A Holistic, Interdisciplinary Decision Support System for Sustainable Smart City Design

Johannes M. Schleicher[1(✉)], Michael Vögler[1], Christian Inzinger[2], Sara Fritz[1], Manuel Ziegler[1], Thomas Kaufmann[1], Dominik Bothe[1], Julia Forster[1], and Schahram Dustdar[1]

[1] TU Wien, Wien, Austria
{johannes.schleicher,michael.vogler,sara.fritz,manuel.ziegler, thomas.kaufmann,dominik.bothe,julia.forster, schahram.dustdar}@tuwien.ac.at
[2] University of Zurich, Zurich, Switzerland
christian.inzinger@uzh.ch

Abstract. With the advent of the smart city paradigm, modern cities have become complex systems of systems with a host of increasingly entangled dependencies and interactions among systems as well as stakeholders from multiple different domains. Efficient design, engineering, and operation of such systems is challenging due to the large number of involved stakeholders and their requirements, which might be conflicting and will change over time. In this paper, we present results from our ongoing efforts towards engineering next-generation smart city applications to provide stakeholders with a holistic and tailored view on their problem domain to support them in managing relevant aspects of the city, and furthermore provide effective assistance for important decision processes. We introduce the URBEM Smart City Application (USCA), an interdisciplinary decision support system, and present different views on its use by involved experts from four central smart city domains in the context of a smart city research initiative in the city of Vienna.

Keywords: Smart cities · Data analytics · Smart city application engineering · Smart city applications

1 Introduction

Todays cities are evolving into complex behemoths consisting of a myriad of sophisticated entangled systems. The recent advent and rapid adoption of the smart city paradigm that enables vital new possibilities, also has significantly contributed to the intrinsic complexity [1] of such systems. Complex systems and models from multiple domains, such as e-government, traffic and transportation management, logistics, building management, smart health care, and smart grids, have become essential drivers for sustained innovation and improvement of citizen wellbeing. In order to enable sustainable, supply-secure, and future-proof planning that can keep up with today's rapid city growth and urbanization,

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it is vital to enable stakeholders to make well-informed decisions. To achieve this they rely on the expertise of domain experts who in turn use complex models for analyzing and simulating various aspects of a city ranging from building physics, energy and mobility systems, to sociological and behavior models.

The most vital part, however, is the ability to effectively integrate these models, allowing them to stimulate each other, which presents the enabling key for creating the foundation for sustainable and future-proof smart city design.

In this paper, we present results from our work in the context of the URBEM[1] smart city research initiative. URBEM is a joint initiative between Wiener Stadtwerke Holding AG (Vienna's biggest energy and mobility provider), TU Wien, and the City of Vienna. Its aim is to research and develop an interactive environment for analyzing scenarios for enabling "a sustainable, supply-secure, affordable, and livable city" in a holistic and interdisciplinary manner. We implement this by enabling a reactive Smart City Loop [2] that allows to integrate multiple domain expert models with each other and enrich them with accurate and timely smart city data in order to provide a solid basis for well-informed stakeholder decisions.

Additionally, we identify the following intrinsic requirements that need to be addressed to fully enable the crucial collaboration of stakeholders and domain experts in URBEM. First, we need the ability to integrate heterogenous, multidimensional data sources that are omnipresent when operating applications in smart city ecosystems. Second, since in smart cities and especially in URBEM, there are various stakeholders involved that enforce and must respect a plethora of different compliance and privacy regulations, we need mechanisms that allow for respecting these constraints, without impeding stakeholder interaction. Finally, to fully support domain experts in URBEM, we can not only provide them with pre-built services and applications, but must allow them to integrate and facilitate their own established and well-known heterogenous tool stacks.

Based on these identified requirements, we show how we achieve this vital integration by developing the URBEM Smart City Application (USCA) and outline how this has benefited involved domain experts and stakeholders.

The remainder of this paper is structured as follows.

In Sect. 2, we present USCA, a representative smart city application that emerged as a result of the URBEM research initiative, and discuss how it tackles the identified challenges. In Sect. 3, we outline how domain experts and stakeholders use and benefit from USCA, followed by a conclusion in Sect. 4.

2 The URBEM Smart City Application

In this section we present the URBEM Smart City Application (USCA). USCA allows for integrating models of multiple domain experts that operate in domains such as building physics, electrical and thermal energy, energy demand modeling, as well as mobility and sociological behavior modeling to provide an interactive,

[1] http://urbem.tuwien.ac.at/.

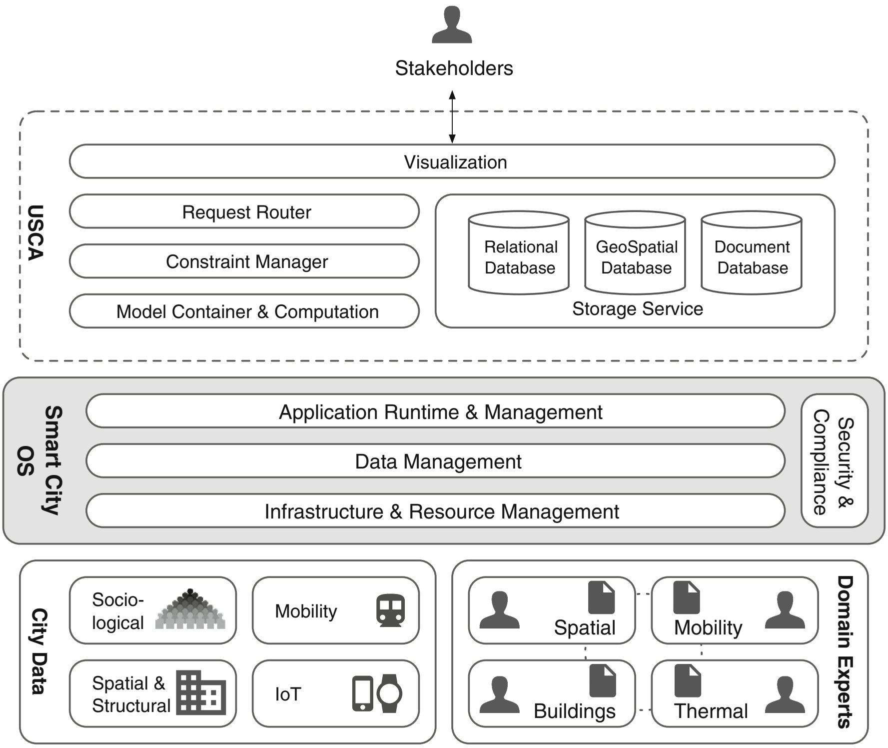


Fig. 1. URBEM cloud overview

explorable, and dynamic visualization for stakeholders. It is an application within the Smart City Application Ecosystem (SCALE), as introduced in [3]. Figure 1 shows an overview of USCA in the context of SCALE.

In USCA, stakeholders interact with a dynamic, web-based, geo-spatial *Visualization* that allows them to freely explore the city as well as different evolving aspects in the context of multiple scenarios with predictions up to the year 2050. Stakeholders can not only explore the city as a whole, but also inspect it in varying levels of detail, from districts, over blocks, down to individual buildings. They can enrich their view with the results of domain expert models by dynamically adding and removing additional layers. This enables them to get a detailed look at various aspects of the city in a dynamic and integrated fashion. Figure 2 shows an example where specific natural gas uplinks for several building blocks in Vienna are explored.

Each of these model interactions spawns specific requests, which are handled by the *Request Router*. The Request Router acts as a smart request proxy and is responsible for elastically scaling up and down the necessary infrastructure resources based on the request patterns of USCA. To achieve this it utilizes the capabilities provided by the *Infrastructure & Resource Management Layer* of the

Fig. 2. Visualization of gas heating uplinks for building blocks in Vienna.

Smart City Operating System (SCOS) and the SYBL [4] language. This allows USCA to maintain a small footprint as it can ensure that resources are only consumed when needed. Additionally, the *Infrastructure & Resource Management Layer* enables infrastructure-agnostic deployments [5] so that USCA can be executed on a variety of different platforms, which is an important factor in the heterogeneous infrastructure landscape of current smart cities. It is further able to manage and operate edge infrastructure resources using LEONORE [6] and DIANE [7]. The Request Router then passes each request to the *Constraint Manager*, which in turn is responsible for ensuring that USCA meets the aforementioned complex compliance and privacy regulations. The Constraint Manager inspects each request to check which data sources and domain experts' models are needed to fulfill the requests. Based on this information it ensures that no privacy or compliance constraints are violated and forwards the specific requests to the *Model Container & Computation* component. If constraints are violated, the Constraint Manager can in turn utilize SCOS's *Security & Compliance Layer* to offer ad hoc compensations using capability migrations provided by Nomads [8]. The Model Container & Computation component ensures that the domain experts' models are correctly executed and are supplied with all necessary data. Along with the *Storage Service*, these components represent the core elements of USCA and are key to enabling a holistic, integrated city view. The Model Container & Computation component provides means for provisioning and executing containers. We currently support two popular container formats, Docker[2] and Rkt[3]. This allows domain experts to continue using their well-known and established tool stacks without sacrificing the ability to integrate them into USCA. The containers are packaged to include

[2] https://www.docker.com.
[3] https://github.com/coreos/rkt.

all necessary runtime artifacts. Additionally, they can be checked and verified to ensure that compliance and privacy constraints are not violated. This vital feature is enabled via the *Application Runtime & Management Layer* of SCOS. To give models access to required data, data containers are transparently integrated by injecting necessary container links. This mechanism enables a minimally invasive approach that allows domain experts to integrate provided capabilities into their own tools. Domain experts then simply access data in the data container via the established link and store the results of their models in the same container. In the background the *Storage Service* is used to provide necessary data via these links, as well as to store the model results in the appropriate data store. Additionally, the Constraint Manager can check at all times if data in transit can be consumed by the respective domain expert, which ensures that all compliance and privacy constraints are also met on the data level. The final element in empowering the Storage Service is the ability to utilize the *Data Management Layer* of SCOS. It enables the Storage Service to access a wide range of city data in various formats ranging from traditional relational data and documents, to live streaming data from the Internet of Things. All this data in turn can be incorporated into domain models as well as directly into the visualization.

3 Domain Expert Perspectives

In this section, we discuss the use of USCA by experts and their models from four different smart city domains. We briefly outline the specifics of each model, how it utilizes and benefits from USCA, and conclude with the observed benefits from the stakeholder's perspective.

3.1 Building Models

One of the key elements in urban city planning is to develop a proper method that allows simulating the effects of different urban development strategies (e.g., for 2020, 2030, and 2050) focusing on all buildings within a district or even an entire city. Therefore, different urban development scenarios are used as initial parameters to run building simulations for the focused building stock. Individual indicators (e.g., heating demand or refurbishment rates) are usually insufficient to run commercial building simulation tools. In order to maintain good performance and a time-efficient calculation period to simulate an entire urban environment, the simulation efforts for single buildings must be as low as possible. This model generates scalable density functions for both, residential and non-residential buildings by considering particular construction periods, different HVAC[4] technologies as well as individual occupancies in the course of a social milieu-based approach. The result is a comprehensive matrix of simulated density functions consisting of all possible combinations of the parameters mentioned above. The ability to expose this model within USCA allows the electrical

[4] Heating, ventilating, and air conditioning.

and thermal grid models to utilize generated results that enable them to use hourly load profiles, which in turn are required for the technical simulations. In order to generate high-resolution load profiles (both temporal and geographic) for each building, only the input of the urban development scenarios generated within the energy demand model and the number of buildings is needed. This significantly increases the possible level of detail for planning decision support in this domain.

3.2 Energy Demand Models

The model concerning the perspectives of building energy demand and supply mainly handles the long-term development of heating and cooling demands. Additionally, it is concerned with the demand for domestic hot water (DHW) in buildings and the interactions with grid-bound heating supply, specifically focusing on gas and district heating. Since the building stock causes a large part of the energy demand of modern cities and the realization of the European energy targets[5] require a decrease in this demand, a reduction of fossil fuels (e.g., gas and oil), as well as the integration of renewable energy sources. This can be achieved by thermal refurbishments of buildings, by changing the heating systems, and by using a different energy carrier. The used model simulates the long-term investments in the building sector and optimizes the investments in the expansion of the district heating and/or gas infrastructure. This model not only considers the current legislative and policies, but also assumptions for the future development of them [9]. The emerging results are spatially resolved. As this analysis is from an economic point of view, the integrated approach within USCA allows enriching the model with more technical details. Based on a thermal grid analysis of the status quo for the base year, information about the spatial heat losses or remaining capacities without expansion can be pointed out and are used as input for the economic model. Subsequently, the long-term results regarding heating and cooling demand, and the expansion of the district heating network for several years within the considered horizon, are the basis for thermal grid analysis. The results of the analysis allow finding appropriate measures regarding the grid to react to these changes.

3.3 Electrical Grid Models

The model of electric supply networks can predict reliability, overloads, and network utilization considering the limits of operational equipment used inside the network. In addition, the model is capable of making statements about which requirements will arise for future power grids through increasing integration of decentralized energy resources, decentralized storage, and energy combined supply networks (energy hubs), while considering demographic change. Modeling and simulating an electric supply network for urban areas requires an approach that

[5] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:178:0107:0108:EN:PDF.

allows for incorporating large amounts of network data. Therefore, power flow studies [10] for distribution areas fed by substations are performed. Transmission areas inside an urban area are neglected. Furthermore, energy and infrastructure (heat, gas, and electrical) combined systems are simulated by direct current power flow calculations within an optimization using an energy hub approach [11]. Possible objective functions of the optimization are the minimization of CO_2 emissions, or the minimization of line utilization, with the explicit constraint that network capacities (electricity, gas and district heating) should not be overloaded. Results from the energy demand and building models inside USCA form the framework conditions and input parameters for the electric supply network model. Based on a technical analysis for a base year, scenarios with increasing integration of renewables and cooling demand that are mainly covered by electric energy reveal the limits of currently used network equipment (lines, transformers, etc.). The obtained results affect future investment decisions in network utilities to address changing requirements within the electric supply networks.

3.4 Thermal Grid Models

Current developments of the European energy market are influencing the operational strategy of heat suppliers. Especially providers of district heating systems fed by conventional heat production have to react with appropriate measures to these changes. The integration of thermal storages, decentralization of heat production, changing heating technologies or adjusting the temperature of district heating networks make it necessary to simulate and analyze existing and future designs of district heating systems. In order to achieve comparable conclusions about operating behavior of district heating systems, it is essential to create a corresponding model including main components like pipes, pumps, storages, and valves. The basic idea of the created numerical model is the combination of a steady state hydraulic and a transient thermal calculation of the district heating network. The results of the iterative hydraulic calculation are the pressure and velocity distribution of the pipe network [12]. These results serve as input parameter for the thermal calculation. To simulate the thermal behavior of the district heating network a discretized one-dimensional pipe model is used. The discretization is done using the finite-volume method and the resulting equation system can be solved explicitly or implicitly. A common way to define the topology of networks is the usage of a node-edge matrix. This so-called incidence matrix is generated automatically from given GIS data. The usage of the simulation model within USCA increases the capability in terms of interactions with more detailed data provided by other models that are integrated in USCA. The output of the model can be used to support economic analysis from a technical point of view or serve as additional input for analysis of energy combined systems. The possibility to link models of different disciplines extends the scope of the overall application.

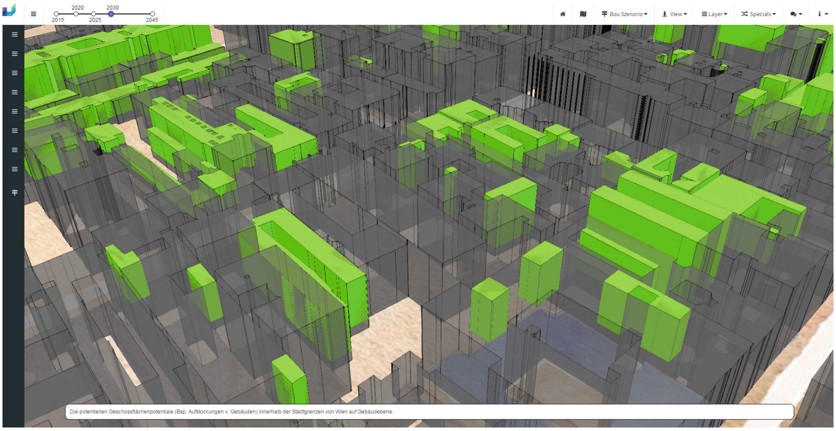


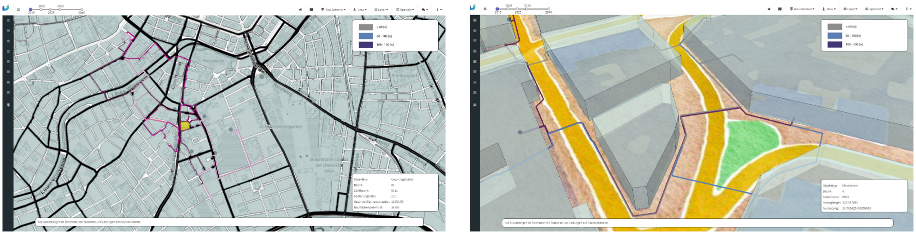
Fig. 3. Floor-space potentials for individual buildings up to the year 2030.

3.5 Spatial Modeling and Visualization

The visualization aspect represents a vital instrument to communicate the results of, as well as to interact with, the models of the domain experts via a simple and intuitive interface. The ability to spatially resolve the results of the models and to evolve them over time is an essential factor in understanding the impacts of complex systems on the city. USCA allows to seamlessly incorporate and combine city data with the results of domain expert models, which enable novel ways for illustrating vital elements for city design. In Fig. 3 we see a spacial placement of forecasted floor-space potentials for individual buildings in the year 2030. Through USCA it is possible to incorporate various city data sources to get an accurate picture of specific development potentials, which is an important factor for spatial modeling.

The development of smart cities requires the integration of multiple stakeholders from different fields. Therefore, USCA provides an easy to manage tool for displaying all relevant information, whereas the visualization enables all involved entities to get an overview about the complexity of the system and to gain an understanding about the main influences and challenges within other disciplines. The consequences of decisions (e.g., investment decisions, legislation, definition of subsidies) within other fields and additional required measures can be highlighted using the visualization. A representative example that illustrates these integration benefits can be seen in Figs. 4 and 5. Figure 4 illustrates detailed district heating demands of all blocks within Vienna's 11th district. The foundation for this is the energy demand model in combination with city data enriched by the building models, which in turn provides detailed load profiles. These high-resolution load profiles are then used by the electrical and thermal grid models to deliver specific grid impacts, which can be visualized at varying spatial detail levels via simply zooming in or out in the Visualization (Fig. 5).

Fig. 4. Energy demand visualization for the 11th district of Vienna



(a) Energy Grid High Level Overview for a district

(b) Detailed Energy Grid for a specific set of buildings

Fig. 5. Energy grid visualizations

4 Conclusion

The smart city paradigm led to a transformation of today's cities to complex systems of systems with a plethora of increasingly complex dependencies and interactions. A large number of stakeholders from multiple different domains pose complex requirements on these systems that might be conflicting and will change over time. Efficient design, engineering, and operation of such systems is increasingly challenging but represents an essential ingredient in supporting stakeholders to make well-informed decisions.

In this paper, we presented results from our ongoing efforts towards engineering and operating next-generation smart city applications that aim to provide stakeholders with a holistic as well as customized view on their problem domain. Such smart city applications must be designed to support stakeholders from different domains in managing and affecting relevant aspects of the city and provide effective assistance for important decision processes. To address these challenges, we introduced USCA, an interdisciplinary decision support system for holistic city planning and management. USCA is a cloud-based application built upon our recent work on smart city application ecosystems that uses a smart city operating system as its foundation. The application provides a holistic, integrated view on multiple complex domains based on models provided by different domain experts to support complex decision processes, while rigorously respecting relevant confidentiality and security constraints. We furthermore reported on the use of USCA by stakeholders from four central smart city domains in the context of a smart city research initiative in the city of Vienna.

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