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A Framework for the Simulation-Based Selection of Social Models for Socio-Technical Models of Infrastructures Using Technical Requirements Analysis

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Abstract

Urbanization increases the importance of urban infrastructures, with computer models and simulation being important tools for their planning and management. Human factors are increasingly included into infrastructure models, creating socio-technical models. This paper proposes a novel framework for selecting these social (sub-)models. For this, requirements analysis of the technical system is used to identify critical physical parameters. The impact of different assumptions in the social model on the critical physical parameters are determined using simulation and hypothesis testing. This impact is used to determine the relevance of the differing assumptions and to select the right social model. Finally, a preliminary case study of the water distribution system of Darmstadt, Germany, is used to show the efficacy of the framework by comparing two water demand models. The results of the case study show, that the framework can be used to quantify the relevant system behavior and test the significance of model assumptions.

Keywords: Model selection, socio-technical model, simulation, water infrastructure, social models, water demand

1. Introduction

As an increasing majority of the global population lives in urban areas, the reliance of citizens well-being on urban infrastructures increases as well (Grimm et al., 2008). Model-based tools, such as digital twins, are promising for the planning and management of such urban infrastructures (Bruchseifer et al., 2021). As their functions and capabilities are deeply interdependent with the behavior of citizens, infrastructures are considered socio-technical systems (Ottens et al., 2006). Therefore, the importance of including human factors into the modeling of infrastructures has been highlighted, leading to the paradigm of socio-technical models consisting of technical and social sub-models. The scientific literature presents a multitude of social models for such socio-technical models of infrastructure (Sattler et al., 2023). It therefore remains an open challenge to select the right model for a given socio-technical system, i.e. making the right assumptions about the inclusion of factors influencing human behavior. A classic approach to this challenge is to choose assumptions based on knowledge about human behavior. One formalization of this approach in the context of natural resource use has been described by (Schwarz et al., 2019).

Such classic approaches have been subject to scrutiny, due to claims of potential subjectivity, especially regarding the inclusion of additional parameters in the models (Healy, 2017). To address this challenge, it has been proposed to reduce models containing many assumptions about human behavior to models only containing assumptions that impact the social models results in a meaningful way (Edmonds and Moss, 2005).

Enhancing this line of thought into the domain of socio-technical models, this contribution proposes a novel framework to evaluate social sub-models based on their impact on the technical sub-model. In particular:

- The proposed framework uses methods of technical requirements analysis on the basis of the technical standards, such as the ISO/IEC 25040:2011 (E) (International Organization for Standardization, 2011).
- These technical standards are used to derive quantitative metrics for the critical physical parameters of the technical system.
- Statistical methods are then used to evaluate the significance of the differences between the different models.

Therefore, the framework can be used to evaluate model assumptions about human behavior based on their relevance for the technical model.

To illustrate the application of the framework and demonstrate the frameworks efficacy, a case study is presented. The case study selects a social sub-model for a socio-technical model of the water distribution system (WDS) for potable water in the city of Darmstadt, Germany. The technical model is identical in both cases. The framework is then used to compare a simpler model of spatially stationary water demands with an extended model that includes the mobility behavior of citizens in the city.

The paper is structured as follows: Section 2 presents the scientific background of this paper. In Section 3, first the methods used to design the comparison framework are presented, followed by a description of the methods and data used to implement the two models in the case study. Then, Section 4 shows the specific steps of the framework and its application for the comparison of models in the case study. This is followed by a brief description of the results of the case study in the same Section. Finally, Section 5 will discuss the applicability, merit and limitations of the presented approach, with Section 6 concluding the paper.

2. Related Work on Human Factors in Socio-Technical Models

The most visible parts of urban infrastructures are typically technical systems, e.g. roads, water pipes, electric transmission cables, or telecommunication transmitters. However, as (Ottens et al., 2006) argued, the behavior and functions of technical infrastructures are deeply interdependent with human factors. Examples for the interactions of social and technical systems are the influence user behavior has on the function of technical systems or how the availability of technical systems might influence user behavior or norms, i.e. laws and standards. Therefore, infrastructure engineering should always consider these interdependencies by defining infrastructures as socio-technical systems, i.e. systems consisting of technical and social components and their interactions. (Ottens et al., 2006) further specified multiple types of potential interactions between social and technical components and implications for systems engineering processes. He highlighted that the interactions including social factors are typically not described by the physical equations used for technical systems.

(Vespignani, 2012) gave an overview of modeling paradigms for socio-technical systems. He highlighted the importance of computationally demanding models, e.g. simulations and non-linear models for the field.

One common modeling paradigm is agent-based modeling (ABM). (van Dam et al., 2013) gave a comprehensive overview of the methods and prospects for the application of ABM for socio-technical systems. They pointed out, that ABM can especially be fruitful due to the ability of ABM to represent spatially distributed systems of multiple heterogeneous actors.

In a prior review, (Sattler et al., 2023) have shown that a multitude of potential social models including various decision variables and structures and are presented in the scientific literature in the case urban water infrastructures. Therefore, selecting the right model for a given socio-technical system remains a challenge.

Selecting model assumptions, i.e. deciding which variables and relationships between those variables are relevant to describe a phenomenon in a given context, is an essential part of modeling. (Schwarz et al., 2019) discussed methods for the identification of theories of human behavior and their translation into computational models. These methods start from the selection of a theory, i.e. a logic or reasoning of how the real system behaves, and formalizes computational models on this basis. However, such methods have been subject to scrutiny.

(Healy, 2017) criticized, that in most cases one could always argue for the necessity to increase nuance, i.e. the inclusion of further variables into theories or models, since every model is an abstraction from the real systems behavior. He further emphasized the importance of simple scientific models, essentially reinforcing the principle of parsimony (commonly referred to as *Occam's razor*).

(Edmonds and Moss, 2005) proposed an approach to solve this problem of the inclusion of additional variables into models of human behavior. Their approach starts from descriptive models including all potential variables, and reducing such models as long as the behaviors of interest are retained. They pointed out, that their approach is context-dependent and one challenge with applying their approach lies in adequately defining the metrics to measure which behavior should be deemed relevant and therefore be retained.

For comparing models and identifying whether two models relevantly differ from each other, (Axtell et al., 1996) proposed the concept of distributional equivalence.

Similarly to (Edmonds and Moss, 2005) they stated, that two computational models will rarely be completely equivalent (which they call numerically equivalent). However, the models can produce statistically equivalent distributions of outputs. Therefore, statistical tests can be used to deduct, whether two models portray the same dynamics, i.e. the same statistical distributions of outputs.

While the aforementioned literature provides many perspectives on the selection or building of adequate models, to the authors knowledge, the application of such procedures to socio-technical models is lacking. Therefore, this paper aims to develop a novel approach for the comparison of socio-technical models, enabling the evaluation of the relevance of assumptions of the social (sub-)model. This is done by identifying the relevant behavior of the technical system through requirements analysis and determining the effect of the social models on this relevant technical behavior. Finally, the notion of distributional equivalence is utilized to judge, whether the effects of the social model on the technical model differ significantly between alternate social models.

3. Materials and Methods

The proposed framework compares two models using social sub-models of differing detail. Therefore, the used methods are twofold:

- First, a methodology for creating the comparison framework is presented.
- Secondly, it is described which methods and data were applied for building the models in the case study.

The relation between the comparison framework and the case study is depicted in Figure 1.

3.1. Requirements Analysis and Comparison Methods for the Framework

To establish a rigorous procedure for the of comparison of the two models, the framework was built based on a reference process. The structure was aligned with a well-established standard for the requirements analysis of technical systems. The ISO/IEC 25040:2011 (E) standard was chosen for this purpose (International Organization for Standardization, 2011). Sections 6.3 to 6.4 of the ISO/IEC 25040:2011 (E) aid to specify the relevant features and the quantitative measures for the comparison of a system to its user requirements. Therefore, these sections were appropriated to build the framework.

On the basis of this approach, technical standards were used as a codification of requirements, identifying the critical physical parameters of the system. Then, metrics for those critical parameters were identified and limits of criticality were assigned on the basis of the standards. These limits indicate, whether the physical parameters recorded during the simulation of the socio-technical model exceed the critical levels of the technical standards.

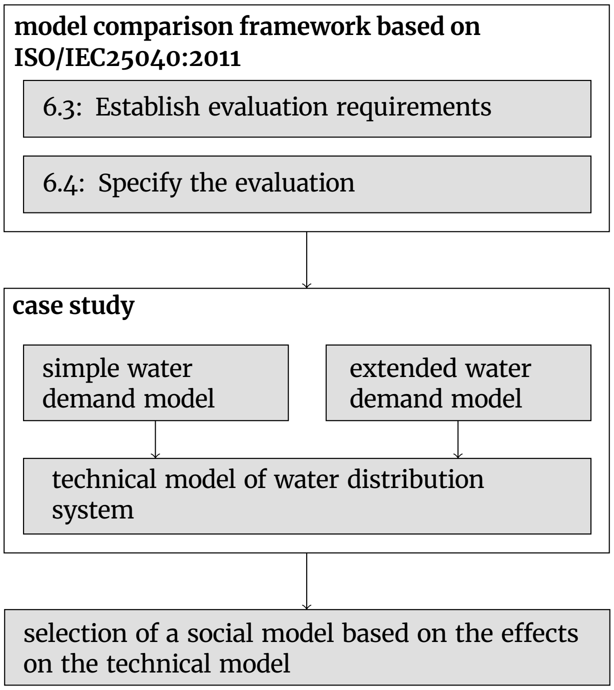

Figure 1. Connection of the framework and the case study. The framework outlines a method for model comparison. This model comparison is illustrated on two alternative socio-technical models of a water distribution system in the case study.

A process to judge the differences or equivalence of the models regarding the physical parameters was defined based on the approach for distributional equivalence proposed by (Axtell et al., 1996). To judge distributional equivalence, frequentist statistical tests were defined to evaluate the statistical significance of the differences between the simulations of the alternative model configurations. The adequate statistical tests had to be selected according to the nature of the underlying statistical variables. For this study, the scale of measurement and sample size of the variables was most important. The scale of measurement refers to the relation between values observed for a variable, i.e. whether the variables describe ordinal data or interval data. Ordinal data is data which depicts an order of values, e.g. variables which only use the values "true" and "false". Interval data relates values by continuous and well defined intervals, e.g. real numbers, for which a distance between two values can be calculated.

Finally, an aggregate metric was defined to summarize the results of all previous metrics as described in the ISO/IEC 25040:2011 (E).

3.2. Models and Data for the Case Study

The framework was then illustrated on the comparison of two socio-technical models of the water distribution system (WDS) for potable water in the city of Darmstadt, Germany.

The technical model was in both cases developed based on the procedure presented by (Rehm et al., 2021). This approach utilizes the parallelity of different infrastructures to reverse-engineer a probable layout of a WDS from openly available map data. The WDS was then implemented as a python model using the Water Network Tool for Resilience (WNTR) (Klise et al., 2017), allowing the simulation of the technical systems behavior as a reaction to water demands. The technical model consists of a total of 242 pipes, 205 demand nodes, 2 tanks, 2 reservoirs and 5 pumps.

This technical model was then extended by two different social models. The social models were build with differing degrees of detail. The extended social model includes the mobility of a synthetic population of the city, while the simpler model does not include mobility.

The extended social model was built by using the Travel-Activity-Pattern Simulation (TAPAS) (Heinrichs, 2011). TAPAS is a micro-simulation of activity patterns based on representative population and mobility demand data in Germany. The output of a TAPAS simulation for Darmstadt was used to calculate the number of citizens demanding water in each section of Darmstadt at a given time increment. The simpler model was built by assuming a stationary position for each citizen according to their position at 6 a.m. in the complex model, i.e. the TAPAS output.

Both social models were calibrated using the same data. The average daily water consumption of the city of Darmstadt in the year 2020 was drawn from (Regierungspräsidium Darmstadt, 2022) and the diurnal water consumption pattern of the city was assumed according to (Klingel, 2018).

Based on this, the hourly water consumption for each agent was calculated according to

$$q_t = \frac{Q}{24}\frac{f_t}{n_t}, \tag{1}$$

where q_t is the water consumption for each agent in hour t, Q is the average daily water consumption of the city, f_t is the factor indicating the water demand of hour t relative to the average hourly demand according to the diurnal water consumption pattern, and n_t is the number of citizens located in the city bounds at the given time. Finally, in both models the hourly disaggregate water demand was assigned to the nearest node in the WNTR model of the WDS. Both models were used to simulate one day. The simulation outputs were then analyzed according to the framework.

4. Results

The results of the paper are presented in two subsections:

- First, the developed framework for the comparison of socio-technical models is presented.
- Then the case study is described, including the results drawn from the application of the framework.

4.1. Framework

As outlined in Section 3, the Sections 6.3. and 6.4. of the ISO/IEC 25040:2011 (E) were adjusted to guide the comparison of two socio-technical systems. The steps of the framework and the corresponding sections of the technical standard are presented in Table 1. In contrast to the ISO/IEC 25040:2011 (E), the framework aims to compare two models regarding their representation of the critical physical parameters of the technical system. Therefore, the identification of evaluation requirements in Section 6.3. of the ISO/IEC 25040:2011 (E) was adjusted in the framework to identify the outputs of the model relevant for the comparison.

Then, technical standards were used to identify physical traits critical for the system. These traits are either critical for the physical integrity of the WDS or for the provision of its objective functions, i.e. the sufficient supply of potable water to the cities citizens. From these critical physical parameters all those were identified, that could be calculated on the basis of the model output. As the model is necessarily a simplified representation of the real world, this excluded requirements that were not within the scope of the technical model, e.g. the WNTR simulator does not simulate dynamic pressure surges which therefore were not included in the comparison. Then, thresholds of criticality for all identified the physical parameters were defined based on the standard.

Section 6.4. of the ISO/IEC 25040:2011 (E) was used to specify the evaluation. In the proposed framework this means that the statistical comparison procedure for the models has to be defined. Following the works of (Axtell et al., 1996), it was assumed that the models were equal, if they were distributional equivalent. For this, the hypothesis "H0: The two models are distributional equivalent." was tested for each metric. Finally the summarized metric of the comparison framework was defined as follows: If the hypothesis was not rejected on any of the metrics, then model equivalence regarding the relevant system parameters was assumed. Therefore, it was assumed that the simpler model can be used as an adequate representation for the given socio-technical system.

4.2. Case Study

Both models are implemented as described in Section 3. As expected, the resulting behavior of the technical system differed between models. This can be seen when plotting the outputs of both models for a specific physical parameter in the same diagram, which is shown in Figure 2. It depicts the supplied water in relation to the water demand assigned at each node for each of the models. As can be seen, the model outputs differed slightly between the two alternative social sub-models.

However, the comparison framework aims to identify whether the differences between the models are relevant on the basis of the critical physical parameters of the system, as explained in Section 1. As tests for the distribu-

Table 1. Framework for the comparison of two different social sub-models. The framework is based on the ISO/IEC 25040:2011 (E). The resulting framework was used to compare two socio-technical models of the WDS in Darmstadt, differing in their social sub-model.

Section in ISO/IEC 25040:2011 (E)	Activity in the framework	Result of framework activity for the case study
6.3: Establish the evaluation requirements	**Identify relevant features for model comparison**	**Outputs of the technical model relevant to the comparison**
6.3.1:Establish the purpose of the evaluation	Establish goal and scope of the comparison	Socio-technical models for the operational management of urban WDS.
6.3.2: Obtain the software product quality requirements	Identify system objectives	Technical standards regarding security of supply.
6.3.3: Identify product parts to be included in the evaluation	Identify physical and functional variables critical for the system objectives or the systems integrity	Variables in the technical model that are critical according to the technical standards regarding water service and technical integrity of the WDS.
6.3.4: Define the stringency of the evaluation	Define the stringency of the evaluation	Thresholds of technical criticality are given by technical standards.
6.4: Specify the evaluation	**Define quantitative metrics for the comparison**	**Statistical evaluation procedure**
6.4.1: Select quality measures	Define adequate statistical measures	Frequentist tests for the distributional equivalence according to (Axtell et al., 1996) specific to the measured physical traits and obtained data types.
6.4.2: Define decision criteria for quality measures	Assert significance thresholds	H0: both models are distributional equivalent. Significance level α = 5%.
6.4.3: Define decision criteria for evaluation	Assert decision rule for the aggregate assessment of the two models	All test must fail to reject the H0 to assume H0 as true.

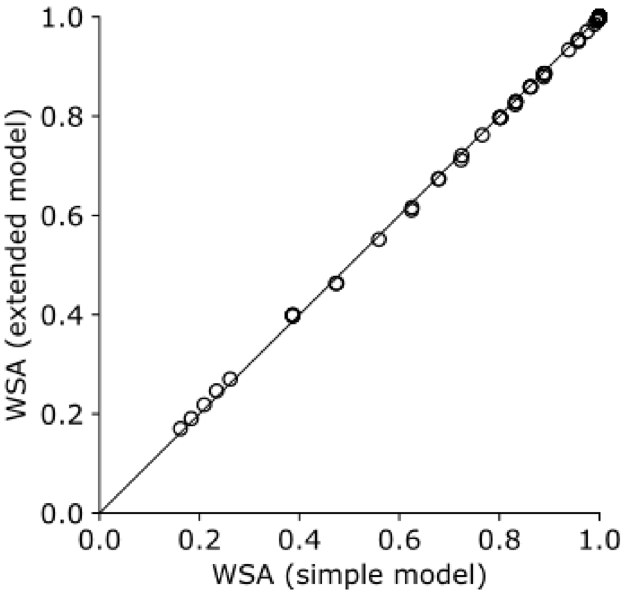

Figure 2. Water service availability at each node in the two different models. As can be seen, the two model outputs were not identical, as not all markers are located directly on the diagonal of the coordinate system. However, the model outputs were highly similar, as was shown by the performed statistical analysis.

tional equivalence, the Kolmogorov-Smirnov-Z-test was used for interval data and the Pearson-χ^2-test was used for ordinal data. Further, for the pressure difference within each pressure zone of the WDS, the Yates correction for the Pearson-χ^2-test was used to account for the small sample size of N = 24. For the pressure differences within each pressure zone, no p-value can be calculated by the statistic test since all values of the metric were identical.

The results of the statistical tests and their statistical significance level is indicated in Table 2. While most statistical tests failed to reject the H0-Hypothesis on a significance level of α = 5%, the number of changes of the direction of flow differed between the models significantly. This metric is presented in Figure 3.

Therefore, the hypothesis was rejected of an aggregate level. This means, that based on the framework one has to assume that the distributions of the models results were not equivalent and citizens mobility had a significant impact on the predicted technical behavior of the technical model.

5. Discussion

Three distinct perspectives should be considered: The relevance and merit of the frameworks approach to model selection, the selected criteria and methods of comparison, and the limitations of the case study at hand.

First, the results of this framework might be limited in their transferability. Since the evaluation was performed on a specific instance of the model, other situations might increase the relevance of certain factors on the social system. An example for such situations might be crises, which might change the behavior of the humans in a system. For the example of the presented case study, changing the assumed mobility behavior due to an evacuation might increase the relevance of the mobility behavior on the technical system, as (Logan et al., 2021) showed. Therefore, like traditional social science approaches, the results of

Table 2. Physical parameters assessed for the comparison and statistical tests for distributional equivalence.

Physical parameter	Reason for inclusion	Statistical test	Data values	p-value
Hours, in which the flow velocity in each pipe surpasses 2 m s^{-1}.	Risk of pressure surges and increased energy cost. (Klingel, 2018; DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015)	Kolmogorov-Smirnov-Z	242	1.000
Dummy variable, whether the average flow velocity in each pipe is below 0.005 m s^{-1}.	Risk for stagnation of the water. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Pearson-χ^2	242	1.000
Hours, in which the pressure at each junction surpasses 8 bar.	Risk of damage to technical components. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Kolmogorov-Smirnov-Z	205	1.000
Hours, in which the pressure at each junction is 0.8 bar or more below atmospheric pressure.	Risk of damage to technical components. (DIN Deutsches Institut für Normung e. V., 2000)	Kolmogorov-Smirnov-Z	205	1.000
Hours, in which the pressure at each junction is below 0.5 bar.	Risk of insufficient water pressure. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Kolmogorov-Smirnov-Z	205	1.000
Maximum pressure difference in the low-pressure zone in each hour.	Risk of insufficient water pressure. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Pearson-χ^2 with Yates correction	24	n/a
Maximum pressure difference in the medium-pressure zone in each hour.	Risk of insufficient water pressure. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Pearson-χ^2 with Yates correction	24	n/a
Maximum pressure difference in the high-pressure zone in each hour.	Risk of insufficient water pressure. (DVGW Deutscher Verein des Gas- und Wasserfaches e.V., 2015), as cited in Klingel (2018)	Pearson-χ^2 with Yates correction	24	n/a
Todini-Index in each hour. (Hydraulic power surplus)	Risk of insufficient water service. (Todini, 2000)	Kolmogorov-Smirnov-Z	24	0.068*
Number of changes in the direction of flow in each pipe during the simulation.	Risk of water turbidity. (DIN Deutsches Institut für Normung e. V., 2000)	Kolmogorov-Smirnov-Z	242	0.009***
Water service availability.	Insufficient water service. (International Organization for Standardization, 2007)	Kolmogorov-Smirnov-Z	188	1.000
Number of pumps failed, dummy variable for computation errors indicating failure for each pump.	A failed pump is seen as a system failure.	Kolmogorov-Smirnov-Z	5	1.000

Levels of significance: * = 10%, ** = 5%, *** = 1%.

this framework are highly context-dependent. Furthermore, it is worth noting, that the approach only aims to identify relevant assumptions about human behavior, if the impact of such behavior on technical systems is the goal of the investigated model. Therefore, the framework is not appropriate, if human behavior is the main subject of study, e.g. for sociological research. However, the framework could also be adjusted to guide the modeling and validation of socio-technical models by assisting the identification of targeted system behaviors and validation metrics.

Secondly, criteria extending the technical standards for the technical systems function will be chosen in the future, as other requirements such as societal expectations might extend the obligations identified in this study. Additionally, the stochastic analysis will be further refined. As the case study showed, a large number of relevant comparison metrics are chosen, if many technical requirements for the technical system are identified. This leads to an accumulation of test errors, which is known as family-wise error rates. This accumulation of errors indicates, that the simple summary of the multiple metrics identified on the basis of the framework is not appropriate, if multiple requirements are tested at once. Therefore, future research will improve the aggregate statistics for the model selection. Specifically, the use of statistical corrections, e.g. the Bonferroni correction, and the evaluation of Bayesian and information theoretic approaches will extend the used measures.

Finally, the case study should be extended to further evaluate the approach and provide a basis for further development. Since the chosen model of the water distribution

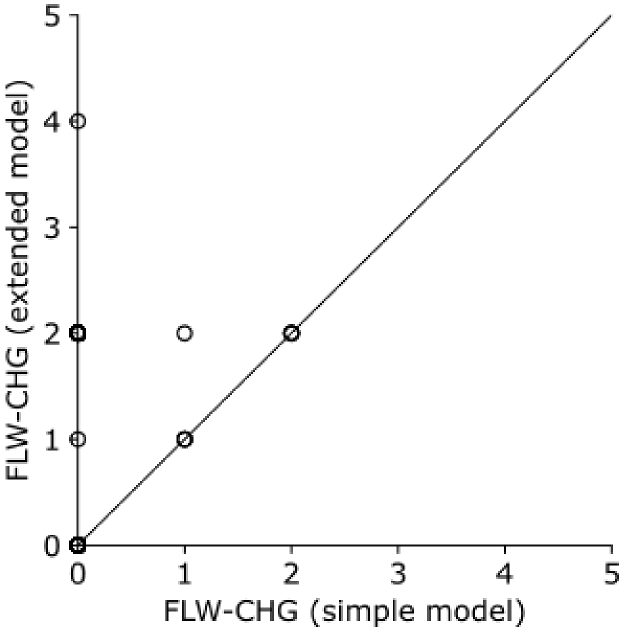

Figure 3. Number of directional changes in the flow velocity in each pipe. As can be seen, more frequent changes in flow direction were observed in the extended model.

grid in Darmstadt is still under development and not yet validated to accurately represent the actual technical system, resulting computations might not have accurately represented the technical systems behavior. However, the case studies illustrated the approach of the framework, thereby fulfilling the objective of the case study.

6. Conclusions and Outlook

The paper presented a novel approach to evaluate and select social sub-models for socio-technical models on the basis of technical requirements analysis. Goal of the model selection was to evaluate the relevance of additional assumptions about human behavior for the models. Differing from other social science methodology, the approach did not judge the relevance of an assumption by judging its impact on human behavior directly. Instead, the impact of the assumption on critical technical requirements was used for the evaluation. Thereby, the presented approach may aid the development of sparse socio-technical models. By identifying assumptions about human behavior that do not impact the technical system to a relevant degree, the models could be reduced.

To illustrate the application and efficacy of the framework a case study was implemented. The case study assessed models for a WDS and its users in the city of Darmstadt, Germany. These preliminary results show, how the framework could be used to judge the relevance of citizen mobility for building a socio-technical model of a WDS. Future research will further evaluate the efficacy of the presented approach both for conceptual modeling and model-based applications of socio-technical systems.

Author Contributions

B.J.S.: Conceptualization, Methodology, Writing - Original Draft. J.S.: Methodology, Software, Formal analysis. A.T.: Writing - Review & Editing. J.F.: Conceptualization, Methodology. P.F.P.: Funding acquisition.

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