Applied Spatial Accessibility Analysis for Urban Design

An integrated graph-gravity model implemented in Grasshopper

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This paper introduces a prototype for a user-friendly, responsive toolbox for spatial accessibility analysis in data-poor environments to support urban design processes. It allows for real-time computation of several evaluation indicators, mostly focused on accessibility related measures. The proposed framework is exemplified with three real-world case studies. Each of them demonstrates one part of the workflow; data gathering and preparation, sketching and developing scenarios, and impact analysis and scenario comparison.

Keywords: *accessibility, urban design, evidence-based design, graph model, gravity model*

INTRODUCTION

Under the assumption that cities are large complex systems, the question arises of how much planning and regulations are desirable. On the extremes, there are two distinct approaches to the urban planning process; 1) readily designing cities and quarters down to the shape of the roof or 2) supporting the self-organization process and consciously plan with it while protecting public interests and the commons.

As of now, most urban master plans are heavily driven by design and normative visions that lack the definition of measurable indicators and often ignore the principles of self-organizational forces that shape cities (Bertaud 2018). Thus, they are more likely to make wrong assumptions on people's behavior (e.g., in terms of location choices of developers or residents). Chances of costly infrastructure being built at places that do not meet the demand appropriately are increased. This mismatch comes with high costs - once built, changes to the infrastructure are difficult to carry out (Oliveira 2016). Therefore, some planners and practitioners advocate for the second approach mentioned above. Planning interventions are thus preferably launched in an on-demand fashion, responding to recent trends. This requires defining indicators that measure city status and their constant monitoring. For new developments, models with predictive abilities are required in order to help with the estimation of the impact of adding or changing elements within the city systems (Achary et al. 2017, Bertaud 2018).

A vast body of literature exists on models and methodologies for correlating and predicting the behavior of urban systems and societies in relation to the built environment and socio-economic factors (Hillier 1984, Batty 2017, Stanilov 2010). Adoption of these models into an accessible and integrated analysis framework might be a promising approach in coping with the issues described above. Especially in rapidly developing regions with high urbanization rates, where authorities are pressured to act fast, and a lack of institutional incentives to conduct an in-depth evaluation of plans is often present, this kind of toolbox might help to improve the allocation of resources and increase the overall efficiency of urban projects and their impact in practice. However, also for smaller cities, projects, or design offices where resources lack for the employment of detailed impact studies, these tools have the potential to contribute to the planning outcomes positively. More so if sufficient user-friendliness allows them to be integrated into an iterative planning and design process from the early phases.

SCOPE AND USE-CASES

The general use-case of the toolbox is for projects where larger, more sophisticated models and simulations are not applicable due to data, budget, or know-how constraints. It offers simplified analysis for planning and design cases that would otherwise be executed without quantitative reasoning. Therefore, in terms of complexity, the toolbox aims for a rather high level of aggregation of the chosen parameters, to ensure greater transparency for non-experts, better transferability to other cases and lower requirements on input data and user experience. The presented scope mainly allows for network and accessibility related analysis in interaction with basic land use categories (eg. residential, commercial) and point of interests (eg. Parks, shopping centers, transit stations and so on).

STRUCTURE AND DESIGN

In an attempt to follow the call for more data-driven, evidence-based (Karimi 2014) approach to urban design for the use-cases depicted above, this paper intends to present a first prototype for an integrated spatial analysis framework with the following characteristics;

A high level of accessibility for users.

- Integration: Complete implementation in popular CAD/visual programming package of Rhinoceros 3D and Grasshopper, modular and easily expandable
- Low data requirements: Few and flexible requirements towards data inputs, mostly depending on open source data such as OpenStreetMap.org or satellite imagery, potentially allowing for "remote-monitoring" of the towns basic state of being
- Standardization: An UI and standardized structure for adding manual data inputs, sketching and creating new scenarios
- Scalability: The resolution and accuracy of calculations can be adjusted to enable faster computation and simulation on the city or regional scale.

Implementation of Design / sketch mode. Allowing for sketching of design variants with near real-time feedback on selected performance indicators

Impact analysis and scenario comparison. After full calculation of all indicators allow for streamlined interface to compare impacts of multiple scenarios at once.

The core of the framework is a weighted graph-model of an area's mobility network (roads, streets, transit lines etc.). Optional weights are population, job or POI density, while POIs can be alternatively placed manually. Most of network related calculations are performed within Grasshopper using the plugin SpiderWeb and its implementation of the Dijkstra shortest path algorithm as the starting point. For the large scale calculation of graphs betweenness and closeness values, DecodingSpaces plugin is employed as an alternative to SpiderWeb. User interface was implemented using plugin Human UI. In terms of complexity the aim is a rather high level of aggregation and few parameters, to ensure higher grades of transparency, better transferability to other cases and lower requirements toward input data.

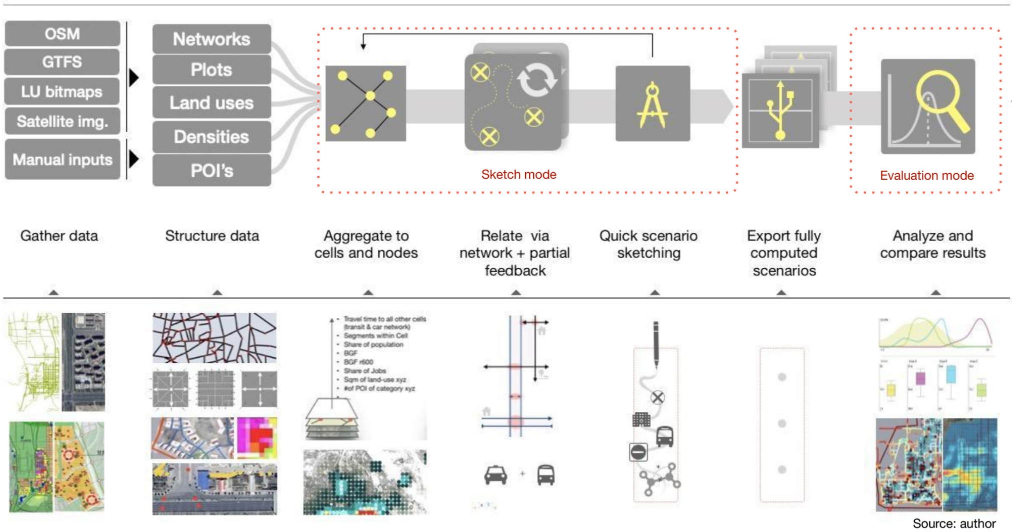


Figure 1
Model structure and workflow diagram

IMPLEMENTATION
Here structure of model and general workflow are illustrated (fig. 1). Each part is described in more detail below. Naturally, the first step is feeding the model with data either from external sources or by manual addition/drawing. Next, the data needs to be structured and prepared. In the sketch mode both, the models parameter and spatial configurations can be changed in order to craft different scenarios. During this process the user gets constant feedback on selected indicators in near real-time. When a scenario draft is finished, it can be exported (with all indicators being computed) as a .ghdata file and, together with other scenarios analyzed and compared in the evaluation mode.

The model offers several channels to model Scenarios: Most importantly the street and transportation network, points of interest (structured in several categories) and land uses which's properties can be defined by the user (eg. Population or job density, FAR etc.) and used as weights or for the computation of indicators.

Data Structure and scalability
The toolbox operates on different spatial scales and supports interpolating, aggregating and disaggregating between them. Basic elements of the model are network edges, network nodes, POIs, shapes (eg. blocks or plots) and two grids: one high-resolution analysis grid (20 - 100 meters), that most other data is mapped on before exporting and one low-resolution grid (125 - 1000 meters) that is used to compute a distance matrix and enables the model to work with larger cities and areas in a trade-off with accuracy.

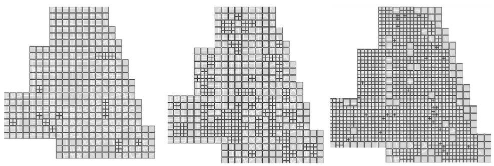


Figure 2
Generated low resolution grids with increasing division threshold.

Graph and network modeling
The basic approach for modeling the network graph is initially constructing the pedestrian and transit net-

works separately before joining them in the very end. This allows to generate graphs from geometries (lines) using the spiderweb library and simultaneously model avg. waiting and exit times for transit modes. Fig. 3 illustrates the graph and data structure. Multiple transit modes can be set-up (eg. Metro, Bus etc.) and individual average speeds, waiting and exit times defined.

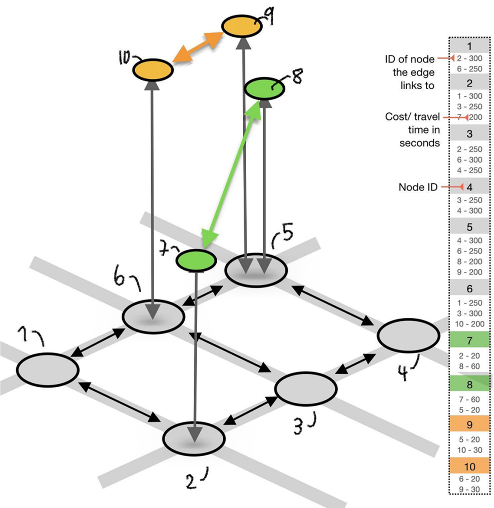


Figure 3
Multimodal network graph structure

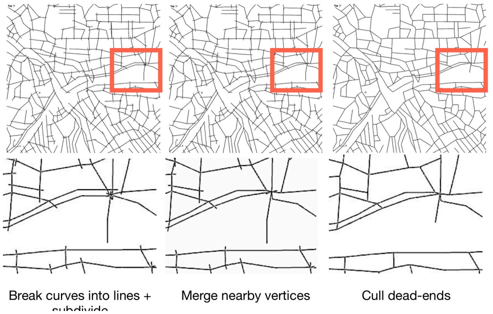


Figure 4
Network geometry preprocessing

We currently use a planar graph where cost of edges corresponds with travel time (or other attributes relatable to street segments) associated to them. Nodes can optionally be weighted with population size, amount of working places, and so on.

Before the graph is created the underlying geometry is simplified and cleaned up. Fig 4 provides an overview of the steps applied. In this process the networks complexity and resolution can optionally be decreased in order to achieve faster calculations.

Gravity function

Gravity models are among the most frequently used model category within geography. Originally introduced by Hansen (1959), they effectively model Tobler's first law of geography that is "everything is related to everything else, but near things are more related than distant things." (Tobler 1970, p. 234). The general gravity function is defined as:

$$G_i = \sum \frac{W_j^\alpha}{e^{\beta \cdot d_{ij}}} \qquad (1)$$

Where Gi is the gravity induced by destination j to origin i. Wj is the weight of destination j (eg. the total floor area of an location) while is parameter that scales the effect of the weights. e is the natural logarithm. dij is the distance between origin i and destination j while is the distance decay parameter. The parameter and are ideally estimated empirically f While in practice is often left to 1, the parameter is crucial. Multiply empirical studies concluded that, in the urban context, a value of 0.002 (when distances are measured in meters) generally delivers good results for pedestrian movements (see Sevtsuk et al. 2017)

$$V_i = \frac{\frac{W_j^\alpha}{e^{\beta \cdot d_{ij}}}}{\sum \frac{W_j^\alpha}{e^{\beta \cdot d_{ij}}}} \cdot pop_j \frac{1}{e^{\beta 2 \cdot d_{ij}}} \qquad (2)$$

The basic gravity model can be extended to model competition between places (such as retail centers or parks) and people's choices on which place to visit. This variation is also known as the Huff-model (see Huff 1963). Its basic assumption is that the probability of a potential visit of a person to a point of interest is a function of the point's attractiveness and its distance to the person (basically equals Gi) relative to the gravity received by all other points of interests. Thus, the function can be defined as:Where

Figure 5
Tracking of selected indicators during sketching scenarios

Visitors i are the total visitors to point of interest i. The first term represents the relative gravity (gravity between point of interest i and origin j divided by the sum of the gravitation between origin i and all points of interest). The second term, pop j, is an additional weight attributed to origin j, resembling the population or potential customers.As, one could argue that if a origin is very far away from any point of interest no visitor at all will originate from that location. This can simply be modeled by adding another distance decay parameter (2) to the model affecting the weighting parameter pop j.This approach can be, and is often applied in modeling origin / destination matrices that form the basic for traffic and foot-fall modeling (for instance see Hensher 2004).

Sketch-mode

This mode serves to sketch scenarios and tweak designs proposals. The sketch mode is thought of to help with preparing multiple scenarios that can then optionally be fully computed and reviewed in detail using the Evaluation mode (see below). The user can deactivate the computation of indicators and measures that have long calculation times in order to get near instant feedback when trying out different configurations. Thus, facilitating an indicator-guided design process (see Fig. 5).

Additionally, creating a GUI to handle all user interactions was considered an essential step for making the toolbox accessible to parties not familiar with Rhinoceros 3D and Grasshopper or CAD software in general: It can be used without having to interact with the Grasshopper canvas nor using any Rhino text commands. The higher level of user-friendliness raises the potential of the tool for employment in workshops and public participation sessions for creating, discussing, and communicating multiple real and hypothetical scenario variations.

Evaluation-mode

The evaluation mode relies on previously calculated scenarios. Up to four of these scenarios can be loaded at the same time and compared to one another.

The core functionality of this mode is filtering, structuring and comparing indicators between scenarios. Fig. 6 and 7 provides an overview of the user interface structure. On top are basic filters for the network type (pedestrian/transit; car, etc.) and (sub) ar-

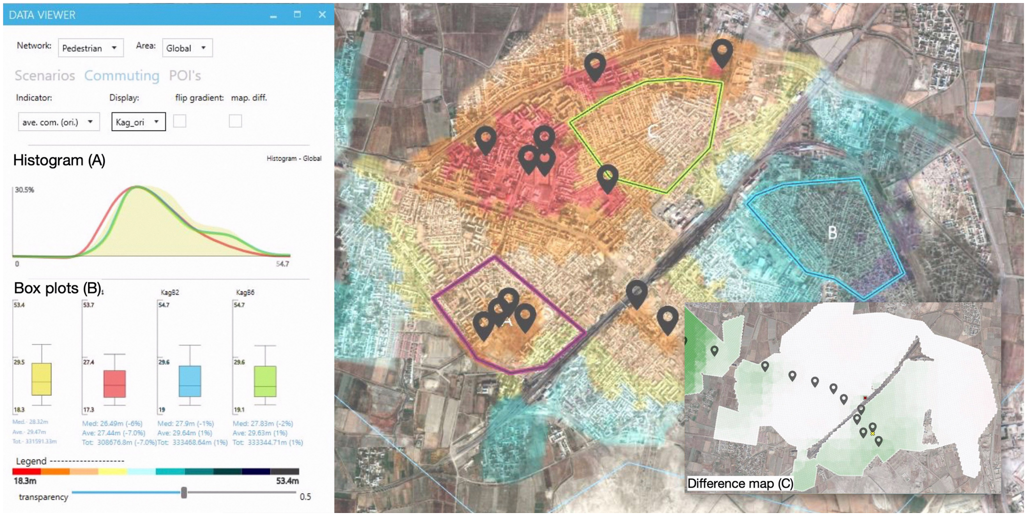


Figure 6
Data dashboard with the data visualized on the analysis grid

eas the indicators should be computed for. Below are several tabs: most importantly for indicators or indicator categories. In case a project required additional evaluation criteria, a new tab can simply be attached to the interface with ease.

Spatial filtering

The toolbox provides functionality to define up to four sub areas to analysis the impact of a proposed intervention on a local level. These areas can either be characterize spatially (by sketching a curve around the area of interest) or by defining filters.

Filters are rule based selections. Only spatial units (such as nodes or cells) that meet all of the selection criteria are included. Criterias such as the population, jobs, income, social-milieu etc. This allows to keep track of, let's say, how low-income groups benefit or disbenefit from an intervention in particular.

CASE STUDY VIENNA

Due to the readily accessible data and the city's reputation for its well connected multimodal public transport system, the city of Vienna was chosen as a testbed city during the development of the tool.

The road network acquired from the OpenStreetMap database was connected to the graph of public transit network built from General Transit System Feed (GTFS) data provided by the Vienna's open data portal. Instead of using connection times parsed from the GTFS, it was decided to calculate public transport connection times from the traveled distance and assumed average speeds of used transit modes. This approach has a disadvantage of introducing slight inaccuracies into the model compared to calculating travel times based on existing transit timetables. On the other hand, it simplifies the model and allows for the streamlined introduction of changes into the model. This approach enables exploration of hypothetical scenarios such as adding a new metro line to the public transport system or measuring the impact of increased speeds as, i.e. converting shared bikes into e-bikes.

After series of tests and optimizations of the average speeds of each transit mode and average assumed waiting times, the error in travel times using public transport was minimized to average of ±15% from the timetable reference (see fig. 8).

Figure 7
Dashboard for point of interest (POI) related data

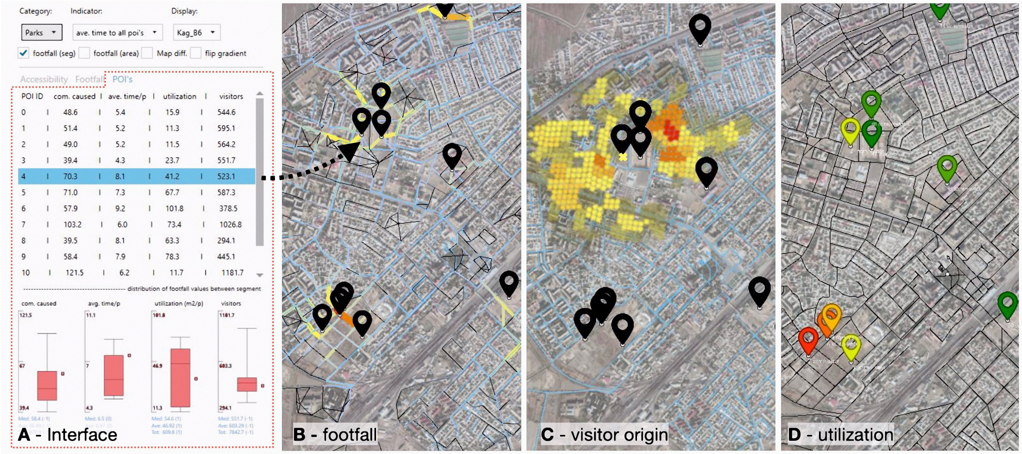
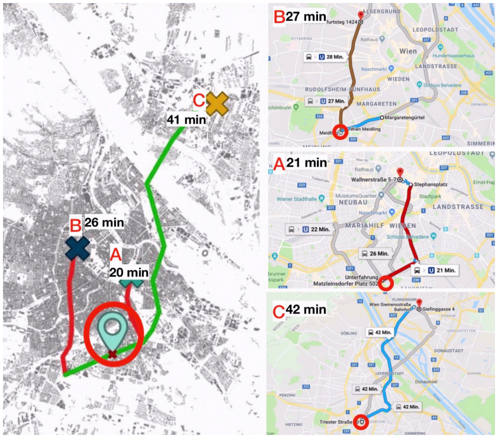


Figure 8
Comparison of the calculated travel times with results from Google Directions API for the same origin - destination pair



Reflection:

The first application of the method has shown promise in assessing both current accessibility patterns of the city and predicting the impact of future developments of the transit network. However, it is to be noted, that due to the simplified way the connection times are calculated, the model is slightly inaccurate. In the future, we would like to implement an updated framework which would enable to preserve the connection time information from the GTFS data, if available, while still allowing for simple modifications of the network and measuring the performance of hypothetical scenarios.

CASE STUDY GELA

In case of Gela, our toolbox was used to simulate addition of new public transport proposals, formed during workshops conducted with the local governance, including introduction of new bus routes, tram-train route and bicycle lane network.

The city Gela is located on southern coast of Sicily, Italy. It has a population of 75,458 inhabitants, and it is largely car-dependant, with almost no existing public transport infrastructure, the only exception being buses without clearly shown routes or time-tables. The quality of sidewalks is also low, and there almost no existing bicycle lanes. The city is however currently in the process of changing this, bringing a whole new public transport network and bike lanes network. Taking the advantage of the toolbox's option of comparing different scenarios, it provided very clearly visible results, showing impacts any of these proposals would have on accessibility from certain locations within the city (see fig. 9).

The toolbox was used to generate public transport network proposals which were further stored in the toolbox's UI. Having the the option to easily control which of them are active for current simulation allowed for comparison of their significance for certain areas. Furthermore, a bike-sharing system (station based) was modeled with the toolbox, assisting in decision making of where these stations will be located.

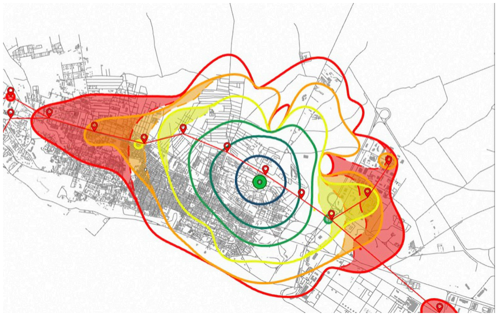


Figure 9
Visualization of changed mobility after the addition of a tram line

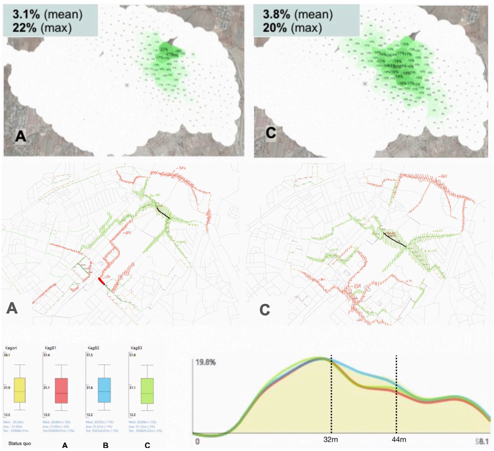


Figure 10
Visualization of selected indicators. First row: access to jobs, difference map; Second row: Change in pedestrian frequency potentials; Third row: Box plots and histogram for the indicator commuting to shopping centers

Reflection:

The case study of Gela was a great example of using the toolbox for comparison and simulation of new additions of public transport to the city. Due to it's almost non-existent current public transport, most of the additions resulted in quite a significant impact, that is clearly communicated through visual means to all the interested parties, resulting in much higher awareness and interest. Furthermore, having access to these immediate simulations proves a great assistance in discussing and modifying the proposals or designing new ones.

CASE STUDY KAGAN

In a joint project by the World Bank, Superwien Architektur and the Austrian Institute of Technology, the toolbox was used in the master planning process for two medium sized cities in Uzbekistan: Kagan and Chartak. The task was to develop between 4 to 8 interventions (eg. implementation of a new eco-trail, renovation of public spaces etc.) for each city and then rank them in a cost-benefit analysis as not all projects could be funded. The toolbox was employed to assist design decisions, to conduct impact analysis of individual projects and to bundle projects by testing which combinations of interventions synergize with each other to bring maximum leverage effects.

As data inputs only the street network, a estimated population and job distribution and points of interests (such as schools, parks, retail centers) were used. Exemplary, the application of the toolbox in deciding upon the location of a second pedestrian railway overpass in Kagan will be outlined below.

First of all, six potential locations for the second bridge were located and evaluated by several indicators. Table 1 provides an overview. Based on the results three options (A,C and D) were selected for further analysis and comparison in the evaluation mode. Next to accessibility and commuting related measures, the potential change on pedestrian frequency and footfall was analyze as well. The latter can be helpful for anticipating and planning of retail locations or prioritizing street renovations among others applications (see Fig. 10). The spatial filtering functional further allowed to estimate the specific impact on the other proposed design interventions individually. After all a decision between option C and D was

Table 1
Overview of indicators and results. In green: short-list of locations for further analysis. Option C ranks first in six out of ten indicators and therefore outperforms both A and D in the quantitative analysis

Indicator/Location	Location A	Location C	Location D
Population within 10m walk	3300	3500	4000
Jobs within 10m walk	980	1200	1400
Access to people (improvement in %)	**3.1%** (mean) **22%** (max)	**3.8%** (mean) **20%** (max)	**3.13%** (mean) **15%** (max)
Access to jobs (improvement in %)	**3.16%** (mean) **22%** (max)	**4.5%** mean) **22%** (max)	**3.5%** (mean) **16%** (max)
Avg. commuting time to jobs (walking) (improvement in %)	**2%** (mean)	**2%** (mean)	**2%** (mean)
Avg. job opportunity index (walking) (improvement in %)	**2%** (mean) **3%** (median)	**3 %** (mean) **4%** (median)	**2 %** (mean) **3%** (median)
Walking time to all shopping centers (improvement in %)	**3%** (mean) **5%** (median)	**3%** (mean) **5%** (median)	**2%** (mean) 4% (median)
Walking time to all parks (improvement in %)	**2%** (mean) **3%** (median)	**2%** (mean) **2%** (median)	**2%** (mean) **2%** (median)
Walking time to Railway-station (improvement in %)	**0%** (mean) **0%** (median)	**0%** (mean) **0%** (median)	**0%** (mean) **1%** (median)
Local integration, connectivity r1600 meter (description of impact)	High	High	Medium
Local integration, pedestrian flows r1600 meter	See images		

recommended with the conclusion that the final decision is a matter of normative standpoints: If spatial equality and a more evenly distributed access to all citizens is prioritized then option C appears optimal. In case the most important goal is strengthening the centre and perhaps fully integrate parts of it into old Kagan, then location D appears to be the better option, despite its lower impact on the overall connectivity.

Reflection:
All in all, the toolbox proved useful in facilitating an evidence-based discussion and decision process on the ideal location for the second railway overpass and was received positively from the project partners. The combination of comparing multiple scenarios against one reference scenario at the same time with spatial filtering options turned-out to be a powerful framework to compare alternatives for one project but also to test for a ideal combination of a set projects in a streamlined manner.

LIMITATIONS
It is important to emphasize that the toolbox at no point claims to cover all issues related to and important for planning and monitoring urban systems. Thus, it can only contribute in the fields it makes dedicated Statements on. Moreover, its accuracy depends on the data quality used as input and the calibration of its parameters. As both can be challenging the toolboxes can be seen as a planning and design

decision support system - as one additional factor to base choices on. But even in cases where the data quality is highly questionable the toolbox could still be used (carefully) to compare relative differences between scenarios or in order to better understand and discuss the underlying dynamics of urban systems and in the use-cases depicted in the beginning of this paper.

CONCLUSION

In all three cases the model was overall well received by the participating parties and in the context of a workshop (Gela), the GUI and CAD-like input methods for sketching scenarios exhibited good usability, the visualization in form of maps and a selected set of key indicators proved useful to communicate and discuss and decide upon design proposals. Similarly, the tools application to quantify and evaluate various urban design proposals was perceived help- and insightful by the involved urban designers that previously have not been in touch with quantified methods.

For the further development, we aim to improve the capabilities for local validation of the model's parameters as well as add a range of new features in terms of data gathering, processing and exchange as well as adding more analytical modules and indicators.

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