station design shows still some water level exceedance, however in practise the existing third pump with gas engine can be kept in use as a backup which is expected to reduce the water level exceedance to near zero.

Table 2. Final design of a robust pumping station.

Design option	Design choice	Motivation
Number of pumps	Two	Two pumps retrofitted with new electrical motor. One gas engine is kept in use
Pump type	Standard pump with fish safe impellors	Fish safe impellers provide a balanced trade-off between fish damage, energy use and investment
Pump inflow	Improved inflow	Pump inflow improvement reduces energy use at a low investment cost
Motor type	Permanent magnet	Permanent magnet motor is both cheaper and more efficient
Pump control	Local control with weather alarm	Local pump control shows robust behavior and is the best choice for energy performance and weather alarm reduces water level exceedance
Electricity supply	100% energy neutral with 50% solar/wind mix	100% energy neutral turns energy from cost to income and is possible within the budget and 50/50 solar wind mix is optimal for local energy use and CO2 emission

5. Conclusions and discussion

Uncertainties about climate change and the energy market constitute a major challenge in designing infrastructures. In situations of large and irreducible uncertainty, a robust design that performs satisfactorily under a wide variety of future conditions is preferred over a design optimized for a single or limited set of futures. There is thus a need for new approaches that can help engineers in developing such robust designs. Our research objective was to provide a proof of concept of Multi-Objective Robust Simulation in designing robust infrastructures, using the re-design of pumping station Vissering as a case study.

To evaluate the robustness of the design alternatives we defined robustness as performing satisfactorily under a wide variety of future conditions. This robustness definition was operationalized using descriptive statistics, where robustness is a combination of a good average performance (μ) and a narrow bandwidth (σ). We first developed the Pumping Station Simulation and Testing model (PSST-model). The PSST-model incorporates the hydraulic and hydrological characteristic of the command area, and the design and operation of pumping station Vissering into an integrated simulation model. The model performed sufficiently well against historical data. The model was used to gain insight into the performance of alternative designs of the pumping station under climate and energy uncertainty. The exogenous uncertainties were composed of eight climate scenarios and six energy scenarios, leading to 48 plausible future states of the world. Eight design choices, in the categories number of pumps, pump type, pump inflow,

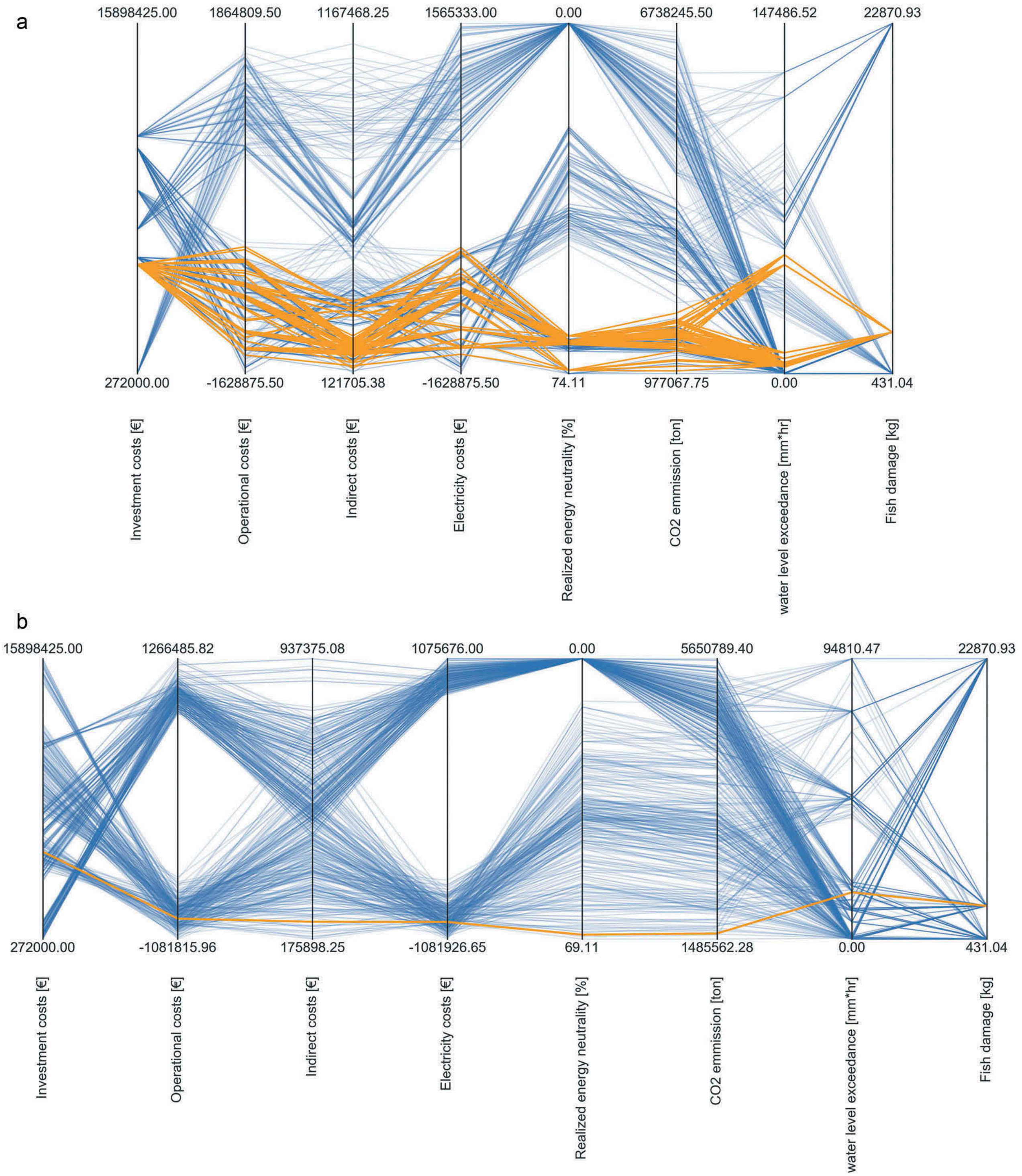

Figure 10. (a) Average performance of the final design (orange) compared to all designs (blue). (b) Performance of the final design (orange) for all scenarios compared to all designs (blue).

motor type, pump control and electricity supply, result in 500 alternative designs. The performance of all design alternatives was evaluated on four categories of performance metrics measuring functional, energy, ecological, and cost performance. Combining the future states of the world and the 500 sampled design alternatives resulted in a total of 24,000 simulations. A complementary set of 5700 simulations with energy neutrality fixed at 100% and the solar/wind mix at 50% was performed for more detailed analysis of the influence of the pump controller on pumping station performance. The results of the simulations were analysed using extra trees feature scoring and scatterplots and Gaussian kernel density estimates.

The first set of simulations resulted in a design choice for 3 out of 8 design levers. Installing two new pumps and maintaining one of the installed gas engines and implementing the weather alarm results in a robust design for water level exceedance. From an energy perspective, the most robust design is a solar-wind mix of 50% combined with local control. From an ecological perspective changing the impellers seems to provide the most balanced trade-off between fish safety and costs. From the perspective of cost performance, the investment costs of improved pump inflow are so minor as compared to their benefit in improving energy efficiency that they should, like permanent magnet motors, be included in all designs and because they are robust under all scenarios. Additional simulations, analytic approaches and technical considerations were required to arrive at specific choices for the choice of the pump controller. The analysis leads to the conclusion that local control is most robust for all energy performance metrics when combined with an energy neutral design of the pumping station, since for local control less energy is being purchased and more energy is sold. This resulted in a final design with two improved inflow pumps driven by permanent magnet motors equipped with fish safe impellors employing weather alarm and local control with an energy neutral power supply with a fifty-fifty solar/wind mix.

The final design, however, comes with four caveats. First, the climate and energy scenarios at used are not weather consistent. This inconsistency in the correlation between solar intensity and wind speed causes a mismatch between the production of solar and wind energy on a national level as described by the climate and energy scenarios used and the local energy production. Second, due to limitations in data availability of the energy scenarios we were forced to limit the length of our simulation to 5 years. This is sufficient for this illustrative application. For final design including longer time series is advised. Third, climate and energy scenarios are assumed to be uncorrelated. Fourth, methodologically it would have been more elegant to include scenarios for tax and subsidy policies as uncertainties in the PSST model to perform a more elaborate exploration of its influence and make the design robust against changing policies.

We applied a robustness metrics based on descriptive statistics that expresses robustness as a combination of a good average performance (μ) and a narrow bandwidth (σ). This metric is transparent, easy to communicate and could be used to investigate trade-offs between design options. The pump control for instance, created a trade-off between the energy bill and sustainability. On the one hand, pump control based on the availability of local wind and solar power showed robust behaviour for CO2 emissions and use of local energy. On the other hand, pump control based on hourly APX electricity prices was extremely sensitive to the energy scenarios, resulting in poor robustness. By considering multiple performance objectives, instead of just a single cost objective, many trade-offs and interactions between design choices and future scenarios were revealed.

As alternative to the Multi-Objective Robust Simulation used in our case study, we could have implemented a formal many-objective optimization. Performing a full optimisation would require us to either assign a variety of a-priory weights to the criteria or apply a many-objective optimization approach (Joseph R Kasprzyk et al., 2016) in order to find the pareto optimal set of designs. In either case, the decision relevant supporting insight as to why and how different decision variables are selected would still be lacking.

We therefore conclude that the Multi-Objective Robust Simulation approach applied not only supports the development of a robust design but also created deeper insights in trade-offs between performance indicators across a range of design choices under different futures conditions. These insights are of interest to the college of Burgomaster and Alderman of Water Board Zuiderzeeland, that, being a democratic institution, can now have an informed discussion and come to a balanced decision in their quest to become energy neutral before 2050.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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