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# A HYBRID APPROACH FOR BUILDING MODELS AND SIMULATIONS FOR SMART CITIES: EXPERT KNOWLEDGE AND LOW DIMENSIONALITY

Elhabib Moustaid
Sebastiaan Meijer

KTH Royal Institute of Technology
School of Technology and Health
Hälsovägen 11C
Stockholm, 141 52, SWEDEN

## ABSTRACT

In face of high urbanization and increasing mobility, models and simulations are used to find answers for urban planning problems. However, simulations face criticism for over-simplifying complex reality, having models disconnected from the context of their use or excluding policy-makers from the building of models. Smart city approaches did not overcome that reality even if they relied more and more on microscopic models, together with data available through technology. This article describes a hybrid approach combining the expert knowledge on the city and its limits in terms of data, with models having the right dimensionality to provide policy-makers and urban managers with the necessary information for understanding and managing the city. This approach has been applied in Venice, but it describes in more general terms a way of bridging the world of theoretically sound models with their potential use.

## 1 INTRODUCTION

Planning, managing, and operating cities and urban networks are hard tasks since these are complex systems with a lot of uncertainties. Cities, as other complex adaptive systems, experience a great deal of emergent phenomena and non-linear relationships of their components, making them most often very unpredictable and deterministically chaotic (Portugali 2012, Batty 2013). Even with the extensive use of simulation and models in smart cities, building simulations is often a matter of intuition. This paper presents a hybrid approach for building simulations to explore urban planning with focus on inclusion of expert knowledge of cities in the building, running, and validation of simulations. In light of decades of modeling for complex adaptive systems, the approach recognizes and specifies the role of expert knowledge and data to steer the building of simulations, as well as circumstances in which expert knowledge can be used as a source for direct quantitative input to low dimensional simulations. This hybrid approach consists of a top-down process of building theoretically sound models and a bottom-up process that includes the context of the use of the simulation, the data available and the expert knowledge. This can prevent modelers from building models that aim for high degrees of realism or high theoretical rigor, without providing tools for validating the results or enriching the knowledge over the model target. Furthermore, the approach lowers the gap between the modeling world and the real world constraints that cities face when applying simulation results (Lee 1994). In this paper, we present the results of the application of this approach in Venice, Italy, during the course of the FP7 Framework EU project PETRA (Personal Travel Advisory Systems).

The remainder of this paper consists of four parts; the next section presents the background of models, simulations, data and expert knowledge for urban planning. The third section presents the details of the proposed approach, followed by a section presenting the application of the method in Venice, Italy. Finally the conclusions about this approach are stated.

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## 2 A REVIEW OF LITERATURE AND INTENDED CONTRIBUTIONS OF THE PAPER

### 2.1 Models, Simulations, Data and Expert Knowledge for Urban Networks

Models and simulations have been used for decades to investigate cities, design new systems and services, or predict the evolution of land-use and urban networks. Models, usually mathematical, relied on optimization, discrete mathematics and operations research to optimize functions on urban systems (Larson and Odoni 1981, Vuchic 2005). Such models investigated for example effects of different routing alternatives or different transport network architectures on the city in general (Pattnaik, Mohan, and Tom 1998). However, the failure to find optimal solutions for most urban problems due to mathematical infeasibility, computational demand or modeling difficulty made reductionist approaches more popular. Idealization in modeling reduced urban systems to yet simpler representations. As is the case in some economic models, simplicity of models and simulations allowed urban planners and scientists in particular to understand first order effects of certain factors on problems related to urban management (Grüne-Yanoff 2009). By isolating particular parameters, models have succeeded in providing more insight into certain causalities in cities. The combination of such sub-systems results, through technical coupling or through comparison and combination of results, allowed city experts and planners to infer to the real systems they represent (Zomer, Moustaid, and Meijer 2015).

The idealizations and levels of details in these simulation models made the creation of knowledge about the real systems of the city often a hard task. In fact, relying on assumptions and heuristics to overcome their limitations, these models sometimes described systems that were totally different from the world they were supposed to simulate (Sugden 2000). Moreover, the view of cities being complex adaptive systems was embraced as they were treated less and less as deterministic systems in a steady–state (Batty 2013). Picking up on the notion of complexity, and taking advantage of more computational powers, there was a shift from highly-idealized approaches to approaches that take every possible source of complexity into account. Similar to micro-economics, this bottom-up approach tried to consider the interactions between city components and aspects such as the self-organizing nature of cities (Lee 1994). Agent-based, fractals, chaos theory or cellular automaton models, fed with data and relying on geographical information systems opened the way for new kinds of analysis (Batty 2007, Santé et al. 2010). Shifting even towards more scenario-based approaches, where the role of simulations and models is to provide decision-makers tools for exploring options, rather than giving a final response to a complex problem. It allows the understanding of complex systems without the need to assume the existence of a steady-state (Batty 2007). This resulted in microscopic simulations that were indeed less idealized when describing the cities as a space, allowing sometimes better understanding of arising complexity. However, the microscopic models often made assumptions regarding microscopic entities and their interactions making them suffer similar validity problems. Such models also require considerable amount of data to run, and to assess their predictions' validity (Ranjitkar, Nakatsuji, and Asano 2004). Models have to overcome these deficiencies by macroscopically assessing their microscopic variables. The lack of data for validation can either be caused by impossibility of sensing the data needed, or by simulations making projections that are not verifiable (Store and Kangas 2001). This again poses a problem as to whether or not microscopic approaches are best to deal with urban systems. Batty (2015) argues that enriching a model hoping to improve its simulation of the existing situation, makes its validation more problematic.

Hence two main issues emerge regarding models and simulations for urban planning. Firstly, highly idealized and simplified models and simulations relate less to reality, making any inference from such models and simulations often hard or impossible. Secondly, highly detailed models were never proved valid for the processes and behaviors they describe, partly because of computational powers, but mainly because of the lack of data for validation. This called for different heuristics that can sometimes involve expert knowledge in different ways. Garthwaite, Kadane, and O'Hagan (2005) define expert knowledge as the expertise someone holds on a subject of interest. This knowledge can be the result of life experience, training or education. The use of expert knowledge has served prior construction of simulations in defining their scope. The scope of simulations and models determines the relevant dimensions and parameters. This choice is usually motivated by intuition and the justified beliefs of urban experts and modelers. Those parameters and dimensions define the boundaries of the system simulated as well as the aspects of the system that experts believe need investigation. Modelers then build simulations to address particular questions (Matthewson and Weisberg 2009). This has been widely used, and the research has usually focused on the best methods to elicit the expert knowledge (Kuhnert, Martin, and Griffiths 2010). Expert knowledge has also been used for validation of simulations through face validation when quantitative or logical methods of validations are impossible or irrelevant (Kuhn 1970). This approach is now particularly used to validate simulations of complex systems, where the only possible validations were to see whether or not the results of the simulation make any sense in the real-world.

### 2.2 Synthesis and Contribution of the Paper

The inclusion of expert knowledge in the building or validation of simulations has been done before but not in structural ways, even less for smart city simulations. Expert knowledge has been successfully used for face validation or scope definition of simulations, but it has been less successful when used as a direct input to run simulations. In this article, we argue that expert knowledge can complement data when using low dimensional models, i.e. models with only a few parameters, with the right level of idealization and approximations. In line with Chahal and Eldabi (2008) hybrid approach, we combine expert knowledge with low-dimensional models in a way that increases the realism and relevance of simulations for smart cities. We regard this as a hybrid approach. This approach also shows a method to reach simulation models that can exhibit the information needed by the simulation users, while taking into account the data and the knowledge available to run the simulation.

The following section presents the details of our hybrid approach. The approach will be applied to Venice, where a low dimensional theory-based model was combined with expert knowledge to construct and run a simulation that provides plausible quantitative results, as well as tools to urban planners to investigate the mobility of the city

## 3 HYBRID APPROACH FOR CONSTRUCTING SIMULATIONS FOR SMART CITIES

Maria (1997) proposes an 11-step process for building simulations consisting of investigating target systems, choosing models, extracting and generalizing results. The approach proposed in this paper, shown in Figure 1, agrees to a large extent with Maria's approach. This approach however focuses on smart cities and is specific to using data and expert knowledge to shape the construction of simulations. It distinguishes itself by defining conditions under which expert knowledge can be used as a direct input for simulations.

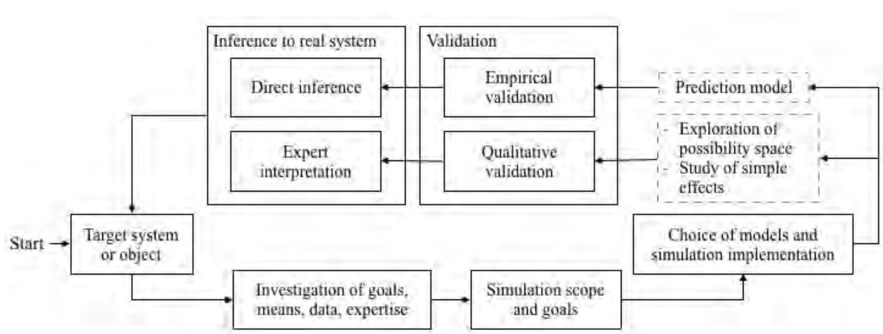


Figure 1: Data and experts in the building of simulations for smart-cities.

Simulation building for smart cities starts from the target object of the simulation, which can be the city or one of its subsystems or aspect systems. This is followed by an investigation of the subject, its means in terms of data and technology and the knowledge around it. From that, the simulation goals can be drawn. Modelers choose the kind of simulation model to use, and then implement the simulation. The improvement, verification and validation of simulations are done before projecting learnings on the original system. The following sections detail these steps.

### 3.1 Target Object, Goals and Means

Goals for smart cities range from designing new services to developing new strategies and measures to lower congestions, traffic, CO2 emissions, new social activities, economic prosperity or even higher social inclusion. Investigating ways of achieving such goals requires a high knowledge of the means of the city, and the factors that can be manipulated to make these goals achievable. City experts and problem owners clearly express the processes and factors of interest. Those can be the exact predictions that are needed for particular factors, but it can also be seeking to investigate sub-systems of the city, or understanding effects of certain factors or behaviors on the goals they seek to achieve (Matthewson and Weisberg 2009, Batty 2013). Experts also have knowledge of possible actions that cities can realistically take as well as social, technical, and economic aspects that cannot be understood through quantitative methods. This work by experts and problem owners is the ground work for defining the simulation scope. It sets the base for a modeler to define the simulation scope.

### 3.2 The Simulation Making, Scope and Level of Details

A perfect simulation of a target would create a one-to-one relationship between the simulation and the aspects of that target. However, Nagy et al. (2007) claim that this is impossible. Simulation construction becomes a process of choosing the focus systems or sub-systems, the relevant variables, and the appropriate idealizations and assumptions. In quest of higher generality or precision, simulations can be coupled to provide better learnings about their target systems. Deciding the trade-offs between different virtues of models, such as generality, realism and precision is the most crucial aspect of this process (Levins 1993, Matthewson and Weisberg 2009). For urban modeling, this is where the data and expert knowledge play a crucial role. The choice of a simulation model is mainly a choice of the details that the model takes into account and the objective of the model. Besides the classical use of expert knowledge to define the scope of the simulation, this approach sees that idealizations can be made in a way that allows expert knowledge to be directly useful for running simulations. Experts in cities can provide direct input to simulations if the simulation parameters correspond to aspects that experts have knowledge on. For example, experts can provide estimates or numbers to run simulations when data cannot provide these same details. A low-dimensional model can elicit the knowledge of experts best as they are not required to provide highly detailed information, but only estimates, probability distributions, and recognized patterns in the city. Hence, a modeler building a simulation should take that into account when choosing the level of details to have in a simulation.

### 3.3 Validation of Simulations and Inference to Real Targets

Validation of simulations has been a major debate between simulation scholars for decades. Kleindorfer, O'Neill, and Ganeshan (1998) show different schools of thought when it comes to simulation validation, resulting in quantitative, qualitative or mixed approaches. They assert that pure logical or empirical validations of simulation in particular have failed in the world of simulation. This is the case particularly for cities and generally complex adaptive systems where sometimes this kind of validation is impossible or even anecdotal. Sargent (2005) and Balci (1986) detail different kinds of methods of validation. They cite for example different quantitative methods of assessing the validity of simulation results as well as the importance of validating conceptual models, verifying simulation models specifications and simulation implementation. In the approach presented in our paper, we make a clear distinction between models that seek to produce data or information that is directly used in prediction or assessment of real targets, and models that, through simplifications or isolations, increase the knowledge about aspects of the system. Both require different kinds of validation. In the first case, the simulation predicts aspects of the real system and claims to provide true predictions. In accordance to Popper's view the predicted data has to be checked against the real-system data, and indeed the model can be improved, calibrated, or even replaced using the results from validation processes (Popper 1959). Validation does not prove the simulation model to be true or false, since in the context of complex systems, such as cities, it is highly improbable that predicted data matches the system data, and even when it is matched to a certain extent, it is hard to assess the validity of the deviation of simulation predicted data from real-system data. At the same time, most models can hardly be proven wrong through assessment of predictions as it is easier to explain inaccurate results with auxiliary assumptions used to make predictions through the model. The difficulty of quantitative methods of validation resulted in the need of face validations, i.e. experts making judgment on whether results of the simulation are coherent with their knowledge of the system. This method of validation recognizes that experts are knowledgeable enough of cities to determine whether or not the results of a simulation are within the scope of possibility (Gigerenzer 2008).

In the second case, i.e. if a model is highly simplified, the validation is value-dependent (Kleindorfer, O'Neill, and Ganeshan 1998). A model can be called adequate if it is fruitful to understand aspects of the city. Those aspects can be social, economic, political or environmental. Such simulation models include for example some of gaming and participatory simulations (Raghothama and Meijer 2015).

The inference from simulation models to their target comes in two categories. Firstly, when simulations models claim truth; their output is directly used to predict, evaluate, replace or assess aspects of the modeled system. Secondly, when simulations are merely tools of investigation; simulation users are needed to make inference into real systems, based on historical knowledge, psychological and social considerations.

## 4 ILLUSTRATION OF THE APPROACH THROUGH VENICE USE CASE

In the following section, a hybrid approach was followed to build a simulation for the city of Venice. The simulation provided urban-planners from different agencies tools that deal with problematic aspects in the pedestrian network of Venice. The process identified the goals of Venice within the PETRA project, and then built a simulation choosing a low dimensional theory-based model that provided enough generality and realism, and which had the right idealization level to use the means of Venice in terms of data and expert knowledge. The simulation was then used to predict some aspects of the pedestrian network. It also served as a tool for investigating the degrees of freedom that urban planners possess to solve problems of crowdedness related to known scenarios in the city. The validation of the simulation consists of both an empirical and a qualitative analysis.

### 4.1 Venice Background, Goals, and Means

Mamoli et al. (2012) describe Venice as a puzzling paradigm of modern cities. Venice, being almost isolated from the mainland, has a historical pedestrian network enabling free movement and creating social, economic and cultural activities for the city users. The increasing number of tourists every year, and the growth of the Venice population make the city constantly test its capacities (Massiani and Santoro 2012). The tourist capacity of Venice was estimated by Canestrelli and Costa (1991) at around 25,000 visitors per day which has been exceeded since the 1980s (Van der Borg and Costa 1993). Today, tourist visits are estimated at about 60-70,000 visits per day causing over-crowding in the pedestrian networks, attractions as well as public transportation. Hence, the objectives of the city of Venice in terms of urban planning within the PETRA project is to have tools to mitigate the traffic states, and to provide tools to urban planners to advise the city users in order to make their journeys in the city more enjoyable. In order to achieve such objectives, the city possesses some technologies gathering data, as well as an extensive knowledge of the mobility in the city, its infrastructure and users.

The study of the mobility in Venice has always focused on the pedestrian movements. The main access points to the historical city are the train and the bus station in addition to the parking space at *Piazzale Roma* (Figure 2). Part of the inflow of pedestrians from these points is then distributed in an uneven way on the pedestrian network. The rest of the flow is distributed through the waterbus transportation. The continuing over crowdedness of pedestrian networks sometimes makes locals change their travel habits in order to get faster or more comfortable travel plans (Massiani and Santoro 2012).

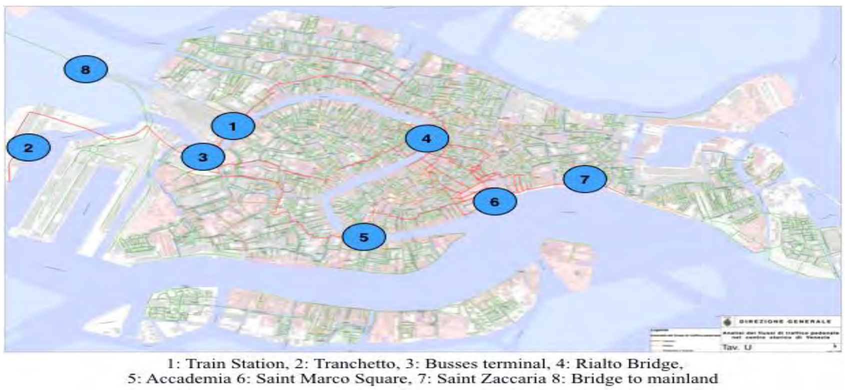


Figure 2: Map of Venice and points with high numbers of city users.

These findings were consistent with the findings of the work done during the PETRA project together with mobility experts from ACTV (Venice public transport operator) and AVM (Venice Mobility Agency). As geographical expansion of Venice is not an option in face of levels of crowdedness that exceed the city capacity, the optimization of Venetian services and information systems is a necessity. The waterbuses provide ways of distributing flows around the city. The distribution of flows over the pedestrian network can be done by providing information to users to prevent crowding, and can make the experience of the city more enjoyable to its users.

Besides the extensive knowledge available through experts dealing with mobility issues in Venice for decades, Venice has few sources of mobility data, mainly highly aggregated and coarse-grained. The data available consisted of (1) counts of ticket validation at the water bus stations, (2) estimation of arrivals from the main train station and land buss stations, (3) counts of parked cars at the main island, (4) estimates of the number of visitors for the main attractions in the city and (5) details of the public transport network such as operating times and capacities. In addition to this data, social media data is available through samples of anonymous Flickr users. Flickr is a service allowing its users to store and possibly share their pictures. The pictures are available with a timestamp, geo-tag, and an anonymous user ID, allowing the assessment of the succession of places users visited. This provides a way to understand mobility patterns in the city.

## 4.2 The Making of the Simulation, Low Dimensionality and Expert Knowledge

Given the later investigation of scope, goals and means of the city, the simulation goal was identified as twofold. Firstly, it aims to provide urban planners and strategists a toolkit to collaboratively assess new strategies and policies via a coherent model of mobility patterns capturing in the simplest way several aspects of the city. The second role is using the simulation to provide information necessary for travel advice given a mitigated state of traffic. Realistic estimation of travel-times on pedestrian routes, at different times of the day depending on crowdedness levels is particularly needed. This information is a direct input to the travel planner that provides advice to city users. Making a simulation of the Venetian network is solving the following problem. How can we build a simulation that can provide information needed to advise users, and a testing platform for different strategies that can be deployed to address mobility problems in Venice? This has to be solved with the limited resources in terms of data and a great knowledge of mobility in Venice. The knowledge of experts included known problematic scenarios and tools to address them.

Pedestrian flows have been treated using various methods. Microscopic approaches include agent-based, social force or cellular automaton models (Helbing and Molnár 1995; Daoliang, Lizhong, and Jian 2006). In order to focus on the essentials (realistic pedestrian travel times), and in order to use best the available aggregated data and the extensive expert knowledge of mobility in Venice, only macroscopic approaches could be considered. In fact, to use best the extensive knowledge of experts on the flows in the city, the simulation should simulate the movements in the city as movements of flows, and not particles. The simulation of the network at the level of flows also makes the highly coarse-grained data useful for the simulation, without further need of assumptions on pedestrian behaviors. In addition, the only aspect of the simulation that required a high degree of realism was travel-times, which required this aspect of the simulation model to be realistic and tested against data. The model of Flötteröd and Lämmel (2015) presents a macroscopic bidirectional pedestrian flow model that relies on few measurable parameters (maximum pedestrian velocity, jam density and an avoidance parameter representing the time that a pedestrian loses avoiding another pedestrian walking in opposite direction). The model shows a good fit when tested against data. The model is adequate for the needs of urban planners in the city of Venice as it has the possibility to provide realistic travel times given crowdedness levels. A generalization of the model to take into account pedestrian intersections has made the model applicable for simulation of pedestrian networks.

The choice of this model enabled the expert knowledge to provide quantitative input that covers up for the lack of data. In fact, the final simulation model needs two parameters to be computed. Data and expert knowledge were used for that purpose as follows. The first parameter is the estimation of incoming and outgoing flows to the pedestrian network. This was done by combining numbers given by the water transportation ticket validation counts, and estimates of influxes and out-fluxes for the main access points to the pedestrian network, with expert knowledge of the distribution of these rates. The experts were able to provide the likely distributions of each of the major access and exit points depending on day scenarios. This increased the realism of the inflow and outflows to the pedestrian network. The other parameter that needs to be computed is the turning fractions at intersections; that physically means the proportion at which pedestrians break when going through an intersection. The Flickr data provided the origin and destinations of pedestrians, while expert knowledge provided the mostly likely paths that pedestrians could take. In fact, the geo-tagged pictures gave the positions of pedestrians at different time-stamps. By knowing the paths that all pedestrians took, one can estimate the turning fractions at the intersections. The paths between geo-stamps are not available through data, but the expert knowledge on flows and tourist paths in Venice through the years provided those paths.

In order to increase the realism of the travel-times, the cartography describing the environment of the application of this model has been gathered to exactly fit its use; providing besides the geographical attributes, the length, and the width of links. The trade-off between precision of the model parameters and generality of the model is done in respect to Matthewson and Weisberg's (2009) criteria of trade-offs, meaning that precision is added only to make the general model fit the context of its use.

Besides the ability to provide verifiable travel-times, the model was flexible to support strategies that urban-planners wish to have in a simulation. This included for example, testing total or partial closing of some pedestrian links, increasing incoming or outgoing flows to the city, as well as adding water transportation stations (the simulation supports adding more access points to the pedestrian network).

The simulation was scenario based. The scenarios investigated were high, normal and low-crowded weekdays or weekends accounting for a total of six scenarios. Expert knowledge provided distribution probabilities for entrances and exits to the network depending on the scenario. The fact that the simulation was scenario-based made it relate to the goals of the city. The defined scenarios described an isomorphism with the states that needed to be mitigated by the city authorities. This allows the app users to get the travel-times between Points of Interest (PoI)s given the mitigated traffic scenario. Figure 3 shows the final architecture of the simulation of the pedestrian network, combining the data, expert knowledge and a macroscopic low-dimensional model of pedestrian motion.

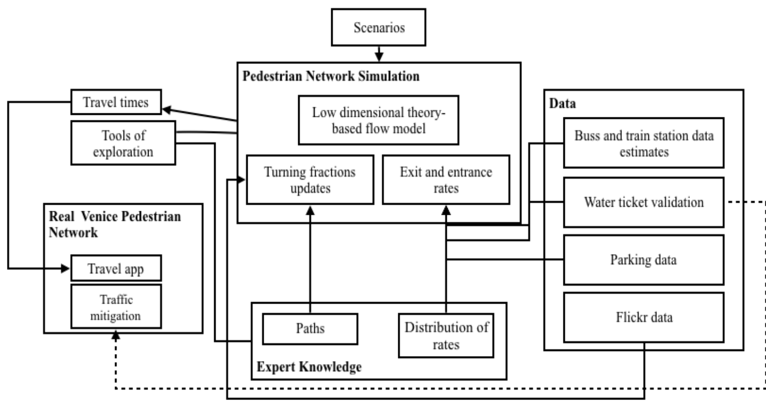


Figure 3: Simulation architecture, including input data, expert knowledge, and outputs.

## 4.3 Validation of the Simulation

The validation of our approach relies on two pillars. First, the part of the simulation that is intended to investigate the pedestrian network is proved valid for providing tools of investigation to decision-makers. Second, a quantitative validation to show that the expert knowledge combined with a low-dimensional theory-driven model and highly aggregated data can provide quantitative results of significance. The two pillars of the validation provide evidence that the two goals of the simulation were met using the proposed hybrid approach.

### 4.3.1 Expert Validation

In line with Kuhn (1970), a validation workshop intended to test whether the level of detail of the simulation and options could be a tool for investigating the mobility in Venice and gain more knowledge of potential strategies. Besides the validation with ACTV and AVM, a workshop was done with different agencies in Venice including the local police, the office of tourism and the city of Venice. The participants had no prior knowledge of the simulation or its abilities before the workshop. This is particularly important so as to avoid influencing their expectations during the workshop. The participants were organized in groups, with each group consisting of members from different authorities and agencies over the city. Each group was challenged with a scenario that affects mobility to elicit the actions they would take against that real-life scenario. The simulation is valid if it provides them with the options to test these actions and if the results were plausible. The scenario discussed by one of the groups regarded the closure of the bridge connecting the historical city with Venice’s main area during morning peak hours. The map on the left hand side of Figure 4 shows the alternative modes of transportation that the group concluded. On the right hand side of Figure 4 screenshots of the simulation of their actions is presented. The darkness of the colors of links indicates their crowdedness. The level of information shown in that visualization was deemed to be detailed enough to understand the behavior of the city according to participants, and the results made sense. The high crowdedness in certain areas such as Rialto Bridge (Point 4, Figure 2) can be explained by higher rates of pedestrians coming through the alternate route 3, Figure 4 and walking pedestrians on routes 1 and 2.

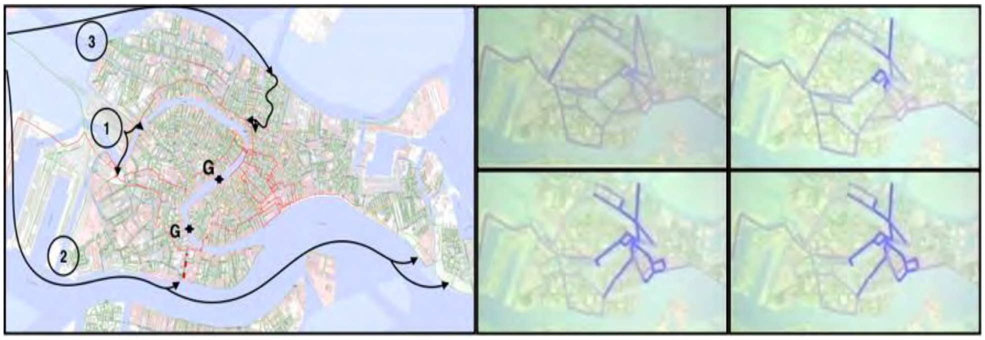


Figure 4: Routes to be investigated on the left, and screenshots of the resulting simulation on the right.

Another scenario discussed by a different group regards the closure of the bridge in evening peak hours when the amount of visitors leaving the city exceeds the available capacities. The actions that were taken in this case were informing operators about the overload in the system, and informing the commuters about other means of transportation as well as providing them with estimates of waiting times to board the available transportation. These actions intended to provide information to city users from operators. Even though the simulation does not at all simulate the microscopic behavior of city users, its effects on flows can be simulated. However, this would require the simulation user to assume the response of city-users to the information they receive. Based on that response, the turning fractions can be updated adequately to see the effect on flows around the network. For example, if the action is to ask users in a part of the city to select other paths, the turning fractions on intersections along those paths should reflect that.

The summary of this validation is that the simulation does indeed in a very simple way provide a possibility space that can be useful to understand movements of flows in the city of Venice, providing plausible results. The face validation, besides showing the plausibility of simulation results, shows that the hybrid approach succeeded in capturing the relevant dimensions of the problem and the right level of details to understand mobility in the city.

### 4.3.2 Quantitative Results

The quantitative results of the simulation that need a measure of realism were the estimates of travel-times. This was investigated by looking into travel times between PoIs. The validation of travel times was done through a travel app in Venice. This travel app's user can report if the travel times provided by the simulation and displayed through the app are valid. The travel app indeed mitigated the traffic scenario by reading on real time counts of ticket validation of public transportations, and then displayed to the users the travel times corresponding to the simulation of that mitigated scenario. Users' response provide a feedback loop of the travel times and evaluates their consistency. The beta testing of the App from ACTV has identified the travel times to be credible. The test on a large audience has however not taken place.

Hence, Figure 5 also shows the results when comparing the travel times returned by the simulation between four major axes of the city of Venice with the travel times returned by Google Maps for the same trips. The comparison to Google Maps is due to its wide use by travelers in Venice. The simulation travel time variation is due to the variation of number of people in the city, and in this case increases with higher visitor numbers. The comparison with Google Maps is only illustrative as the models behind Google Maps travel times are unclear; hence a more substantial comparison is hard to reach. The results show that simulated travel times are very close to Google Maps estimates. Deviations however might occur between results. This is explained by the simulation feature where travel times depend on crowdedness levels.

Further sensitivity analysis of these results shows the origins in the difference of travel times between the simulation and Google Maps. In fact, for the road Academia-Train station where Figure 5 shows a difference of about 8 minutes; depending on the crowdedness level, the simulated travel-time for this path changes from 21 minutes for a minor crowdedness level to 44 minutes at extremely crowded times. Google Maps' travel time for that trip is within that interval. Those numbers make sense as the effect of increased crowdedness is known to decrease travel time in traffic theory.

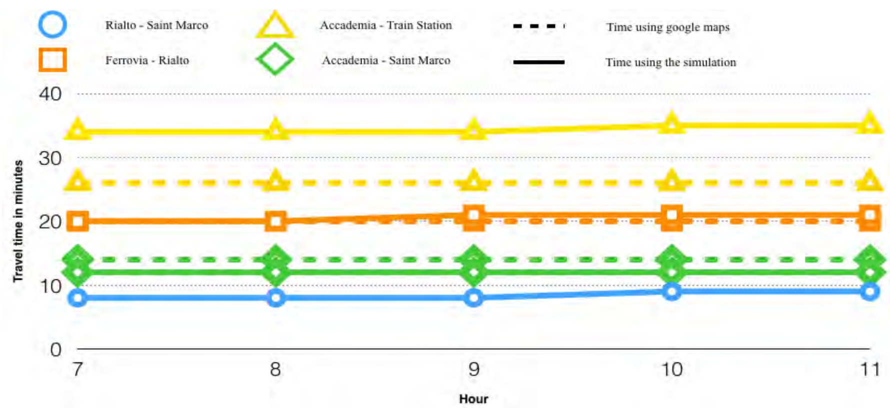


Figure 5: Simulation results (for a normal day) compared to a widely used time-traveler calculator in Venice.

## 5 CONCLUSION

In this paper, a hybrid approach for constructing simulations for smart cities was presented. The essence of this approach is the inclusion of expert knowledge and data, in the best possible way, in the development and execution of simulations. The authors argue that the use of simulations for urban environments requires such a hybrid approach in order to embrace the complexity of the problem, but also to cover for the often lacking or imprecise data available in cities. In particular, local expert knowledge on the exact dimensions of the problem can be combined with low dimensional model-based simulations to avoid suggestive over-precision and incomprehensive simulations.

The proposed hybrid approach was used to build a simulation of the pedestrian network of Venice that suffers from high number of tourists. As a result, the developed simulation combined a theory-based model with available data and expert knowledge. Due to the low dimensionality of the model, it was possible to incorporate the expert knowledge in a way that increased realism of travel-times in the pedestrian network. Moreover, the use of this hybrid approach resulted in a simulation environment that addresses exactly the required dimensions of the problem by the city's urban planners and policymakers. In fact, it does not do anything more than this, and therefore it is not claiming any more generic representation of reality than those dimensions included.

The simulation was validated through both a quantitative analysis and a face validation. The validation shows that the approach succeeded in providing plausible results as well as a space of exploration of options for decision-makers in the city of Venice. This proved that the hybrid approach is useful for constructing relevant simulations for smart cities; by addressing the right dimensions, choosing the right models, and using efficiently data and expert knowledge.

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## AUTHOR BIOGRAPHIES

**ELHABIB MOUSTAID** is a PhD student in Logistics and Informatics for Healthcare at KTH Royal Institute of Technology. He holds a M.Sc. in engineering degree in Computer Science and Communication from KTH, and a M.Sc. in engineering in Applied Mathematics and Informatics from Grenoble Institute of Technology. His research interests are systems engineering, statistics and the combination of mathematical models and social models in complex adaptive systems. His e-mail address is elhabib.moustaid@sth.kth.se.

**SEBASTIAAN MEIJER** is a full professor in Logistics and Informatics in Health Care at KTH Royal Institute of Technology and part-time associated with TU Delft. He leads the gaming and participatory simulation lab (GaPSlabs), focusing on games, simulations and visualizations for design of complex systems in society. Meijer is coordinator for several EU projects, chairman of ISAGA, and frequent reviewer for a series of journals and conferences, especially when gaming and simulation methods are involved. His email address is sebastiaan.meijer@sth.kth.se.