Exploratory modelling for transport infrastructure planning under future uncertainty

Conference Paper

Author(s):
Roman Garcia, Orlando Marcel; Elvarsson, Arnor B.; Adey, Bryan T.

Publication date:
2023

Permanent link:
https://doi.org/10.3929/ethz-b-000648146

Originally published in:
https://doi.org/10.1201/9781003323020-314

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Exploratory modelling for transport infrastructure planning under future uncertainty

O. Roman, A.B. Elvarsson & B.T. Adey
Chair of Infrastructure Management, ETH Zürich, Switzerland

ABSTRACT: Planning transport infrastructure is particularly difficult due to infrastructure's long-lived nature, unpredictable technological progress and changing mobility trends in society. In complex systems facing major uncertainties, exploratory modelling can help define salient system characteristics and discover potential risks and opportunities by evaluating large ensembles of potential conditions during the planning process. This paper demonstrates how exploratory modelling can provide planning support for a federal highway from Dübendorf to Hinwil in Zürich, Switzerland. We model the future traffic flows at peak hours considering uncertainty in urban development, jobs distribution and future modal share. Current road infrastructure and further potential capacity expansions and reallocations are then tested on their robustness to provide adequate performance (in terms of travel delays) in multiple future scenarios. We use quantitative methods to identify the subset of scenarios representing risks and opportunities for the infrastructure system. The visualization of such subset of scenarios in uncertainty maps can help target interventions only when needed.

1 INTRODUCTION

Transport infrastructure planning is particularly difficult due to its long-lived nature, unpredictable new technologies, changing trends in society, and environmental change effects. Furthermore, transport infrastructure has widespread economic, environmental and social impacts and therefore numerous stakeholders, with different interests and value frameworks, are involved in the decision-making process. The difficulty of estimating the future, the complexity of how infrastructure systems work and the uncertain valuations that can be put into infrastructure outcomes by different stakeholders make decision-making particularly challenging. Therefore, transport infrastructure planning often involves making decisions under deep uncertainty.

When dealing with complex systems under deep uncertainty, the assumption that we can identify a "best-guess" future condition might no longer be appropriate. Instead, the projection of multiple plausible future scenarios is increasingly seen as an alternative even when those scenarios cannot be ranked in terms of their likelihood (Maier et al., 2016). A wide exploration of many potential alternatives is warranted to gain a better understanding of the system and identify decision-relevant scenarios (e.g. scenarios that could result in high risks or valuable opportunities). This approach is commonly known as Exploratory Modelling (Bankes, 1993) and includes the use of quantitative techniques such as Feature Selection (Kwakkel, 2017) and Scenario Discovery (Bryant & Lempert, 2010). To measure system performance under multiple scenarios, robustness is often the preferred metric as it rewards plans that perform satisfactorily under many future conditions instead of focusing on isolated predictions (Maier et al., 2016). Common robustness metrics include regret metrics (e.g., quantification of performance in each scenario in comparison with a baseline) and satisficing metrics (e.g. quantification of the number of scenarios that meet certain requirements) (Herman et al., 2015).

Despite the increasing recognition that transportation systems face deep uncertainty, traditional methods for transport planning are inadequate to deal with this level of uncertainty

DOI: 10.1201/9781003323020-314

(Lyons & Davidson, 2016; Wall et al., 2015). Most research efforts have focused on increasing the granularity and complexity of models to gain accuracy, which further impedes a wide exploration of scenarios (Milkovits et al., 2019).

This paper uses a macroscopic transportation model to simulate a wide range of future scenarios and quantify robustness. Exploratory modelling techniques are used to identify the most relevant uncertain factors and subsets of decision-relevant scenarios. Furthermore, we show how the identification of such scenarios, through the development of uncertainty maps, can inform transport infrastructure planning by targeting interventions, such as road expansions only when needed, and road space reallocations, only when feasible. As an example, we use the road infrastructure between Dübendorf and Hinwil and their potential expansions and modifications in the future. Travel times on the corridor are estimated as a measurement of the level of service provided by the infrastructure. Future changes in travel times and potential delays are modelled annually to evaluate system performance's adequacy in multiple plausible futures.

2 STUDY AREA AND MODEL

The corridor Dübendorf-Hinwil extends from the Zürich city border between the Pfannenstiel and the Zurich Highlands. Table 1 shows the population (Statistisches Amt des Kantons Zürich, 2022a) and jobs (Statistisches Amt des Kantons Zürich, 2022b) in each of the towns within the corridor, being Zurich the major urban centre. Different population projections for the Canton of Zurich vary between 0.5% and 1.1% per year (Bundesamt für Statistik, 2020) which might also drive growth in job opportunities and further changes in the region.

Table 1. Population and jobs within the corridor in 2020.

Town	Population	Jobs
Zurich	420'891	495'223
Dübendorf	29'854	19'362
Schwerzenbach	24'034	14'169
Uster	35'295	17'370
Seegräben	1'423	593
Wetzikon	25'038	14'088
Hinwil	11'344	7'150

The A15 federal highway (4 lanes) is a main component in the corridor connecting Dübendorf to Uster. After Uster, a cantonal road (2 lanes) continues to connect Uster to Hinwil. The Federal government has given the green light to the extension of the A15 from Uster to Hinwil but it is still not clear when the expansion will be realized. These expansion plans are being discussed and considered at both the cantonal and federal levels.

In this paper, the corridor is modelled as a simple linear link-node network as illustrated in Figure 1. The road infrastructure capacity along the corridor is estimated to be approximately 100 lane-km, including the federal highway and the cantonal road. To calculate the number of trips originating and ending in each of the towns, a gravity model is used with the population and jobs generating travel demand from each of the node pairs (de Dios Ortúzar & Willumsen, 2011). The generalized costs of travelling between the nodes, which are used to distribute the trips in the corridor model, are assumed to be related to the distance between each node pair. The modal share of cars in the canton of Zürich is estimated at 25% according to the 2015 Microcensus (Bundesamt für Statistik, 2017) and was used in the generation of trips.

Zürich, as the largest city, is a regional hub that serves and influences multiple networks in its surroundings, including the corridor from Dübendorf to Hinwil. Jobs in Zürich attract people living in the corridor, and people living in Zürich are also attracted by jobs in the corridor, both generating more trips. Several model parameters were calibrated to fit the traffic levels at peak hours for the traffic measuring points in the corridor (Kanton Zurich, 2019) including the portion of Zurich generating trips along the corridor which was estimated as 10%.

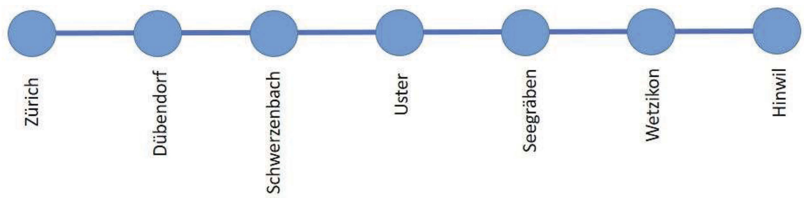

Figure 1. Simplified illustration of the corridor zürich-dübendorf-hinwil.

In the corridor model, as the population and jobs grow, the traffic volume is expected to grow. Increasing population leads to increased travel demand and potentially, to increased travel delay, particularly when demand is closer to the road capacity.

The average traffic flow at peak hours in the corridor is modelled using a Macroscopic flow model (de Dios Ortúzar & Willumsen, 2011). The input variables are the travel demand (expected traffic flow) and the infrastructure supply (road capacity available). We use a fundamental diagram of traffic flow to estimate the relationship between speed, flow and density in the model as shown in Figure 2.

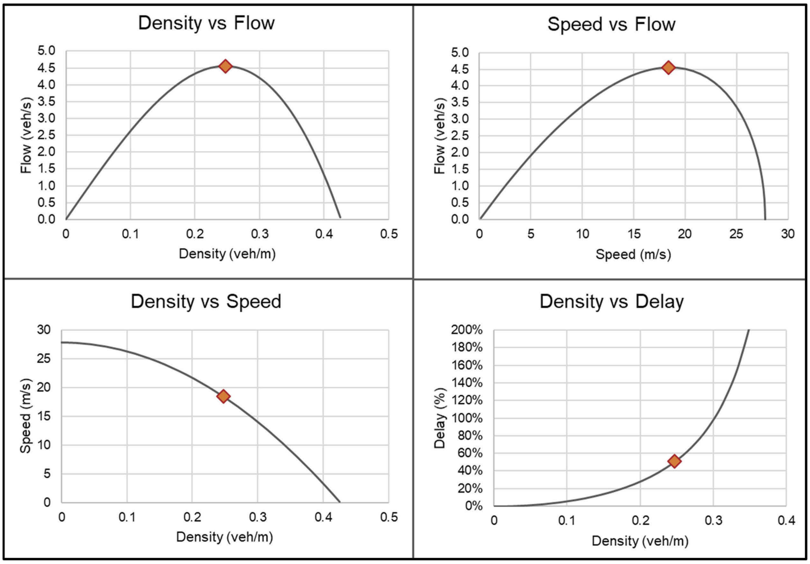

Figure 2. Fundamental diagram of traffic flow for the corridor. The critical density is shown in orange, i.e. the number of cars, as a ratio of the supply of lane-km available, that generates the maximum flow in the road. This will result in a certain speed being travelled on average across the system.

Besides classical flow-density, flow-speed and speed-density curves, Figure 2 also shows an estimation of the travel delay-density curve. Travel delay (in percentage) is estimated, as the additional travel time with respect to the free flow travel time (i.e. the travel time at the maximum allowed speed on the road). The calibrated model estimates that current delays are about 5% in the corridor. Figure 2 shows that reaching the critical density (orange diamond) generates a delay of about 50%.

For the evaluation of the ensemble of future scenarios, robustness was calculated by defining satisficing criteria (i.e. the level of performance considered adequate). For the satisficing criteria in this paper, we defined a delay of 20% as tolerable if it is not permanent. Therefore the first satisficing criterion is to not reach more than 20% of delay for more than 5 years until 2050 (one-sixth of the time). Additionally, reaching a delay of 50% (i.e. reaching road capacity and entering the congestion phase) is considered inadequate. The corridor performance will be simulated until 2050 under multiple scenarios and will be considered adequate if both satisficing criteria are met. The satisficing criteria set for this paper reflects the need to avoid severe delays (e.g. the congestion state) and also assume the ability of infrastructure managers to act when delays reach 20% and consequently improve the performance in a reasonable time. Satisficing criteria can also be based on planning instruments, historic performance or elicited from stakeholders (Hadjimichael et al., 2020).

3 EXPLORATORY MODELLING

The model was used to evaluate the corridor performance under multiple future scenarios. Exploratory modelling was then carried out to identify the most relevant uncertain factors and the subset of decision-relevant scenarios (risks and opportunities). A scenario is defined as a particular combination of uncertain factors. Risk scenarios are the ones in which current capacity will not meet the satisficing criteria, indicating that expansions are needed. Opportunity scenarios are the ones in which reduction of road capacity (50% of the A15 federal highway) will still meet the satisficing criteria, indicating that road space can be reallocated to other uses (e.g. bike paths or bus priority lanes).

When scenarios are developed to represent a broad range of future conditions, their generation is usually done using numerical modelling and/or sampling (Kwakkel et al., 2015; McPhail et al., 2020). Key uncertain factors are first selected based on literature (Kwakkel et al., 2012; Milkovits et al., 2019; Wall et al., 2015) and during the process of model calibration (selecting the factors with bigger impact on performance). The selected uncertain factors were: 1) population growth, 2) job growth, 3) the change in the modal share of cars, and 4) the change on the influence of the city of Zurich in the corridor. Table 2 provides a short description of the factors along with their respective ranges of uncertain values. We develop an ensemble of future scenarios by sampling within the ranges using the Latin hypercube sampling method (McKay et al., 1979).

Table 2. Uncertain factors considered to generate future scenarios.

Uncertain Factor	Short Description	Range
Population Growth	Annual population growth rate in each town	(0%, +3%)
Job Growth	Annual job growth rate in each town	(0%, +3%)
Change in the influence of Zurich	Annual change in the portion of Zurich population and jobs that generates trips within the corridor	(-1%, +1%)
Change in Modal Share - Cars	Annual change in the proportion of trips done by car	(-1%, +1%)

As the gravity model works by generating trips based on population and jobs, they were selected as key uncertain factors for the future. Population growth forecasts for the canton of Zurich range between 0.5% and 1.1% per year (Bundesamt für Statistik, 2020). In this paper, we expand the potential range of population growth from 0% to 3% in order to explore a wider set of future scenarios. We use the same range for jobs growth as specific job projections are not available.

During the calibration of the model, the most sensitive parameters were the proportion of Zurich influence on the corridor and the car share, therefore, they were selected as key uncertain factors of the model. The proportion of Zurich influence on the corridor in the future will depend on regional dynamics which are uncertain. Future mode share is also uncertain as societal preferences (e.g., towards active mobility or automated vehicles) can drastically change mobility patterns. We selected a plausible but wide range of potential change of +-1% per year for each factor (i.e., ranging between -26% and +35% by 2050).

We generated 500 equally plausible scenarios (i.e. without assigning probability distributions) using the Exploratory Modeling Workbench (Kwakkel, 2017). For each of the 500 scenarios generated, a single value in the range was selected and applied to each modelled year until 2050. The factors were assumed to be consistent across all sub-regions. As part of the exploratory modelling, we identified the most relevant uncertain factors by applying feature selection techniques which are typically used to rank and prioritize the input variables in a model. Table 3 shows the results of the feature selection over the 500 modelled scenarios by using two common algorithms: an extra trees and a random forest algorithm. As a higher score means a higher influence of the factor with respect to meeting the satisficing criteria (as defined in Chapter 2), Job growth and the Change in modal share are the most relevant uncertain factors for the corridor model.

Table 3. Feature selection scores to identify the most relevant uncertain factors.

	Algorithm	
Uncertain Factor	Extra Trees	Random Forest
Population Growth	0.098	0.076
Jobs Growth	0.49	0.54
Change in the influence of Zurich	0.12	0.093
Change in Modal Share - Cars	0.28	0.28

Figure 3 shows the uncertainty map of the performance of the road system over the 500 modelled scenarios for the road infrastructure along the corridor. As the robustness metric, we calculate the fraction of scenarios that meet the satisficing criteria (Herman et al., 2015; Schneller & Sphicas, 1983). In Figure 3, each point represents one scenario as a combination of the uncertain factors. Dark diamonds (48% of the total) indicate adequate performance of the current infrastructure by 2050. Red circles (14% of the total) indicate inadequate performance of the current infrastructure by 2050 (i.e. risk scenarios). Blue squares (38%) indicate adequate performance by 2050 with a reduced road capacity (i.e. opportunity scenarios). The two most relevant uncertain factors, identified in Table 3, are used as the axes of the graph so it is possible to visualize the combination of uncertain factors that generate risks and opportunities. A high increase in mode share for cars and high jobs growth represent high likelihood of inadequate performance with the current infrastructure. On the other hand, decreases in car share and low jobs growth represent high likelihood of adequate performance with reduced road capacity.

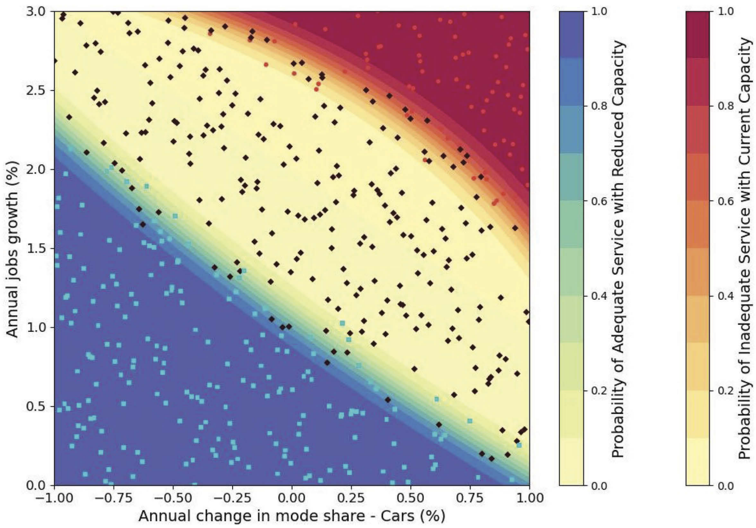

Figure 3. Uncertainty map and scenario discovery results for the future performance of the road infrastructure along the corridor.

Scenario discovery is used to estimate the boundaries of the adequate/inadequate performance regions of the uncertainty map. Some common algorithms for scenario discovery are

Patient Rule Induction Method (PRIM) and Classification and Regression Trees (CART), however, one limitation of them is that they divide the space with boundaries orthogonal to the axes (Reed et al., 2022). Given that the adequate/inadequate boundary in our case study shows a non-orthogonal and non-linear shape, we use logistic regression, as the classification algorithm, for the scenario discovery (Hadjimichael et al., 2020). Figure 3 shows the classification as colored regions according to the probability of obtaining risk and opportunity scenarios in the uncertainty map.

Exploratory modelling techniques help identify likely risk and opportunity regions of the uncertainty map and therefore, shed light on which combinations of uncertain factors require particular attention of infrastructure planners. For this paper, we use the expansion of the road infrastructure capacity as the only intervention to reduce delays and meet the satisficing criteria in the risk regions. We use the reallocation of road capacity (i.e., for others uses) as an intervention in the opportunity regions. The model was rerun by targeting expansions and reallocations to be deployed in the risk and opportunity regions in Figure 3. As road expansions have a considerable time from planning decisions to implementation (assumed to be 4 years in this case), planners need to decide well in advance of reaching inadequate performance (e.g., congestion). The triggering of expansions is modelled as a simple decision rule of expanding 10 lane-kms of capacity (approx. a double lane road between any two nodes in the corridor) every time the corridor reaches 75% of road capacity (i.e., the maximum flow in the fundamental diagram). The triggering of road reallocations is also modelled as a simple decision rule of reallocating 10 lane-kms of capacity when the road capacity use is lower than 60%.The decision rules are implemented as function of the traffic flow as the traffic flow is an easily measurable indicator given that several real-time traffic monitoring stations function along the corridor.

The implementation of decision rules to trigger road expansions and reallocations conditional to traffic flows will produce different number and timing of interventions for different future scenarios. Higher travel demands will produce more frequent expansions while lower demands will produce sporadic expansions only, in the risk regions. Higher travel demands will produce sporadic reallocations while lower demands will produce more frequent reallocations, in the opportunity regions Figure 4 shows the uncertainty map for the 500 modelled scenarios with the targeted interventions. Dark diamonds (97% of the total) and red circles (3% of the total) indicate an adequate or inadequate performance by 2050, respectively. Figure 4 shows that the targeted implementation of the expansions greatly increases robustness (i.e. the number of scenarios with adequate performance). The residual number of scenarios with inadequate performance can be tackled by additional targeted interventions or just left untreated if stakeholders consider such a combination of uncertain factors as unlikely to happen. The absence of blue squares indicate that the decision rule was able to reallocate road space in all opportunity scenarios.

4 DISCUSSION

In this paper, we present a simple macroscopic flow model for the road infrastructure in the Dübendorf-Hinwil corridor. The model estimates the number of trips originated and attracted by each town, depending on the population and job numbers, and calculate the average flows, densities and speeds on the road. The model is used to evaluate the robustness of the road in an uncertain future (i.e., the provision of adequate performance under multiple future scenarios). While current performance indicators for transportation planners are numerous including carbon emissions, sustainable development indicators, accessibility or economic impacts, we focus on travel times only as an example. Similar techniques can be applied to evaluate multiple performance indicators and the trade-offs between them in an exploratory manner. Furthermore, while we assume arbitrary satisficing criteria for robustness evaluation purposes, this can be established in planning guidelines or directly elicited from stakeholders.

The model developed in this paper is able to capture some non-linear dynamics between supply of and demand for infrastructure through the fundamental diagram of traffic flow. However, the model can be further expanded to better represent the complexity of the road system along the corridor. For example, the model could be expanded to capture network effects in the region, to consider the different travel modes explicitly, or to include a broader

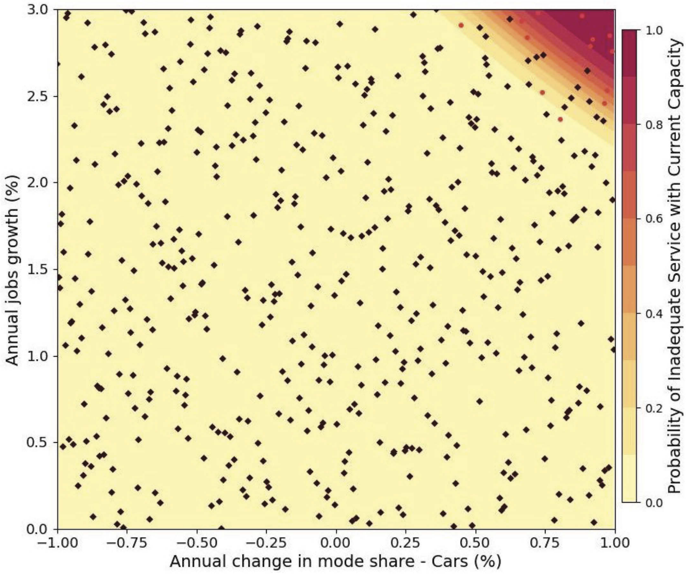

Figure 4. Uncertainty map and scenario discovery results for the future performance of the road infrastructure by targeting expansions and road space reallocations.

range of interventions such as further modifications of the current infrastructure, demand management and other transport policies. Modelling efforts can also be directed to include endogenous feedbacks such as induced travel demand and spatial dynamics in the region.

The paper showcases the importance of considering a wide spectrum of future scenarios when planning transport infrastructure. The set of uncertain factors used in this paper can be further expanded and the development of future trends can be refined for more detailed results. It is the belief of the authors that further refinements and expansions of the modelling side will only bolster the value of the techniques presented in this paper, as exploratory modelling is particularly suitable to navigate complexity and uncertainty.

5 CONCLUSIONS

This paper demonstrates that the use of simulations and quantitative techniques, when displayed in an interpretable way, can provide valuable planning support in infrastructure planning. We produce uncertainty maps in which decision-makers can visually identify risk and opportunity regions. Furthermore, we implemented simple decision rules for expansion and reallocation interventions targeted to the risk and opportunity regions, respectively, on the uncertainty map to increase the robustness of the road.

The results show that the current road infrastructure capacity in the corridor might not be able to provide adequate service (risk) in 14% of the scenarios. Furthermore, 38% of the scenarios can provide an adequate level of service even if the road capacity is reduced by 50% in the A15 federal highway (opportunity). Feature selection and Scenario discovery methods helped identifying the combination of uncertain factors that result in risk and opportunity regions. Therefore, the techniques shown here can help decision-makers to target efforts only in a subset of scenarios. In this case, the implementation of targeted interventions result in the seizing of opportunities and a reduction of the risk scenarios to only 3% of the uncertainty map.

ACKNOWLEDGEMENT

This research was conducted at the Future Cities Lab Global at ETH Zurich. Future Cities Lab Global is supported and funded by the National Research Foundation, Prime Minister's

Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and ETH Zurich (ETHZ), with additional contributions from the National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore and the Singapore University of Technology and Design (SUTD).

REFERENCES

Bankes, S. (1993). Exploratory Modeling for Policy Analysis. *Operations Research*, *41*(3), 435–449. https://doi.org/10.1287/opre.41.3.435

Bryant, B. P., & Lempert, R. J. (2010). Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change*, *77*(1), 34–49. https://doi.org/10.1016/j.techfore.2009.08.002.

Bundesamt für Statistik. (2017, May 16). *Verkehrsverhalten der Bevölkerung, Kenngrössen—Schweiz—2015 | Tabelle*. Bundesamt für Statistik. https://www.bfs.admin.ch/asset/de/2004970.

Bundesamt für Statistik. (2020, May 28). *Szenarien zur Bevölkerungsentwicklung der Kantone der Schweiz 2020-2050—Ständige Wohnbevölkerung nach Kanton gemäss 3 Szenarien—2020-2050 | Tabelle*. Bundesamt für Statistik. https://www.bfs.admin.ch/asset/de/12107013.

de Dios Ortúzar, J., & Willumsen, L. G. (2011). *Modelling transport* (4th ed.). John Wiley & Sons.

Hadjimichael, A., Quinn, J., Wilson, E., Reed, P., Basdekas, L., Yates, D., & Garrison, M. (2020). Defining Robustness, Vulnerabilities, and Consequential Scenarios for Diverse Stakeholder Interests in Institutionally Complex River Basins. *Earth's Future*, *8* (7),e2020EF001503. https://doi.org/10.1029/2020EF001503.

Herman, J. D., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2015). How Should Robustness Be Defined for Water Systems Planning under Change? *Journal of Water Resources Planning and Management*, *141*(10), 04015012. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000509.

Kanton Zurich. (2019). *Strassenverkehrszählung, Oberland-Autobahn (A53) Daten 2019*. https://maps.zh.ch/.

Kwakkel, J. H. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling and Software*, *96*, 239–250. https://doi.org/10.1016/j.envsoft.2017.06.054.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2015). Developing dynamic adaptive policy pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, *132*(3), 373–386. https://doi.org/10.1007/s10584-014-1210-4.

Kwakkel, J. H., Walker, W. E., & Marchau, V. A. W. J. (2012). Assessing the Efficacy of Dynamic Adaptive Planning of Infrastructure: Results from Computational Experiments. *Environment and Planning B: Planning and Design*, *39*(3), 533–550. https://doi.org/10.1068/b37151

Lyons, G., & Davidson, C. (2016). Guidance for transport planning and policymaking in the face of an uncertain future. *Transportation Research Part A: Policy and Practice*, *88*, 104–116. https://doi.org/10.1016/j.tra.2016.03.012.

Maier, H. R., Guillaume, J. H. A., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software*, *81*, 154–164. https://doi.org/10.1016/j.envsoft.2016.03.014.

McKay, M. D., Beckman, R. J., & Conover, W. J. (1979). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, *21*(2), 239–245. https://doi.org/10.2307/1268522.

McPhail, C., Maier, H. R., Westra, S., Kwakkel, J. H., & van der Linden, L. (2020). Impact of Scenario Selection on Robustness. *Water Resources Research*, *56* (9),e2019WR026515. https://doi.org/10.1029/2019WR026515.

Milkovits, M., Copperman, R., Newman, J., Lemp, J., Rossi, T., & Sun, S. (2019). Exploratory Modeling and Analysis for Transportation: An Approach and Support Tool - TMIP-EMAT. *Transportation Research Record*, *2673*(9), 407–418. https://doi.org/10.1177/0361198119844463.

Reed, P. M., Hadjimichael, A., Malek, K., Karimi, T., Vernon, C. R., Srikrishnan, V., Gupta, R. S., Gold, D. F., Lee, B., Keller, K., Thurber, T. B., & Rice, J. S. (2022). *Addressing uncertainty in multisector dynamics research*. Zenodo. https://doi.org/10.5281/zenodo.6110623.

Schneller, G. O., & Sphicas, G. P. (1983). Decision making under uncertainty: Starr's Domain criterion. *Theory and Decision*, *15*(4), 321–336. https://doi.org/10.1007/BF00162111.

Statistisches Amt des Kantons Zürich. (2022a). *Bevölkerungsbestand und -wachstum des Kantons Zürich*. Kanton Zürich. https://www.zh.ch/de/soziales/bevoelkerungszahlen.html.

Statistisches Amt des Kantons Zürich. (2022b). *Gemeindeporträt*. Kanton Zürich. https://www.zh.ch/de/politik-staat/gemeinden/gemeindeportraet.html.

Wall, T. A., Walker, W. E., Marchau, V. A. W. J., & Bertolini, L. (2015). Dynamic Adaptive Approach to Transportation-Infrastructure Planning for Climate Change: San-Francisco-Bay-Area Case Study. *Journal of Infrastructure Systems*, *21*(4), 05015004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000257.