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Exploring multi-modelling approaches in Hamburg, Germany's evolving digital urban twin infrastructure

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Abstract

Digital urban twin technology is currently being developed, prototyped and tested to address multiple challenges related to sustainable urban development. Crossing specialist sectors and departments, such technology aims to integrate, orchestrate and govern multiple models across domains and paradigms. However, currently available solutions are largely confined to singular, tailor-made and proprietary solutions that structurally limit the development and connection of various multi-paradigm and multi-scale models. In this paper, we present our work-in-progress on the use of multi-modelling approaches within Hamburg's evolving modular digital urban twin infrastructure. Based on participatory multi-stakeholder workshops, we address the multi-domain issue of energetic renovation and its potential gentrification effects by creating a city-scale system dynamics and a neighborhood-scale agent-based model. Connecting them via an urban model platform, preliminary findings show that such a system-of-systems approach combined with a multi-stakeholder model development seems promising for the future of multi-modelling in the context of digital urban twins.

Keywords: Digital Urban Twin, Urban Model Platform, Multi-Modelling, Energetic Renovation, Gentrification

1. Introduction

Cities are complex adaptive systems that face numerous challenges related to sustainability, resilience, and social equity. The ongoing urbanization process and its associated consequences, such as increasing energy consumption, carbon emissions, rent price development and its resulting housing crises, have made it crucial to develop solutions to address these challenges.

Digital urban twins in that regard promise to support decisions by enabling and providing "what-if scenarios" of various solutions based on multifaceted computational models. While being ambiguous in their concrete definition, the concept of digital urban twins entails a city's digital resources (i.e. urban data, visualization and analysis algorithms, simulation models) and the surrounding governance aspects. Different instances of digital twins for specific use cases can be assembled from a modular infrastructure (Schubbe et al., 2023).

From a technological perspective, there are few approaches that showcase a combination of cross-sectoral and multi-paradigm models within a digital urban twin infrastructure. For instance, scholars and practitioners propose a "T-Cell architecture" that orchestrates multiple simulation models and brokers the information flow in between (Raes et al., 2022). Others develop custom individual connections between models based on open-source visualization systems (Dembski et al., 2019). Private companies entering the growing market typically sell their own proprietary suite of software with multiple domain-specific models. Although such approaches are highly useful for their intended use cases and showcase the potential of connected models and simulations in an urban context, they are usually associated with one of two strategic disadvantages. Either adding new simulation models require a custom integration leading to resource-intensive and tailor-made solutions. Or there is a proprietary wrapper around a non-extendable set of models. At the same time, incorporating truly multi-paradigm, multi-scale and multi-model approaches into digital urban twin infrastructure is of particular importance because the complex adaptive nature of the urban calls for them (Batty, 2021).

A possible solution to the combination of multiple models is a "system of systems" approach as outlined in the context of open urban platforms in DIN SPEC 91357. A core principle of such a reference architecture for urban data platforms is to not fundamentally change the various data management systems in different domains, but to create a platform that connects different data silos using open standards. In a similar fashion, an urban model platform based on open and interoperable standards could act as a universal and standardized interface between models of various methods, paradigms and scales.

From a model development perspective, scholars increasingly advocate for dynamic multi-stakeholder modelling approaches to represent multiple perspectives in a socio-technical model (van Bruggen et al., 2019; Tolk et al., 2022). In the context of digital urban twins, catchphrases like "no model without the modeled" (Tolk et al., 2022) and calls for increasing co-* principles (Nochta et al., 2021; Arcaute et al., 2021), currently meet little empirical case studies and best practices.

In this context, this paper presents ongoing work on the use of multi-modelling approaches within Hamburg's evolving modular digital urban twin infrastructure. By conducting participatory multi-stakeholder workshops with representatives from public administration, civil society, and the private sector, we (1) collaboratively select a specific case study within the larger umbrella topic of climate protection and social equity, (2) discuss the various scales that simulation models should represent and questions it should address, (3) develop a system dynamics model of Hamburg on a city scale that covers the aspects and their relations identified by the stakeholders, (4) create an agent-based model on a neighborhood scale to examine local actors, resources and their interactions more closely, (5) integrate both models on an urban model platform architecture, (6) simulate various scenarios with policy levers selected by the participating stakeholders and (7) evaluate the simulation results and the participatory modelling process collectively. With a clear focus on the multi-stakeholder modelling process and the technological multi-model implementation, we select two main objectives for our research:

1. Exploring requirements and challenges of multi-stakeholder modelling processes with the help of digital modelling and simulation tools
2. Investigating in the technological feasibility of a "system of systems" urban model platform approach capable of providing, executing and integrating multi-paradigm models by combining multi-scale agent-based and system dynamic models

The following paper is structured as following: In the material and methods section, we provide detailed information about the process and tools deployed. In the results section, we describe the resulting models and their integration an urban model platform architecture. This is, at the current point in time, partially work-in-progress. In the discussion section, we reflect upon our research goals and formulate preliminary conclusions.

2. Material and Methods

Given its size, growing population, and status as a frontrunner in Germany's digitalization efforts, we select the city of Hamburg as a real-world laboratory in which we intervene by designing real-world experiments (Bergmann et al., 2021). Real world experiments can be defined as "experiments with participatory control over the intervention" where researchers and their transdisciplinary partners - in our case the stakeholders involved in the multi-modelling process - shape the direction and outcome of the experiment together (Caniglia et al., 2017). In the federal republic, Hamburg is one of three city-states and Germany's second largest city in terms of population. Its pledge to become carbon-neutral until 2045 shows its ambition to actively engage in more climate protection activities than national or EU regulations would require. Due to Hamburg's large working class population employed in the omnipresent port and its downstream industries, the social democratic party is governing the city-state since 1945 with the exemption of only around 15 years of conservative leadership. This emphasis on social equity issues ultimately adds weight to the question on how to design climate protection in Hamburg in a socially equitable way. At the same time, Hamburg's existent digital infrastructure and ongoing digitalization projects in the digital urban twin domain provide beneficial conditions for our research.

To guide the multi-modelling process we modify the ten step modelling process as described by Dam et al. (2013) with co-design and participatory modelling methodologies that aim to integrate multiple perspectives (van Bruggen et al., 2019; Etienne et al., 2011). Following the calls of Nochta et al. (2021) and Arcaute et al. (2021) to incorporate co-* principles capable of capturing urban complexity into digital urban twin development, we aimed for a high intensity of each of the three dimensions of participation as measured in the participation cube (Thoneick, 2021). As displayed in Figure 1, we methodologically combine a multi-stakeholder engagement strand with a technological implementation strand.

2.1. Multi-stakeholder engagement strand

To iteratively arrive at an issue of collective relevance, we designed an co-creative process where most decisions are moderated by us, but made by the collaborating stakeholders. We started in the summer of 2022 by developing "wicked questions" in the context of our case study of climate protection and social equity at Hamburg's "Schülerklimakongress" (pupil's climate congress). During autumn and winter, we interviewed a total of ten stakeholders from

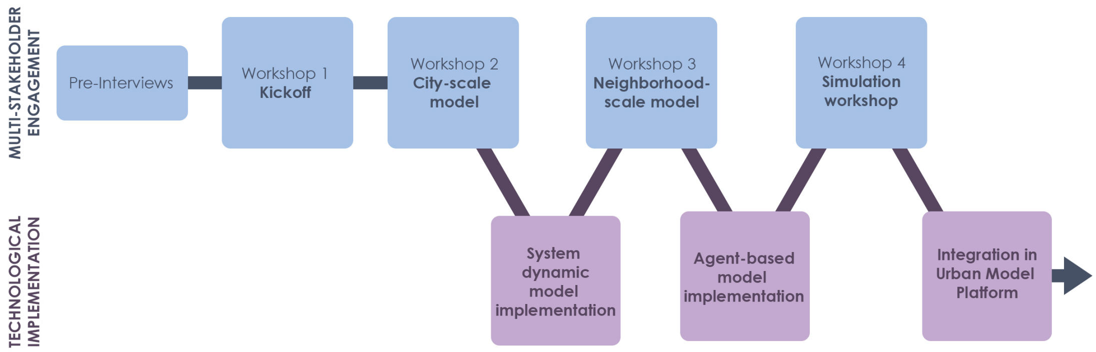

Figure 1. The interplay of the multi-stakeholder engagement strand and the technological implementation strand results in two simulation models of different scales and paradigms and structures the real-world experiment

public administration, civil society and NGOs to gather further background information and form a network in the specific field. As a result, we identified the two main topics of (1) energetic renovation and gentrification effects and (2) zero land sealing and social housing construction. With these inputs, we invited multiple stakeholders from Hamburg's public administration, civil society and private corporations to a kick-off workshop. Its goal was threefold: Firstly, we aimed to introduce and explain our undertaking and thereby convince the stakeholders to participate in the experimental research project. Secondly, we intended to collectively arrive at central questions to each of the two main topics identified beforehand. Thirdly, we wanted to gather preferences regarding the future process in terms of one of the two main topics and their modelling scales, possible dates and time slots. Based on the majority preferences of the kick-off workshop, we chose the topic of "energetic renovation and gentrification effects" and the collective question on possibilities to decouple both processes. Participants spoke out for a focus on the neighborhood scale with links to a city-scale development. Based on these outcomes, we scheduled three further workshops: the first one dedicated to formalize a broad city-scale system dynamics model and to selecting a fitting neighborhood within Hamburg, the second one to formalize an agent-based model of the selected neighborhood, and the third one to experiment with the models, simulate various scenarios of interest and evaluate the modelling process. Within the modelling workshops, we leveraged the web-based modelling tool "Insight Maker" which allows for the conceptual development and simulation of system dynamics and agent-based models (Fortmann-Roe, 2014). The collective discussion took place in a structured way in front of large touch tables with a clear distinction of the different roles involved. While the invited stakeholders provided their perspectives and model content, we facilitated the process and provided general modelling guidance.

Referring to the modelling process outlined by (Dam et al., 2013), the multi-stakeholder engagement strand largely covers the steps of problem formulation and actor identification, system identification and decomposition, concept formalization, model formalization, experimentation and model use.

2.2. Technological implementation strand

The technological implementation of the formalized models took place between the multi-stakeholder modelling workshops. Wherever possible, we translated the information collected in the modelling workshops into fully operationalized model structures. For the system dynamics model, we leveraged the web-based simulation capabilities of Insight Maker (Fortmann-Roe, 2014). For the agent-based model, we used the common ABM simulation software NetLogo (Tisue and Wilensky, 2004), as it also provides the possibility for web-based simulation.

For the integration of both models, we developed an urban model platform architecture capable of integrating models of multiple paradigms and methodologies. Building on the Open Geospatial Consortium's (OGC) API Processes standard, we deploy both models on a modified instance of the pygeoapi Python server implementation. The OGC API Processes describes a standardized way of packaging "computational tasks into executable processes that can be offered by a server through a Web API" (Open Geospatial Consortium, 2021). The standard builds upon the JavaScript Object Notation (JSON) format and the Representational State Transfer (REST) protocol and thus integrates well with many existent software libraries and tools. Its core describes seven endpoints that are to be implemented: A landing page (1) that conforms to the Open API scheme and links to the server's conformance classes (2), as well as to a list of all available processes (3). Via a specific processID, a process description can be accessed (4) and the process can be executed either synchronously or asynchronously (5). For each asynchronous process execution (i.e. a process that takes longer than the average HTTP request timeout) a job will be created. Its status can be obtained from the job status info (6) and - once computed - its results from the job results endpoint (7). Within each of these endpoints, there are further requirements on how to provide e.g. detailed metadata about the required inputs, outputs and job status (Open Geospatial Consortium, 2021). Each of the processes deployed is separately accessible and executable via the specified API endpoints. At the same time, due to the standardized interface to the different processes, the models are capable of communicating not only with a client, but also with one another. In that way, the output from one model can serve as the input of another. Thus, the API Processes can serve as an open system-of-systems standardized interface that is structurally capable of connecting models without the need for custom and tailor-made connectors.

Referring to the modelling process outlined by (Dam et al., 2013), the technological implementation strand largely covers the software implementation and model verification steps.

3. Results

To focus both on procedural and technological aspects of the real-world experiment, we describe the results of each workshop consecutively. Since the present research is still work-in-progress, there is no fully functional integration of both models into an urban model platform yet.

3.1. Kickoff and problem formulation

In the first workshop, a total of eight participants from Hamburg's ministry of urban planning and housing, the municipal urban development company, two tenant protection organizations, two district initiatives, and a private urban planning bureau met in an online environment. There were two hours of in-depth discussions around key aspects, central questions and useful scales for modelling two pre-selected topics of (1) energetic renovation and gentrification effects and (2) zero land sealing and social housing construction. Discussing their preferences, a clear majority of stakeholders indicated that they would want to continue working on the issue of energetic renovation and gentrification. They identified the following key questions:

- How can the current relationship between energetic building renovation and gentrification effects be decoupled as far as possible?
- What effects can be expected from energetic renovation measures on different social groups and milieus in the city?
- Who should pay for which renovation measures on which buildings?

In order to model this issue, the district level was deemed to be the most suitable scale, if decision-making structures on a city scale as well as building-specific information are also included. Furthermore, areas with a social preservation ordinance should be considered separately, since special framework conditions for energy-related renovations apply here.

3.2. The city-scale model

In the second workshop, a total of three participants from Hamburg's ministry of urban planning and housing and a tenant protection organization took part in an in-person half-day workshop setting. Three additional stakeholders expressed their interest, but could not participate due to sickness or scheduling conflicts. As displayed in Figure 2, a high-level systems diagram was developed with the stakeholders. Central aspects of the model are "housing costs" and "energy-efficient renovation measures". Via the factor "modernization rent increase according to current legislation", housing costs increase with energetic modernization. Via lower energy consumption due to the modernization measures, housing costs and the city's CO_2 emissions decrease. A tenant's possible decision to relocate, i.e. economic gentrification, happens through a reduction in available income and an increase in housing costs. At the same time, inflation, interest rate levels and legal requirements for climate protection set the framework for many key aspects of the model.

For the model's operationalization, participants referred to multiple data sources such as various rent indices, operating cost surveys or detailed building stock data. Largely building on these and adding as much details as necessary, we then transferred the main model structure into an operational system dynamics model after the workshop. This model contains seven sub-models:

1. **Population and living**. Based on the city's official population predictions and the average living space per resident, the total living space and the number of buildings with residential use are simulated.
2. **Measures of energetic modernization**. This sub-model simulates the public and private invest in energetic modernization of the building envelope and in renewable heat supply. Based on the investments, the required energy for heating and carbon emissions will reduce.
3. **Building heat supply**. Fossil, renewable and district heating of the building stock is modeled based on the measures of energetic modernization and the population and living sub-model.
4. **Energy and climate**. Energy demand, cost and related emissions are calculated based on the building heat supply and the measures of energetic modernization sub-model.
5. **Increase of rent due to modernization**. Based on the investments in energetic modernization, the rent increase decisions of property owners are modelled.
6. **Cost of living**. This sub-model simulates the development of average living costs with its three main components net cold rent, non-heating-related operating costs and heating costs. Both the increase in net cold rent due

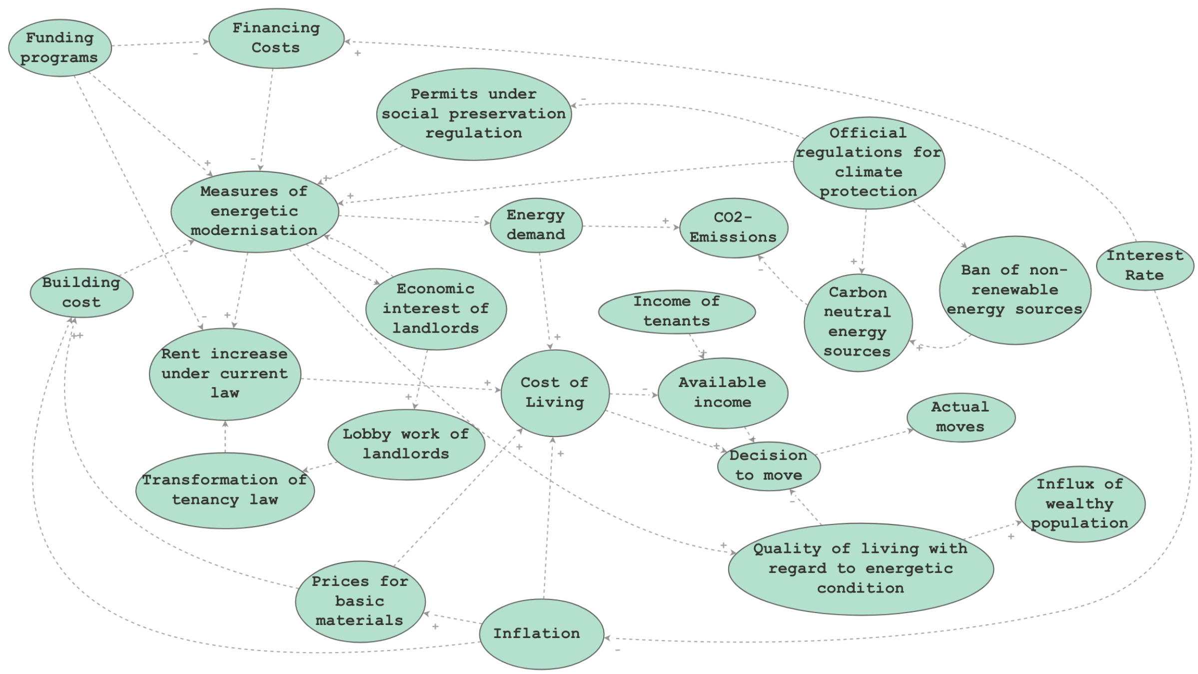

Figure 2. A high-level causal loop diagram was developed in the second workshop (translation by the authors)

to energetic modernization, as well as the reduction of heating costs influence the total average cost of living.

7. **Economic gentrification**. This sub-model simulates the number of people that are being gentrified due to an increased cost of living and their disposable income.

For the further process, potential districts were jointly selected with the stakeholders on the basis of current development areas, areas in the social preservation ordinance and census housing data. In this context, stakeholders considered the following points important:

- The predominance of rented apartments
- Mixed owner structure
- Necessity for energetic renovation with available income below the city's average

The districts discussed in this context were Steilshoop, the Generalsviertel, Wilhelmsburg, Veddel and Rothenburgsort. Due to the upcoming urban development in the Elbbrücken neighborhood, the resulting increasing gentrification pressure and the potential for further stigmatization of the neighborhoods of Wilhelmsburg, Veddel and Steilshoop, the researchers decided on district of Rothenburgsort.

3.3. The district-scale model

In the third workshop, a total of six participants from Hamburg's ministry of urban planning and housing, two tenant protection organizations, Hamburg's property owner organization and residents of Rothenburgsort took part in an in-person full-day workshop setting. Following the methodology outlined in Etienne et al. (2011), we collectively mapped, clustered and ranked actors, resources and processes that are present in Rothenburgsort. As a last step, the interactions and touching points between the actors, resources and processes were mapped in a single interaction diagram.

Three major clusters of directly involved actors can be formed: Firstly, building owners are comprised of landlords, individual property owners, cooperatives, hedge funds, the SAGA and homeowners' associations. Secondly, there are residents who may or may not be tenants. Thirdly, tradespeople consist of economic actors from the retail trade, industry, gastronomy and hotel businesses, of which there are many in Rothenburgsort. Indirectly affecting the issue of energetic modernization and economic gentrification are consultancy services (of a social nature and those specific to energetic refurbishment), district institutions, public authorities, housing seekers and political institutions/committees. The district council acts as an information platform for the exchange of information between all actors. Locally specific are temporarily housed refugees and art and cultural institutions such as Mikropol.

In a second step, resources to which the actors have access were collected, collated and clustered. They were then prioritized by the participants by assigning points. Accordingly, a higher score next to a resource represents a higher level of importance in relation to the question about the connections between energy modernization and economic gentrification. Major clusters are:

- **Money**: This includes access to credit, available subsi-

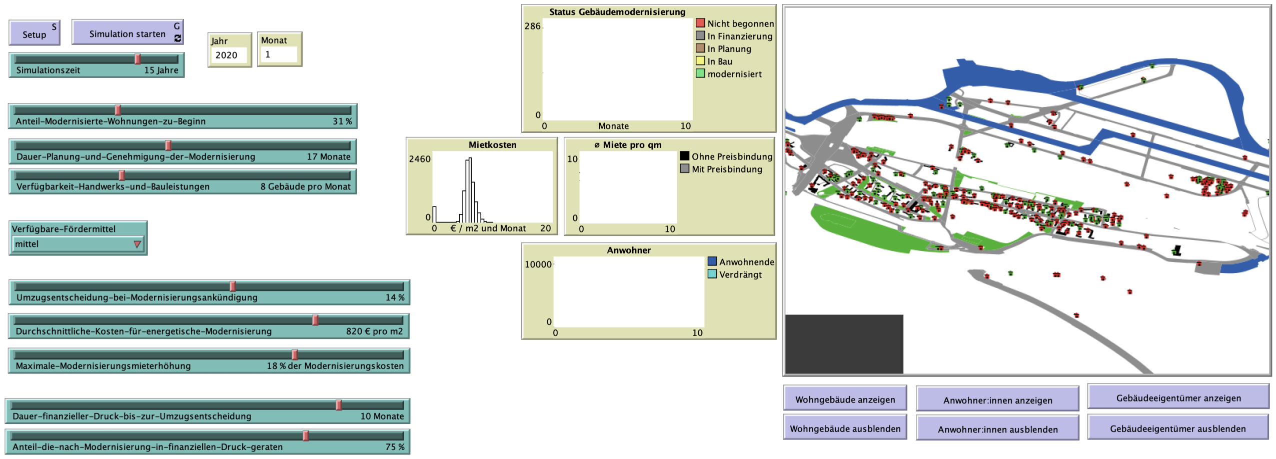

Figure 3. The user interface of the NetLogo model containing parameters for the percentage of renovated buildings at the beginning of the simulation, the average duration of planning and permitting a modernization, the availability of craftsmen resources, the available subsidies, the percentage of people leaving when a modernization is announced, the average costs of a energetic modernization, the maximum amount of modernization rent increase, the duration for how long residents will withstand financial pressure before moving away and the percentage of residents that get into financial pressure after a rent increase.

dies, rental income, tenants' disposable income, and equity. Willingness to invest is also closely related to the cluster.

- **Land**: Here, housing in particular should be mentioned as an important resource.
- **Knowledge**: In addition to knowledge about energy-efficient refurbishment and about subsidy programs, knowledge of tenancy law was identified as a key resource in this cluster.

Other resources identified as important are consulting services and craft and construction services. There was considerable discussion about how to operationalize the resources. Questions raised include: How do you measure existing knowledge? How does one map a social network in the model? Wherever a classification into scales did not seem possible, the participants agreed on a classification into the levels "low" - "medium" - "high".

Processes taking place in the neighborhood as part of energetic modernization and economic gentrification were also first collected and then scored by the participants according to importance. The following two processes were discussed in more detail:

- **Displacement**: Here, either a rent increase or compulsory modernization is at the beginning of the process. Some of the residents then come under financial pressure, which could lead to a decision to move away. This is influenced by the search for housing and finally leads to renting or buying a new property. The final step in the process is to move away.
- **Rent increase**: The modernization decision of the owners is the starting point for the process of rent increase. This is followed by the financing and planning of the (energetic) modernization. As soon as the measure is approved, construction measures and rent increase are announced, if necessary. The construction work is then carried out, the rent increase is calculated on the basis of the actual costs incurred, and finally the tenants receive the rent increase declaration.

Finally, participants connected actors with the resources and processes and identified and described actors-actor and actor-resource relations. For the model's operationalization, we implemented the high-level actors, as well as the prioritized resources and processes into a NetLogo model of the district Rothenburgsort. Gathering data from Hamburg's Urban Data Platform, as well as from the last official census data, we modeled 8945 residents of the district connected to a building that is either modernized or not. In the connection between resident and building we model the relationship (rented or not), the rent price, if the building contains social housing apartments with controlled rent prices, and the number of rent increases. Each building is connected to one owner and has a specific status of modernization that resembles the modernization steps discussed in the rent increase process. Figure 3 shows the resulting model interface with the different parameters and output plots.

3.4. Simulation and evaluation workshop

In the forth workshop, a total of five participants from Hamburg's ministry of urban planning and housing and two tenant protection organizations took part in a half-day workshop. After we presented the operationalized simulation models and their specific user interfaces, we invited the participants to openly play with the model and discuss potential scenarios. After two rounds of scenario building, participants engaged in a reflection round of the whole process and collaboratively discussed future steps.

Before starting to build various scenarios with the city-scale model, participants engaged in a multi-layered discussion about the model's content, its validity, potential use-cases and their implications, as well as the model development process. For the model content and its validity, multiple participants mentioned that although there are already many factors present, specific details such as residential buildings within the social preservation ordinance or the differentiation between general inflation and inflation of rent prices are important, but not yet resembled in the model. One indicator of the model, the absolute CO2-emissions of the city from heating energy, was deemed to be impractical and was therefore changed to per-capita and per-square meter emissions during the workshop. For potential use cases, participants brought up applications in their domains, such as simulating potential effects of various measures. For the implications of the model usage, participants highlighted its capability to rationalize the emotional discussion around energetic modernization and potential gentrification effects. At the same time, one participant raised concerns that the model could contain "fatal mistakes" that could lead to a "political blow-up" if not managed correctly. For the model development process, participants agreed that they would not have expected such a sophisticated result based on their input and that they were "very impressed". During the scenario building, participants noticed the complexity of various parameters and their interplay. Aiming to handle such complexity, some asked for a functionality where they could ask the computer to come up with solutions that would fulfill their key performance indicators. Some proposed to exclude the parameters on which they had no influence. Others suggested to find consensus on realistic parameter values and take these as a baseline scenario. Eventually, it was not possible to collectively arrive at suitable scenarios for the city-scale model in the short amount of time available. There however was consensus that the model provides a convincing starting point, and - given certain modifications discussed before - could be used for testing various measures effectively. Turning towards the city-scale model, participants had much less questions about the logic behind the different types of agents and resources in Rothenburgsort. While discussing the different levers and uncertainties, some participants remarked that they had access to very specific and closed data that could help remedy some of the uncertainties. Adding to such starting points, the benefits of having something tangible for future policy testing were mentioned.

During the reflection round, all participants mentioned that they were "impressed" with the model results and see them as a great baseline to build upon. When specifically asked about the modelling process, they highlighted its educative aspects. At the beginning of the experiment, participants repeatedly mentioned that they are very interested in, but could not envision a final simulation model based on their inputs. After the simulation workshop, there was general agreement that such a process could stimulate new ideas and possibilities, and that there are many benefits in

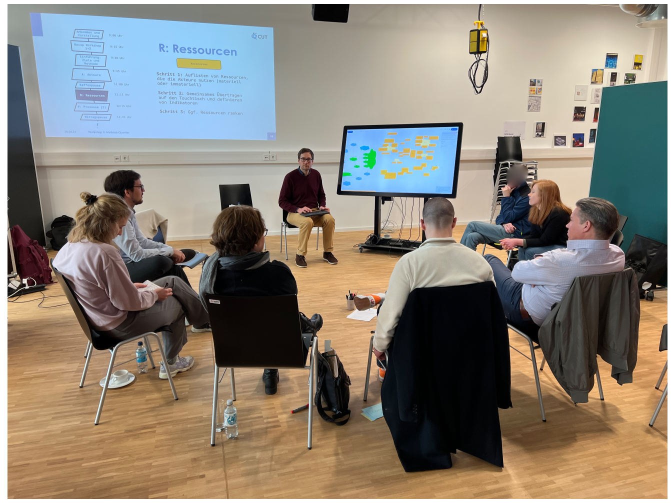

Figure 4. Touch tables running the insight maker tool served as the main model building and facilitation tool during the multi-stakeholder modelling process

having something to build upon and to develop further. At the same time, concerns were raised regarding the communication of the results to a broader public, since they could impact the political landscape for the worse when used by non-responsible persons.

4. Discussion and Conclusion

By exploring multi-modelling approaches within Hamburg's evolving modular digital urban twin infrastructure, in this paper we present a multi-stakeholder process as one way of developing multiple models. We combine this process with a technological solution to integrate the resulting multi-scale and multi-paradigm models in a digital urban twin context.

Exploring requirements and challenges of multi-stakeholder modelling processes with the help of digital modelling and simulation tools, our results indicate several procedural and technological aspects. On a process level, we find that managing the multi-stakeholder engagement strand is a resource-intensive task that requires substantial organization, moderation and public relation skills for the persons leading the modelling process. Participants require sufficient time and openness to engage in an open-ended process. Aiming for a balanced set of perspectives, it is especially difficult to find formats that allow for the participation and encounter of both institutional stakeholders and volunteers who follow other daytime jobs. It is equally important to manage a changing composition of stakeholder groups in between workshops. In our experience, it was a challenge to establish a common knowledge base when new people entered the process. At the same time, a substantial amount of time, especially during the simulation workshop, had to be dedicated to explaining fundamentals of modelling and simulation, the main principles of computational models and the role of uncertainties within the model's parameters. As one participant mentioned, "looking into the machine room" of such models gives a glimpse of the complex interactions and dynamics of the real-world system. On a technological level, the digital modelling and simulation tools used provide a transparent and user-friendly interface that is usable together with multiple stakeholders (see Figure 4 for the setting). One key advantage is an instantaneous digitization of the aspects discussed, as well as a clear and accessible documentation. Browser-based tools such as Insight Maker facilitate sharing and simulation of models via web-based simulation approaches. Working together on technological artefacts, such as large touch tables, helps in bridging the gap between the on-site discussion and the computational model. At the same time, such a common interface can also become an obstacle to a balanced discussion. For instance, one participant was not able to stand for a long time due to health issues as was thus partially excluded from the discussions by people standing in front of the touch table.

Investigating in the technological feasibility of a "system of systems" urban model platform approach, our preliminary findings show multiple advantages. Since both models not yet fully implemented on the platform, these advantages can only be discussed conceptually. Firstly, separating the model logic from a specific user interface creates a level of abstraction that seems both general and specific enough to connect multi-paradigm and multi-scale models. As the OGC API Processes standard specifies only the model's inputs and outputs, enough information is exposed to link various user interfaces for setting up simulations runs and displaying their results. At the same time, the standard user interfaces of various digital tools can still be used as the API Processes only provides an additional interface to access the algorithms and logic behind the user input. Secondly, the ability to choose from a synchronous and asynchronous execution of the model within the API Processes facilitates a fast and efficient interaction between models wherever feasible, but also ensures a storage of intermediate results wherever necessary. Thirdly, the API Processes as a recent open standard published by the OGC is likely to resonate with multiple actors in the domain as past developments such as the Web Map Service or the Web Feature Service show. Fourthly, this architecture enables multiple models as outlined by Page (2018) andBatty (2021) that could be used side-to-side to mitigate each other's blind spots. Specifically in the context of digital urban twins, domain-specific simulation models could in the future either be developed or procured by the city and integrated in an urban model platform. At the same time, there is still considerable uncertainty around possible solutions for automated and non-tailor-made model orchestration. We believe that given the standardized list of in- and outputs, it is possible to develop easy-to-use tools and link the specific models. However, one would potentially need to expand the current OGC standard with additional metadata about time, state and interdependencies. Further research is necessary to provide a coherent state management between multi-paradigm and multi-scale models in a spatial context.

Limitations of our study are linked to the selection of participants, model development iterations and data gaps. Although we aimed to create an open and inclusive process, some stakeholders either did not respond or were not available for a continuous participation. We thus consider the aspects discussed and operationalized to be biased towards the ones continuously represented during the workshops. Additional model development iterations would also improve both quality and validity of the models as multiple suggestions were gathered in the simulation workshop. They also brought forward data gaps where better model results could be obtained by improving the data base of the models, especially the district-scale model.

Overall, we found the separation into a multi-stakeholder engagement strand and a technological implementation strand to be very productive. In that way, discussions were focused on the content and could be moderated accordingly. The resource-intensive work of translating the concepts into code was outsourced, but could at the same time be discussed at later stages of the consecutive workshop design.

Although still work-in-progress, we see much potential in our approach, especially in it being a proof of concept on how to (1) engage multiple stakeholders in a modelling processes and (2) leverage existent open standards for a system of systems multi-model integration. In our point of view, this combination provides a way forward for multi-modelling in the context of digital urban twins, particularly in addressing complex issues such as energetic renovation and gentrification. With the approaches presented we showcase how a dynamic and open-ended co-creative process, supported by a technological infrastructure that allows for the integration of multi-paradigm and multi-scale simulation models, can create the conditions for an open and extendable digital urban twin.

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