A methodology to identify and assess transport infrastructure development considering land-use uncertainty

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Abstract

This paper presents a methodology to identify and assess transport infrastructure development considering land-use uncertainty, emphasizing the challenges posed by divergent stakeholder views, uncertain assumptions, and the time-consuming consensus-building process. In this paper, the methodology is explained through an example of an algorithm designed to generate potential new highway access points, the associated land use scenarios, and their effects on mobility demand. The mobility demand is dependent on the land use scenario and is allocated to the highway infrastructure using travel-time based Voronoi polygons. The demand defined in an origin-destination matrix is allocated to the highway via its access points, i.e., the Voronoi polygon centroids and can be dynamically reallocated dependent on the proposed development. The generated infrastructure development is then assessed using factors like construction costs, travel time delay, noise externalities, and environmental emissions. This methodology enables planners to prioritize the generated developments at an early stage in the planning process both effectively and efficiently. As a consequence, the planner may allocate resources and facilitate transparent communication to stakeholders in early planning stages. The methodology can be used to help accelerate the early stages of the planning process, reducing iterations and efforts required for consensus among diverse stakeholders. It is expected to enhance the effectiveness and efficiency of transport infrastructure planning in anticipation of evolving societal needs.

Keywords

Infrastructure planning; infrastructure; transport infrastructure; land use; uncertainty; Voronoi; decision-making; responsiveness

Preferred citation style

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1 Introduction

The effective use of planning support tools (e.g., transport models or land-use models) at the right level of detail can make infrastructure planning more efficient and more effective. The right tools used at the right time in the process can help accelerate the currently relatively long and iterative endeavor by facilitating well-informed decisions that align with changing societal needs considering an uncertain future. In early planning stages, regional infrastructure planners may ask themselves "Where are the potential bottlenecks in the transportation network in the mid- and long-term?" and "how can spatial development be directed to enable the use of existing transport network capacity reserves and, as possible, steer away from the formation of traffic bottlenecks?". This requires the consideration of change in both infrastructure and its uncertain environment. A planning decision can then be made based on the robustness of the planned interventions in the face of deep uncertainty.

This paper presents a methodology that is useful for early-stage planners in generating and assessing a large pool of possible solutions considering a large ensemble of future scenarios to quickly assess societal needs accommodated by highway networks with generated infrastructure interventions, and if so, which ones should be studied further. This can be useful to Swiss early-stage planners, for example, the Federal Office for Spatial Development engaging in coordinating work for sectoral plans, the Federal Office for Transport in preparing regional master plans for rail, the Federal Office for Roads for generating variants for a planning study or the Cantonal Offices for initial steps of integrated mobility planning.

This paper discusses the methodology together with an algorithm that can be used for its implementation, including the steps to generate and assess new highway infrastructure. After an overview of related research, the methodology is presented and the data requirements for the algorithm implementation are listed. Furthermore, the paper contains an outlook for potential future research and further use cases.

2 Related research

Transport infrastructure change has typically been modelled using either network development tools to explain (or emulate) historical development or to solve optimization problems with the objective of accommodating societal needs.

Network development and the contributing factors have been studied using both ex-post and ex-ante approaches with differing purpose. Glover and Simon (1975) examined the ex-post relationship between population density and road density with empirical data. Levinson & Karamalaputi (2003) then explained past highway network growth with a logit choice model selecting growth that maximizes accessibility using a node-link network. Yamins et al. (2003) and Levinson & Chen (2007) then extended a cellular automata model to predict land cover change to highway infrastructure.

In describing the interactions between infrastructure, mobility demand and land-use, models have also been developed to explain the co-evolution of these interacting components of spatial systems. Gaudry (1980) suggested an aggregate bi-modal urban travel model and Cervero & Hansen (2002) followed showing empirically the positive impact of highway infrastructure supply on travel demand and vice versa and Jiwattanakulpaisarn et al. (2010) did the same looking at infrastructure supply and employment accessibility.

Ex-ante approaches have also used co-evolution modelling (Levinson, 2008) based on land-use transport interactions (LUTI) and with more extensive modelling efforts to explain road investment decisions based on an optimization problem (Li et al., 2016). The problem that these approaches run into are (i) that they require a lot of data to calibrate and validate (Acheampong & Silva, 2015) (ii) which in turn impacts the parsimony of these tools (Wegener, 2011) and lastly, (iii) because of the large amount of assumptions and effort required to calibrate and validate the model, the creators themselves have started posing tough questions related to the added value of the model predictions (Batty, 2020; Batty & Torrens, 2001).

Other approaches have utilized topological network-graph metrics to recreate current network from scratch (Hackl & Adey, 2019), to explain development of roads over time (Casali & Heinimann, 2019; Zhao et al., 2016) and how network metrics could be used to assess planned rail interventions (de Freitas & Blum, 2024). Grolle et al. (2024) developed a European High Speed Rail (HSR) network structured as a Transport Network Design Problem based on societal benefits achieved by replacing flights between large European cities with HSR.

For early stage planning, the task at hand is identifying potential interventions for further studying and planning, making the scanning for network development interventions useful (Hensher et al., 2020). Transport planning support tools only have limited capability in addressing such tasks. The state-of-the-art in transport planning support tools is the proprietary PTV Visum for macroscopic modelling, using four-step modelling where travel demand is generated within a particular traffic zone (i.e., a predefined zone containing the location of a user's destination) and originates in another traffic zone (e.g., a user's home) (Ortuzar & Willumsen, 2011). For mesoscopic modelling, the open source agent-based MATSim (Horni et al., 2016) uses travel diaries of agents representing individuals in the population. Although the infrastructure network is typically a given for both simulation types, there exists a possibility to compare different simulations with a change in network. There persists a gap to bridge between development of transport models and real-world applications in infrastructure network planning (Heyken Soares et al., 2021). This has motivated the creation of a bespoke LUTI model for the Sydney metropolitan area to scan for beneficial interventions and policies in the strategic early-stage of the planning process (Hensher et al., 2020).

A study looking at the impact of infrastructure network design on network performance using MATSim was made by Maheshwari et al. (2023). Using "Sketch MATSim", a planning tool based on MATSim analysis, Maheshwari and colleagues analysed different road network configurations, by changing attributes of its elements in one possible future including automated vehicle deployment. Studying such infrastructure planning approaches using large ensembles of future scenarios can provide useful to make planning more effective and efficient (Elvarsson et al., 2023; Roman et al., 2023).

3 Methodology

3.1 General

The methodology combines naively generated infrastructure interventions and a large number of spatially explicit future scenarios. The result combines macroscopic tools modelling of the impact of infrastructure, mobility and land use on societal needs while considering the range of possible future scenarios, facilitating improved decision-making under uncertainty. The general steps to do this are shown below, visually summarized in Figure 1: (1) naïvely generate changes to infrastructure, (2) generate the uncertain development through a large ensemble of spatially explicit scenarios impacting the accommodation of societal needs and (3) assess the change in comparison to a reference case of no change to visualize possible development benefits. The three modules are integrated into the implementation of the algorithm for an example of the development of highway infrastructure (Marggi, 2024). The steps of the implementation are shown in the process in Figure 2 and further described in Table 1.

Figure 1: Visual summary of the methodology split into three modules

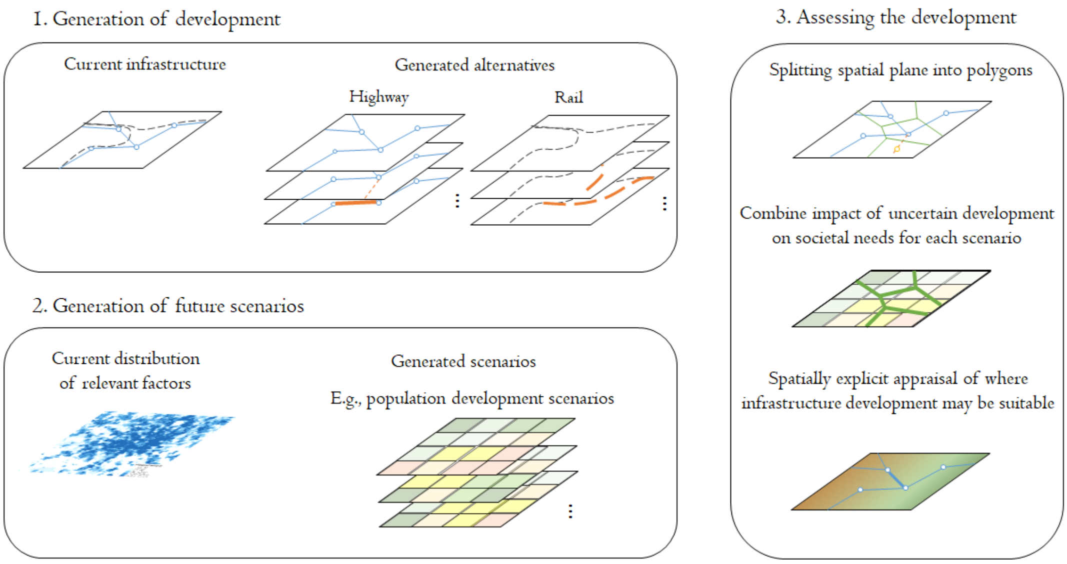
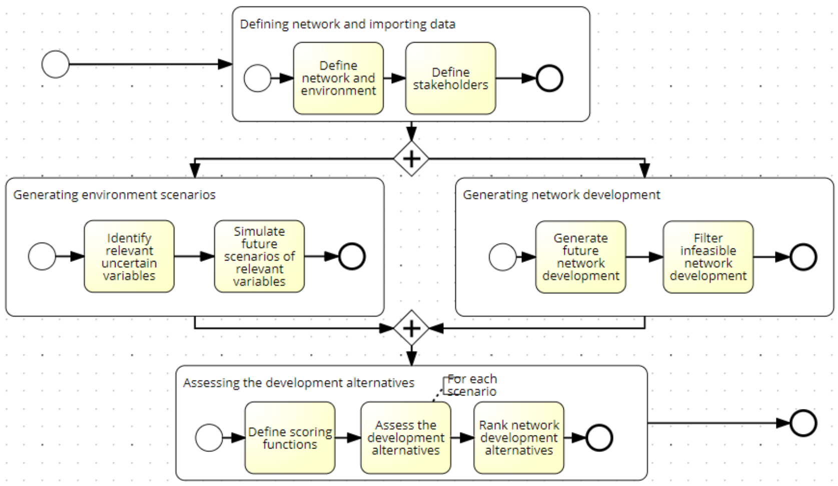


Figure 2: Visual summary of a general algorithm for implementing the methodology for highway network development using Business Process Modelling Notation



The algorithm has been implemented in Python and the steps shown in Figure 2 are explained in the following subsections.

3.2 Defining network and importing data

Switzerland has a large amount of data openly available, whereby some of it must be restructured to fit the underlying structure of the model. This flexibility is important as data comes in various forms and can vary dependent on the office responsible for collecting it. The used data is listed in Table 1. The output of this step is a node-link graph of the highway network, the data relevant for generating scenarios and for assessing the generated alternatives.

3.3 Generating network development

The methodology is based on naïvely generating new highway links which then are assessed to be suitable (or not). Over the studied perimeter, points are generated at random and then tested to see whether they are within a protected area, under which condition they are deemed infeasible. The path to the nearest highway node, not intersecting any protected or built area, is generated. The output of the infrastructure generation for the next step should include feasible alternatives for change.

3.4 Generating environment scenarios

In the example situation, population growth and employment growth are considered to impact how well societal needs can be accommodated. The canton sets a growth forecast for population per district (Kanton Zürich, 2022). The spatially explicit scenarios are generated by randomly allocating new population to parcels where potential growth has already been defined by policy-makers and planners using spatial and construction zoning ordinances (PLUS, 2024).

3.5 Assessing the changes to the transport network

The assessment is based on a summary of society's stakeholders and their needs. A planner is tasked with proposing a planned outcome that addresses all concerns and appropriately takes them into consideration in the assessment. These concerns in terms of stakeholder impacts include the construction and maintenance costs, environmental externalities, and time reduction benefits, taking both into consideration the time needed to access the highway as well as the travel time on the highway network itself.

Table 1: Algorithm steps: Highway development example

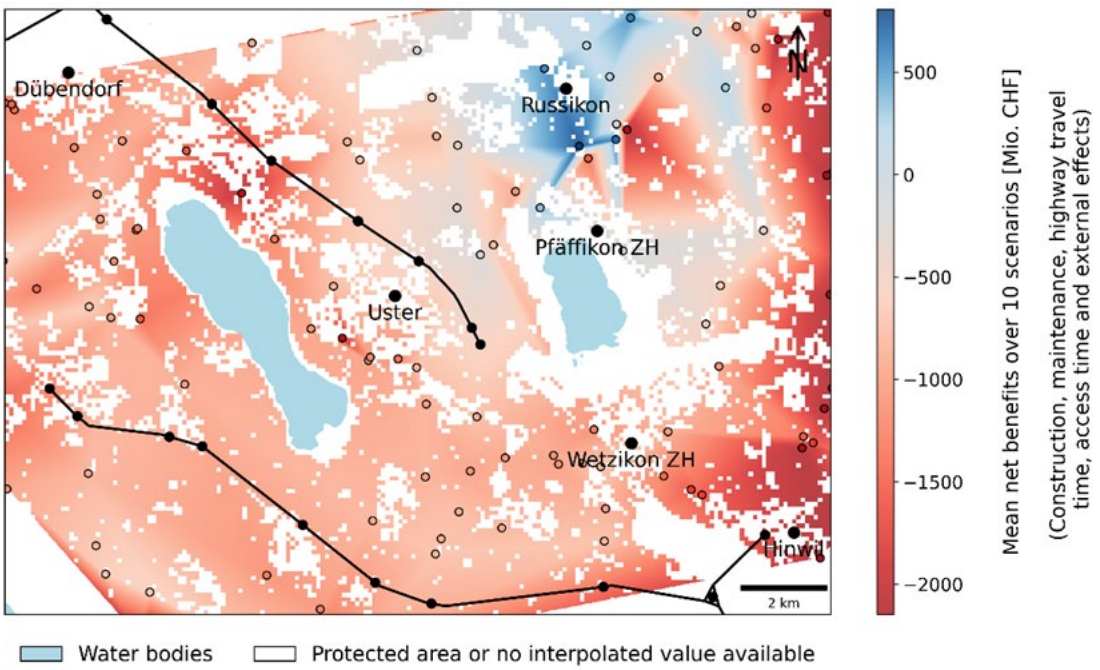
Algorithm		**Description**
Module	Step	
Defining network and importing data	Define network	For setting up the model in Switzerland, a georeferenced node-link list of network elements (e.g., highway elements in Switzerland based on (Fröhlich et al., 2005)) was used to describe the network and the following data to define the environment in which the network is embedded: population and employment data per hectare (Bundesamt für Statistik BFS, 2023b), origin-destination travel demand data per commune (Amt für Mobilität, 2023)), land use data (Bundesamt für Statistik BFS, 2023a), land use potential data (PLUS, 2024) and digital elevation models (Bundesamt für Landestopografie Swisstopo, 2023).
	Define stakeholders	Infrastructure interventions were assessed and compared in a transparent, evidence-based manner facilitating effective and efficient consensus-building. To do this, all stakeholders relevant to decision-making were defined i.e., user, owner, the directly affected public and indirectly affected public. Stakeholder needs, objectives and constraints were identified as well as ways to quantify them so they could be represented in a scoring function, e.g., a user's travel delay costs.
Generating network development	Generate future network development	Based on the current highway network, 1'000 coordinates for a new access point within the boundary of the study area were randomly generated. The access point was then linked to the nearest node on the highway. Network development could also be generated through linking two existing highway nodes with a link, although this was not done here as a prototype was only built around one type of topological change to the highway network.
	Filter infeasible development	Land use and land cover were used to identify infeasible locations of a highway access point. Similarly, new links were not allowed to intersect certain types of land use, e.g., wetlands which are nationally protected. These rules enabled infeasible network development to be removed quickly from the analysis.
Generating environment scenarios	Identify relevant uncertain variables	Based on literature, population and employment distribution were determined to be the most relevant factors driving demand for mobility and, consequently, infrastructure development.

(table continues on next page)

Algorithm		**Description**
Module	Step	
	Sample future scenarios of uncertain variables	The future scenarios were sampled per hectare cell and allocated absolute population growth dependent on the development potential available according to a method provided by Raum+ (PLUS, 2024) and based on Cantonal and Communal Zoning ordinances defined by policy-makers. 10 scenarios were sampled with spatial variability in the growth within the pre-defined development parcels.
Assessing the changes to the transport network	Define scoring function	A scoring function was defined to include the relevant costs and benefits for the different stakeholders. These costs and benefits were quantified and monetized. They were the benefit of user travel delay savings while traveling on the highway, the improved access to a highway to the entire population within the study perimeter, the cost of construction and maintenance and the environmental emission costs. More costs and benefits could be added to this scoring function if desired. Travel delay on the network was computed using a stochastic user equilibrium routing algorithm based on (Nogal et al., 2016)
	Assess the development alternatives	The development alternatives were assessed for all scenarios, using the no development scenario as the base scenario. The costs and benefits were monetized in CHF
	Rank development alternatives	The results showed how societal needs can be accommodated by the different development alternatives considering multiple plausible futures. Different alternatives will have different net benefits, the results will differ in variability across the different scenarios.

One of the major challenges with any modelling of transport infrastructure is allocating spatially distributed demand to spatially confined infrastructure supply. To assess the generated infrastructure developments, demand was allocated to the network taking into consideration variability of each scenario and every new infrastructure development. For highways, that are accessible by car and can be reached from anywhere in the canton, the demand can be allocated to the infrastructure through Voronoi tessellation of the landscape with highway access points as the polygon centroids, i.e., the nodes of the highway network. The data was then restructured to fit this tessellation, e.g., the OD matrices were converted from the communal tessellation to a time-travel based Voronoi tessellation and a hectare-based population distribution was aggregated to the Voronoi polygons. The output of the assessment included a score for each development for each scenario as shown in Figure 3. Finally, the outputs of all scenarios for each development were summarized. The results of the case study are explained in (Marggi et al., 2024).

Figure 3: Example results showing net benefits based on newly generated access points connected to existing highways, where blue area indicates potential benefits of providing improved highway access via a single access point development



4 Discussion and Outlook

The methodology and the algorithm are useful for assessing naively generated infrastructure developments considering uncertainty of relevant factors. The implementation is shown for single access point addition to the current highway network and is shown in more extensive form in (Marggi et al., 2024). This results in predicting potentially suitable infrastructure developments and their location relatively quickly. The assessments are made considering a large ensemble of future scenarios. A planner will be well equipped to choose robust planning outcomes based on the analysis.

This methodology is designed to support planners in finding solutions for infrastructure interventions in a transparent, evidence-based manner. This is important for consensus building.

Consequently, the rest of the process may be smoothened as less need will be for iterations in the process as a large-scale generation of alternatives occurred in the early planning stages.

Population scenarios can further be developed based on planner's wishes, e.g., using land use scenarios built with tools like CommunityViz's Scenario 360 (CommunityViz, 2024) to, for example, understand the impact of different densification policies. The algorithm has been prototypically developed for the described case study in (Marggi et al., 2024). It can be further expanded and used for public transit network development and cycling network development. Furthermore, making links between existing nodes and changing existing link attributes, e.g., road capacity or bus frequency can also be performed within this methodology.

5 Conclusions

This paper presents a methodology to identify and assess transport infrastructure development considering land-use uncertainty, emphasizing the challenges posed by divergent stakeholder views, uncertain assumptions, and the time-consuming consensus-building process. This methodology enables planners to prioritize the generated developments efficiently. As a consequence, the planner may allocate resources and facilitate transparent communication to stakeholders in early planning stages. The methodology can be used to help accelerate the early stages of the planning process, reducing iterations and efforts required for consensus among diverse stakeholders. It is expected to enhance the effectiveness and efficiency of transport infrastructure planning in anticipation of evolving societal needs. The algorithm works by 1) naively generating changes to infrastructure, 2) preparing a large ensemble of spatially explicit scenarios impacting the accommodation of societal needs and 3) assessing the change in comparison to a reference case of making no change to be able to indicate where development may be beneficial.

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