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Resilience Management Of Critical Infrastructures: Assessing Control Strategies Under Societal Values And Model Uncertainties

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Abstract

This study presents a novel approach to enhance the resilience of critical infrastructure systems by integrating control theory and societal values. We translate societal value personas into simulation parameters using a linear model and fit matching coefficients. The approach enables decision-makers to identify resilience abilities and compare enhancement options. The application to a railway infrastructure demonstrates the versatility of the methodology, providing insights into system behavior under diverse stakeholder perspectives. The study contributes to a comprehensive understanding of critical infrastructure resilience, addressing uncertainties through a unique combination of control theory and societal values.

Keywords: resilience management, control strategies, societal values, decision making, uncertainties

1. Introduction

Critical infrastructure systems are part of the broader system of society by providing essential services to citizens and therefore require careful consideration in terms of maintenance and development. The concept of resilience has become increasingly important within the context of protecting critical infrastructures under the uncertainty of stressors. (Carlson et al., 2012; Chester et al., 2021; Kanno et al., 2019; Rehak et al., 2019) To improve the resilience of a system, it is essential to develop methods to accurately quantify relevant resilience metrics (Pimm et al., 2019). Weighing the costs and benefits of infrastructure projects plays an important role in the decision-making process (Annema, Mouter and Razaei, 2015). However, decision makers are especially interested in tools highlighting the political trade-offs of policies, for which classical cost-benefit-analysis is less suitable (Annema et al., 2015). Where resilience seeks to account for all possible threat scenarios and infrastructure systems touch upon the lives of many stakeholders with different interests, decision-making in this domain faces deep uncertainty (Kwakkel and van der Pas, 2011). This is where stakeholders and decision makers do not know or cannot agree on the system model and the probabilities for uncertain parameters of a decision problem (Lempert, Popper and Bankes, 2003). This research aims to investigate how the perception of different stakeholders can influence the expected behavior of a control system model and how this information can support decision making. Stakeholders' expectations about the behavior of a system also hold implications for the expected resilience of a system or the resilience gain from decisions. This will enable decision makers to better identify resilience abilities, to assess and compare the various resilience enhancement options and decide on the best course of action.

Importantly, throughout this research the presented results and system behavior are not supposed to represent actual system performance but the subjective expectation of the respective stakeholder about how the system would perform. To this end, the resilience of an infrastructure system can be quantified through the evaluation of the system's performance during a disruption with respect to the stakeholders' expectations. In the following we use societal values to represent stakeholders and derive their expectations.

Combining the approaches of (Demmer et al., 2023) and (Schönwandt et al., 2022) this work proposes to join control theory and the concept of societal values (Schwartz et al., 2012) for evaluating the state of a system and possible measures to increase its resilience. From the perspective of control theory, the objective of resilience theory is to bring a time-variable system to a certain state, called a resilient state. Here, a challenge is the imprecise knowledge about the system and various influencing variables. A technical solution to this challenge is to control such system by feedback. This does not necessarily require an accurate model of a system, but the measurability of influencing parameters and variables. Adding the perspective of societal values, these parameters as well as the resilience metrics are susceptible to the endowment of societal values that represent the stakeholders' point of view.

To illustrate our approach, we employ a first-order differential equation model representing a generic public infrastructure framework (Muneepeerakul and Anderies, 2017). Our study showcases the application of a Proportional-Integral-Derivative (PID) controller (Doyle, 2009) to enhance resilience under different conditions. Furthermore, societal values are drawn from Schwartz's motivational continuum (Schwartz et al., 2012), emphasizing the integration of diverse perspectives in the pursuit of resilient critical infrastructure systems.

2. Background

The basis of resilient design of infrastructures requires consideration of all threats and actions that may occur during operation. But different stakeholders have different preferences and views on a system. This becomes especially important when making predictions about the system's response to future conditions, which is mostly necessary to model disruptions that have not happened before.

2.1. Societal values and value personas

In order to represent individual stakeholders, the approach uses value personas, comprised of sets of societal values, from which the model parameters are derived. The societal values describe congruent ideas about something estimable and worth aspiring to (Deci and Ryan, 2000; Scherr, 2016). Whereas people may share the same needs, only their values distinguish their unique individuality and guide their choices (Locke, 1991). Within a social group instead of uniformly valid values there are only value complexes that critically depend on the context (Scherr, 2016). Importantly, societal values are neither given and stable, nor equally and naturally acknowledged by all social groups (Stehr, 1998). Following the approach in (Schönwandt et al., 2022), the societal values understanding follows the works of (Schwartz, 1992) and (Schwartz et al., 2012). Encompassing a range of values with personal focus and social focus, they can be used to represent the personas of discernible stakeholders, that are further called 'value personas'. A value persona combines an individually weighted set of the societal values so that it represents the distinguishable personality of an individual or group of people as suggested by Locke (1991). In the following, a value persona addresses a group of people. An important aspect in Schwartz' motivational continuum is its circular arrangement of societal values, in which neighboring values are related and oppositely located values exclude each other (Schwartz et al., 2012).

2.2. The infrastructure model

To demonstrate the application of societal values in a controlled system, we use a model based on one first order differential equation, adapted from (Muneepeerakul and Anderies, 2017). The original framework focuses on different classes of public infrastructure that affect how utilities interact with a natural resource. Here, the model is stripped down to an interplay between a railway infrastructure provider and the state of a railway infrastructure, as visualized in Figure 1. It should be noted, that the general perspective of this model is not restricted to any type of critical infrastructure or provider.

In this abstraction, users pay the railway infrastructure provider. The infrastructure provider then has a maintenance budget based on the revenue and the state of the infrastructure depends on the invested money and leads to more users. We extend this model with a varying natural depreciation rate that affects the state of the infrastructure to simulate stressors. Equation (1) represents this behavior:

$$\frac{dI}{dt} = \mu y C p H(I) - I\delta \tag{1}$$

with the performance of the infrastructure (*H(I)*) defined in (2):

$$H(I) = \frac{100}{1+e^{-2\left(I-1.65\ ^{j}/_{100}\right)}}. \tag{2}$$

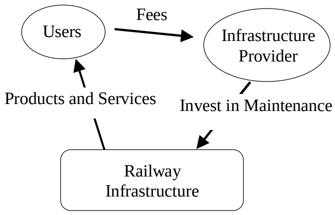

Fig. 1. Schematic diagram of the Infrastructure-Provider-Model.

As in Muneepeerakul and Anderies (2017), I is the state of the infrastructure [Unit I], μ is the maintenance effectiveness [I/$], C is the revenue as the fraction of utility provided to users by the system performance $H(I)$[-], y is the fraction of C which infrastructure providers invest in maintenance [-], δ is the depreciation rate of the infrastructure over time [1/T], j is the level of aspired infrastructure state at which full performance is achieved [-] and g is the infrastructure providers profit. The system reacts differently to stress, here implemented by a changing amount of δ. Figure 3 shows the exemplary situation where we look at different reactions of the system to stress. The initial situation is: μ = 0.001; C = 0.6; y = 0.6, I = 3.5; p = 10 and δ = 0.1 (see Muneepeerakul and Anderies, 2017). We then model a stressor through the increase of the depreciation rate to $\delta = 0.3$. As resilient systems should adapt to varying conditions, we introduced a closed-loop controller. The PID-controller has the objective to keep the system performance constant for all disruptions. The controller adapts y depending on the system state I with (3). It should be noted that every value persona has a different understand of the reference point.

$$y_i = y_0 + K_P e_i + K_I e_{sum,i} + K_D \Delta e_i \tag{3}$$

where e_i is the current error, $e_{sum,i}$ is the current sum of errors and Δe_i the current change in errors. K_P is the proportional, K_I the integral, and K_D derivative term coefficient (Doyle, 2009). Error is here the deviation between the current and the desired system state. K_P, K_I, and K_D control how fast y increases when a disruption happens and how fast it decreases in case whenever the state is better than desired. Of course, the stressor intensity and duration are highly uncertain and could also be subjective to different value personas. In this work we assume one fixed scenario, so that all personas consider the same disturbance.

The systems infrastructure providers profit is described with (4):

$$g = \sum(1 - y_i)CpH(I_i) \tag{4}$$

The profit is the residual cumulative value of the share not invested into maintenance from the amount paid for using the infrastructure (C).

3. Application

The above described model is generic and can represent a control mechanism in many different contexts. However, a decision can only be made with respect to a specific context and also societal values are context specific (Scherr, 2016). Therefore, to fulfil the prerequisites for combining control theory and societal values in this research, a railway network infrastructure for personal transport is chosen as the context. Focusing on personal regional transportation, the railway network of a city competes in varying capacities with walking, cycling, road-based public transport (bus) and road-based private transport (car). Consequently,

Fig. 1 is interpreted so that the infrastructure provider manages railways and stations, obtains revenue from train tickets sold and re-invests part of this revenue into the railway infrastructure for maintenance, repairs, and development. From the point of view of the users, the passengers, the railway network offers a service in form of mobility so that they can accomplish their activities. In turn they pay a fee to the infrastructure provider. Furthermore, bringing societal values into this context enables to evaluate the system from the points of views of stakeholders under different value personas.

The full range of societal values presented by Schwartz et al. (2012) is not applicable in this case. Instead, the most relevant are chosen to be used in the model. The societal values are chosen based on the understanding of Schwartz (1992, 1994) and Schwartz et al. (2012). In this example, railway infrastructure is an affordable means to provide a significant level of mobility for anyone in a society, expanding the radius of travel and allowing of all people to find work further away from their living place while also being more sustainable. The inherent characteristics of social justice and protecting the welfare of people and nature address the value "Universalism". Simultaneously, the increased mobility strongly supports one's freedom and thus addresses the value "Self-Direction". While the added mobility can also enable people to improve their income by expanding their region of operation, also the provider of the railway network as a company follows economic principles and thus the value "Power" is relevant. Additionally, railway travel compared to other modes can satisfy certain security needs by offering a shelter from the weather and an easy-to-use, reliable transportation, especially for people who do not feel well to or cannot drive a car. For these reasons the four societal values "Universalism" (UN), "Self-Direction" (SD), "Power" (PO), and "Security" (SE) are chosen for the following experiment.

In application, each societal value within a value persona is given a weight. For simplicity the weights can be set to low (0), medium (0.5) or high (1), while respecting the exclusivity of opposing values, put forth by Schwartz (1992). In this case, the two antagonistic pairs of societal values are {UN, PO} and {SD, SE}. Thus, within a value persona only one of each societal value in these pairs can have a high or low weight but not both simultaneously. The next step seeks to establish a relationship between the societal values and the actual model parameters.

3.1. Parameter fitting using 4 value personas

Following the storyline-approach, first, personalities are derived from the defined context that can be expressed both in the form of value personas and in parameters for the simulation model. Table 1 depicts the four defined value personas (left) and the respectively assumed model parameters (right). They serve as starting values in order to establish a relationship between societal values and model parameters for later simulations. These starting values are used to derive coefficients to formalize this relationship.

Table 1. Definition of value personas and model parameters.

	Societal Values				Parameters					
Persona	Universalism (UN)	Self-Direction (SD)	Power (PO)	Security (SE)	K_P	K_I	K_D	j	y	C
Capitalist	0	0.5	1	0.5	0.4	0.1	0.3	100	0.6	0.9
Socialist	1	0.5	0	0	0.4	0.2	0.9	80	0.9	0.4
Special Needs Person	1	0.5	0	0.5	1.0	0.1	0.5	90	0.8	0.4
Traditionalist	0.5	0	0.5	1	1.5	0.1	0.6	90	0.8	0.7

The "Capitalist" persona is argued to focus strongly on individualistic values, especially Power, complemented by Security and Self-Direction because it may equally strive to secure its position as well as maintain independence. This attitude translates into the model parameters with lower investment levels (*y*) and higher costs for users (*C*) in order to maximize profits. Additionally, this persona assumes only 100% structural integrity to be 100% performant (*j*) and a PID controller that accepts certain disruption and rather aims to smooth-out disturbances and avoid overshoot (K_P, K_I, K_D).

In contrast, the "Socialist" persona has a high value for Universalism due to its aim for social justice, equality and partially also health of the ecosystem, whereby the aspect of equality and social justice is also supported by the value Self-Direction. Consequently, the parameters are set so that infrastructure investments are higher (*y*), transportation fees lower (*C*), and the utility is perceived high as long as the structural integrity is above 80% (*j*). Being generally less sensitive to structural integrity the controller is also set to react less (K_P, K_I) with the exception to rapid changes in order to dampen hard shocks (K_D).

Similarly, the "Special Needs Person" persona incorporates the same societal values as the Socialist, further complemented by Security because it represents those citizens that experience a temporary or permanent handicap and rely on a certain amount of extra protection, such as among others children, elderly, disabled, injured, and pregnant persons. In contrast to the parameters of the Socialist persona, the Special Needs Person persona parameters show several differences. It assumes slightly less but still high investments (*y*) and lower fees (*C*) as well as a higher level of structural integrity for maximum utility (*j*). Simultaneously, the PID controller is more sensitive to proportional and steep changes of structural integrity (K_P, K_D), less so to cumulative change (K_I).

The "Traditionalist" persona aims to conserve status quo, therefore characterized by the societal values on Security, supported by Universalism and Power. The parameters are thus set to a decent amount of investments (*y*), at medium costs for users (*C*), while allowing for minor disruptions and still obtaining full utility (*j*). Similarly, the PID controller is argued to respond quicker to disruptions, is especially sensitive to larger offsets (K_P), less sensitive to cumulative disruption (K_I), and medium sensitive to quick onset events (K_D). The input parameters for the simulations in Fig. 2 are shown in Table 1, highlighting a weighing between aggressive and moderate controller settings (K_P, K_I, K_D), as well as different perceptions of reality.

In this work, we assume that there is no ground truth. No persona knows exactly how the system will behave during future stressors, it only reflects their individual expectations. This represents that many models in the field of resilience engineering are based on expectations and cannot be validated. Fig. 2 shows the expected behavior from the perspective of each defined value persona over an undefined duration of time. With respect to a rail network infrastructure the time frame could refer to a day of 24 hours, for example. It stands out how the Capitalist persona expects to make large profits by achieving the best operating capacity with less costs. The other personas expect higher expenditure to cope with a disruption and thus make less profits. Specifically, the persona Special Needs Person is less focused on profit and only barely maintains slight profits, enough to balance out losses from minor disruptions. However, together with the Socialist persona it expects to receive external financial support to pay for larger deficits because its priority is serving as many customers as possible at affordable prices. The Traditionalist persona aims to achieve small but steady gains and thus shows slightly higher profits than the Socialist and Special Needs Person personas but lower than Capitalist's. Consequently, this behavior appears consistent with the line of argumentation designing the value persons, which supports the choice of parameters.

These personalities are then applied in a simple linear model that describes how the weights of the four societal values in each of the value personas affect the model parameters (equation (5)).

$$P_{p,k} = a_{p,v} * V_k + c_p \qquad (5)$$

Here, $a_{p,v}$ represents a matrix of coefficients for each combination of model parameters p and societal values v. The exact correlation between the value personas and model parameters is unknown and thus (5) follows the assumption that there is a linear correlation. A value persona k is part of the collection of value personas (V_k) and comprises a weighted set of societal values (v) that characterize this value persona. The set of model parameters for each value persona $P_{p,k}$ is obtained by multiplying the respective range of coefficients $a_{p,v}$ with the vector of weighted societal values (v) that defines the value persona k in V_k, adjusted by a constant value per model parameter c_p. This term is solved for $a_{p,v}$ and c_p in order to obtain the set of coefficients and constants for translating value personas to model parameters.

The target parameters are y, C, j, K_P, K_I, and K_D. We assume the effectiveness of maintenance μ and the depreciation rate δ to be external factors that are not affected by personal perspectives. Solving the linear model (Equation (5)) results a set of coefficients and constants that can be used to convert any value persona of the four chosen societal values into parameters of the simulation model. For validation and verification, the obtained coefficients are applied to all possible value personas and the resulting parameters analyzed. Due to the simplicity of the model and the reduced set of societal values used for the parametrization of the coefficients, there is certain imprecision involved and some of the calculated parameters based on the derived coefficients exceed their logical boundaries. Therefore, buffers are added to the coefficients to mitigate these effects. The final set of coefficients and the constants are shown in Table 2.

Table 2. Matrix of coefficients $a_{p,v}$ and the set of constants c_p with respect to the model parameters p.

Coefficient	K_P	K_I	K_D	j	y	C
$a_{p,UNN}$	-0,1	0,15	0,35	-12	0,1	-0,2
$a_{p,SD}$	-0,45	-0,1	-0,4	2	0,05	-0,2
$a_{p,PO}$	-0,4	0,15	0,1	2	-0,2	0,35
$a_{p,SE}$	0,9	-0,1	-0,3	7	0,15	-0,1
c_p	0,9	0,1	0,6	90	0,7	0,7

With these coefficients, all model parameters are within the pre-defined boundaries, only four value personas might be considered as unusable because they show strong oscillations due to a bad combination of controller parameters.

3.2. Selected Results

There are 49 possible combinations of value personas. Because it is not suitable to show all of them, we selected the four extrema in Table 3 to present our results.

Table 3. Definition of selected calculated value personas and model parameters.

	Societal Values				Parameters					
Value Persona	Universalism (UN)	Self-Direction (SD)	Power (PO)	Security (SE)	K_P	K_I	K_D	j	y	C
vp6	0	0.5	0.5	1	1.38	0.02	0.15	99.0	0.78	0.67
vp12	0	1	1	0	0.05	0.15	0.3	94.0	0.55	0.85
vp30	0.5	1	0	0.5	0.85	0.02	0.22	89.5	0.88	0.35
vp45	1	1	0	0	0.35	0.15	0.55	80.0	0.85	0.30

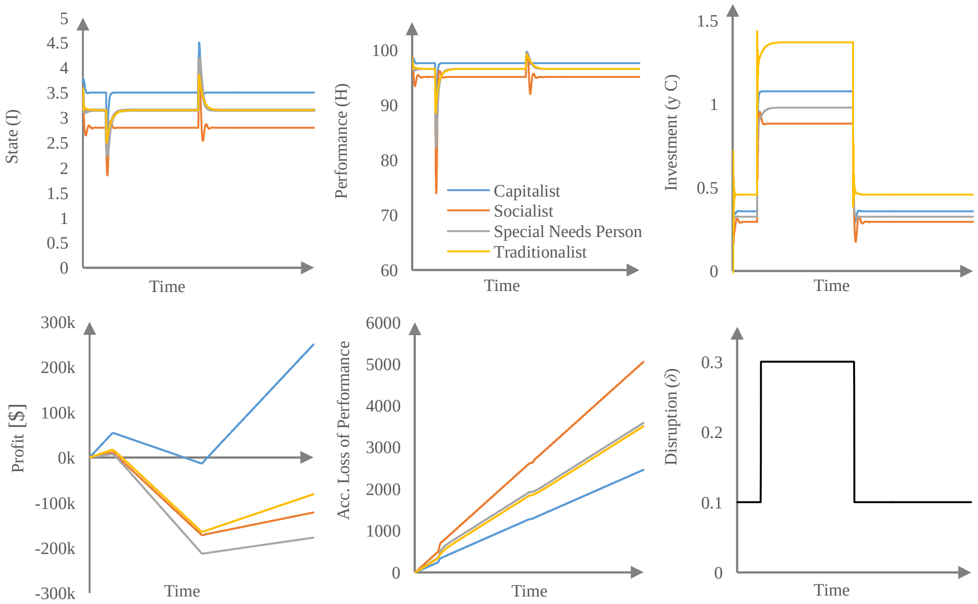

Fig. 2. Verification of the behavior of defined personas before deriving the coefficients.

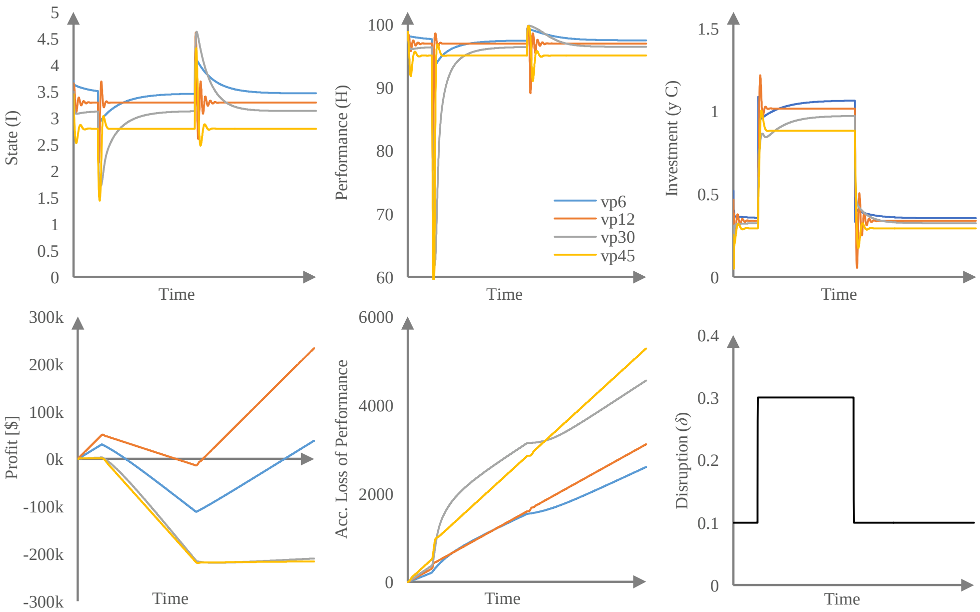

Fig. 3. Simulation results for all worldviews.

The simulation output is presented in Fig. 3 and shows a wide range of possible solutions for the modelled system. Persona 6 configures the controller to be slow but steady without overshooting. This leads to a slow reaction time to changing conditions. Simultaneously the variable investment in maintenance is set on a rather high level during normal operation ($yC = 0.36$) as well as under disruption ($yC = 1.06$). This leads to a decent profit (38 k$) and the lowest downtime (2595).

In contrast, Persona 12 configures a very reactive controller that tends to overshoot. The estimation of the system behavior is worse (j = 94), but with a comparable amount of investment in maintenance during the disruption (yC = 1.01). The quicker reaction time results in more profit (233 k$) and slightly more downtime (3110).

Persona 30 again has a slow controller and a more pessimistic understanding of the system (j = 89.5). This persona invests less in maintenance (yC = 0.97) to get the same system performance and therefore makes a loss of 209 k$ due to an expected extended downtime.

Persona 45 has an even more extreme approach to system understanding (j = 80), is only able to invest less in maintenance (yC = 0.88), and has the most loss of performance (5278). This persona configures a very reactive controller setting, that tends to overshooting. This understanding makes the most loss (215 k$) due to the worst expected system performance even during normal operation (95).

4. Discussion

This contribution is aimed to advance the application of control systems and societal values in decision processes. Joining both topics in this research using a simplistic and abstract differential equation model and a reduced set of four, yet normatively complex, societal values presents a challenge. In order to bridge this gap defining a context for this experimentation is indispensable. While the generic model is independent from a context and finds useful application in abstract research (Demmer, 2023), the use of societal values to represent stakeholders is strongly context dependent (Scherr, 2016). Nonetheless, providing a context also benefits the model to find more vivid application. Considering the importance of providing a context for this research, its description remained rather abstract and short as well. Its level of detail follows that of the model in order to match its functionality and prevent the creation of artificial limits. Simultaneously, this leaves a lot of room for interpretation that should be handled carefully in this discussion. The theme of the context is picked at random from the pool of present topics on the German agenda of infrastructure topics.

The selection of societal values also reflects the low level of detail of the model and context description. Based on Schwartz (1992), all four societal values used are aggregated versions and could further be distinguished, such as Self-Direction with respect to action and thought, Security with respect to personal and societal, Power with respect to people and resources, and Universalism with respect to nature, community, and tolerance. In some cases, a different aspect of a societal value group could be relevant than in others. However, due to the low level of detail of the model and the simplicity of the case, the four groups show better applicability across the range of value personas than distinct societal values from within the value groups. Consequently, the application of the value groups for constructing different value personas in dependence of the context appears straightforward, suggesting a good fit. Nonetheless, applying these value groups also implies more flexible interpretation so that the defined value personas are not as clear-cut as Table 1 suggests. For example, the Socialist persona is set to a medium value for Self-Direction. However, arguments could be made equally in favor of raising or lowering this weight depending on the expectation of a socially oriented person to believe social policies to foster the freedom of action and thought of citizens or the believe that both are not correlated.

Translating the value personas into model parameters relies on a number of clues on both sides that help identify their relationships. However, the previously mentioned simplicity of the present case complicates identifying correlations and the nature of effects. Introducing a context mitigates these deficiencies to some extent by wrapping the model in characteristics the societal values can relate to while the mathematical structure remains the same. Nonetheless, the lack of detail persists and hides relevant information regarding the order of the function that describes the relationship between societal values and model parameters. Therefore, assuming a linear correlation seems logical and maintains simplicity. However, the choice potentially oversimplifies the complexity of human decision-making and may inaccurately propagate stakeholder perspectives in this case.

Moving on to the results, applying societal values, represented by value personas, adds a layer of complexity to the evaluation process but also enhances the level of information. It clearly highlights the relevance of underlying assumptions. By recognizing that stakeholders may have diverse interests and priorities, the model attempts to capture this variability through differently weighted societal values that differentiate the value personas. This approach follows the understanding that decisions related to critical infrastructure are not only technical but also shaped by societal expectations and values. In an environment of incomplete information, assumptions and expectations carry significant weight in a decision. The presented results for the selected personas illustrate possible effects. vp6 strongly values Security, suggesting that an effort should be made to maintain a high-quality infrastructure system. This could be motivated from a traditionalist and egalitarian view, seeking to protect what you have as much as possible. This persona could also represent a more fragile group of people, similar to the Special Needs Person persona (Table 1), who relies significantly on the infrastructure's functioning. This is supported by high values of j (Table 3) and yC (Fig. 3). vp12 focuses on Self-Direction and

Power values, such as small to medium sized economic actors who aim to expand their business to gain a larger share of the market while remaining flexible to the desires of customers. In order to achieve high profits, vp12 expects the second highest investment level (*yC*). In contrast to vp6, vp12 funds the investments from higher price levels (*C*) from which a larger portion is retained to drive profits. Such behavior is typical for businesses in vendor markets and monopolies, such as premium goods or some capital-intensive sectors. vp30 focuses on Self-Direction and supported by Security and equality aspects. The missing Power value allows the focus to shift away from profit to other aspects. Therefore, the price is set low (*C*) while a large portion of the revenues (88%) is re-invested into the infrastructure (*y*), resulting in a slightly lower investment level (*yC*) but also achieving less financial burden on users. vp45 has a strong focus on nature, social justice, and self-determination. It is thus more socially oriented than the previous value personas. The minimum required system state is 80% (*j*), while also the prices are lowest (*C*), and the share of investments from revenues is second highest (*y*), which suggests that the value persona gets more utility from allowing many people affordable access to a mainly functioning infrastructure than few people expensive access to fully operational infrastructure. A degree of inefficient allocation of investments could also be attributed to investments into side-topics. The partial focus on nature and social aspects under vp45, for example, may result in spending on natural habitat as part of the investments. However, the system model does not account for contributions to nature and thus the effect does not show. vp30 and vp45 both ask small fees from customers but a higher share of spending from the revenue of infrastructure providers. This contributes to social justice by reducing the financial burden on individuals, especially for those with low income who depend on the train network in their daily lives. However, as the profit curves of both personas show Fig. 3, in both cases the financial losses from disruptions cannot be recovered easily from operational income. Therefore, these two personas would expect the costs from disruptions to be covered by a third party that is not part of the modelled system. In socially oriented societies, such costs could be covered by the government. Especially infrastructure investments are often government funded because of enormous investment and maintenance costs.

Compared to the expected behavior of personas vp12 and vp45, the PID controller under vp6 and vp30 is set to react slower to the disruption. Its reaction to the disruption sets in around a similar pace as the others but the recovery rate degrades quickly to smoothen the curve until it reaches the desired state. This behavior could be explained with less spending due to less concern about quick recovery. Which contradicts the societal value composition of vp6, focusing on Security under the support of Power. Thus, it could be argued that this persona does not believe the recovery processes could realistically go quicker. In contrast, vp12 and vp45 show high recovery rates that easily overshoot which leads to an oscillating behavior. The oscillations under vp12 last multiple times longer than under other value personas. However, the model is sensitive to certain parameter constellations, leading to strong oscillation as mentioned previously. Therefore, the behavior of vp12 could in fact indicate realistic overshooting behavior or could be caused by systemic imprecision of the used model. This model sensitivity is a limitation to be aware of in the future.

Furthermore, regarding the practice of cost-benefit-analysis in infrastructure planning the use of societal values illustrates several implications. The value persona shown in Fig. 3 must not be confused with alternative strategies to be evaluated and selected from. The graphs illustrate the expected performance of the same strategy under different perspectives, the value personas. With respect to cost-benefit-analysis the different value personas represent uncertain scenarios of different evaluations of a strategy. First, the graphs highlight the different expectations of some of the costs and benefits. For example, it raises awareness for the uncertainty that the expected costs change significantly with the underlying point of view and assumptions. Therefore, it could be useful to take the range of possible scenarios into account. Additionally, looking closer at the properties of a value persona can reveal more aspects. Costs are commonly expressed in economic terms, which is practical for quantitative analysis. In contrast, a value persona may consider non-monetary aspects of the state and performance of an infrastructure as more important than the monetary aspects. Considering someone from the Special Needs Person persona, the ability to access a train network can have tremendous impact on that person's life in terms of invaluable experiences through the boost in mobility. Any moment of downtime of this infrastructure presents great sacrifices for that person. Not so from the point of view from other personas. The use of societal values can thus enrich such analysis by supporting different stakeholder perspectives. These results are the basis for the search of compromise strategies and more elaborate sensitivity analysis to identify critical dependencies between infrastructure systems and their stakeholders. Moreover, this approach can help to better understand the current properties that stimulate a decision and how these properties could be evaluated in the medium to long-term future when an infrastructure is still there but the desires of stakeholders have evolved.

With this in mind, the success of the proposed approach relies on accurate data inputs and parameterization. Obtaining real-world data that precisely represents societal values and their impact on critical infrastructure decisions can be challenging. Validating the model against empirical data is crucial but may be limited by the availability of comprehensive datasets. Similarly, the above exercise applies deterministic modelling, potentially overlooking the probabilistic and uncertain nature of societal values. Future developments in the methodology could incorporate probabilistic modelling to acknowledge the uncertainty in stakeholder preferences.

5. Conclusion

Resilience management of critical infrastructures relies from a technical perspective to certain extent on control theory in which a system is controlled based on feedback to adapt to adverse effects. We argue that resilience management presents a decision problem characterized by a range of different stakeholders. Each of whom with their individual perception on the system properties, the target resilient state and available means to control a system, resulting in different expected system behavior.

The work proposes a novel approach by combining control theory with societal values to assess and enhance the resilience of critical infrastructure systems. In order to better understand the implications, we expand a simplistic first order differential equation model with the concept of societal values. We discuss the process of converting value personas into model parameters, involving the fitting of coefficients. The use of linear equations to establish this connection suggests a pragmatic approach to a complex problem. The iterative method described for adjusting coefficients to ensure personas remain within realistic simulation boundaries demonstrates a commitment to maintaining the integrity and applicability of the model. The simulation results across 49 possible value personas show significant differences between the expected utility of each strategy. This is highly important to consider in a cost-benefit analysis of measures to enhance the resilience of long-living critical infrastructure.

Future work shall respect the simplicity of the used model and its sensitivity to the parameters, running the risk of unrealistic oscillating behavior. Additionally, the application of four societal values on this simplistic case leaves great room for interpretation, which may be stifling for specific research agendas. Increasing the detail of the used model as well as increasing the detail of data and information about a research case could help there.

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