Temporal Challenges in Data-Driven Scenario-Building for Climate-Neutral Cities

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Abstract

This position paper examines temporal challenges in data-driven urban and climate transitions. It argues for scenario-building to understand implications of current development and planning processes towards emission reduction, climate action, and increase of liveability of our cities. Temporal challenges arise for example out of data quality, data availability, or integration issues. These are present in domains such as digital twins, GIS, simulation and forecasting tools, participatory approaches, decision-support systems, and organisational and system workflows.

CCS Concepts

• **Information systems → Spatial-temporal systems**; **Information systems applications**; • **Human-centered computing**;

Keywords

Urban Transitions; Urban Digital Twins; Temporality; Smart Sustainable Cities; Multi-Stakeholder Digital Ecosystems; Climate-Neutrality; Climate Action; Spatio-Temporal Information Access

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1 Introduction

Cities worldwide are working to reduce their greenhouse gas emissions and to progress on the path to climate-neutrality, to reach the Paris Agreement's climate objectives within shrinking timeframes. Such climate-mitigation and decarbonisation efforts affect all sectors and include emission reduction, renewable energy generation, new ways of urban planning, and new structures and processes to enable these. These activities are connected within multi-faceted transitions that are happening simultaneously, such as climate transition, energy transition, mobility transition, and urban transition; while maintaining and improving liveability.

In our work, we aim to accelerate these transitions and to ensure that any actions, constructions, or interventions done today are done with this urgent need in mind. It is vital that informed decisions today clearly connect present-day actions with long-term future impacts and consequences. For example, anything in the built environment that is being developed or built now will lock in decisions and emissions for the next 20–100 years, far beyond the critical milestones to counter climate change and transform cities towards climate neutrality by targets of 2030 or 2050. This calls for urgency and also calls for clear understanding of the future impacts of current planning options to ensure that they can support the goals and strategies. It includes the whole built environment of individual buildings, neighbourhoods, districts, and cities, including infrastructure, mobility, public space, nature, etc.

Targeted urban planning can have a significant impact on future emissions. The ways urban functions are structured and urban life is supported have a strong influence on liveability [6, 10], and dependent impacts for example on mobility needs and associated energy needs and emissions [3, 4]. Participatory approaches and co-creation with inhabitants and other stakeholders are important, to include all relevant viewpoints and suggestions early on and use the full innovation potential of cities for these challenges[1]. Simply said, are at the point where wrong or suboptimal decisions cannot be reverted anymore in time, so we need to ensure that planning and construction locked-in now can contribute in the best way towards climate-neutrality.

These complexities and the need for integration are followed in our work and align with the ambitions of the EU Mission for 100 climate-neutral and smart cities by 2030[1] (Cities Mission) and the New European Bauhaus[2]. Altogether, these developments require urban planning to deal with much more complex and integrated contexts and requirements, and also mean that the consideration of future states becomes less static and much more dynamic in a complex interplay of influences.

In previous work we presented temporal aspects in the context of spatio-temporal urban digital twins and a need towards treating the temporal dimension as a core feature in smart city systems [2]. One observation was that the temporal dimension, apart from clear timeseries data, is often treated as a vaguely defined 'present', which becomes a particular issue in the forecasting and scenario-driven work discussed here. We revisit our earlier use of Kitchen's concept of "timescapes" in smart cities [8]. Here we use in particular temporal changes, "time-space compression", and the move from the "real-time city" [7] to the *future and forecasting city*, in line with the observation "Smart city technologies, although most often framed around managing the present, are future oriented

[1] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en
[2] https://new-european-bauhaus.europa.eu/

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with respect to plausible and preferable scenarios, dispositions, optimisation, and contingency" [8]. At the same time, urban planning is bridging smaller time horizons and higher frequency of updates [5]. This can bring down temporal scales for urban planning and forecasting/simulations from static situations measured in years to include high-frequency (daily) patterns for future scenarios.

2 Future Scenario-Building

Digital twins or simulations as support for climate action currently often focus on individual or closely related domains for detailed forecasting of static scenarios. Future needs will include complex dependencies between sectors and respective different simulation tools, and integration of different time horizons and dependencies.

As a case study for such future scenarios, we discuss data-driven scenario-building [9, 11] in the Re-Value project. It aims to integrate data-driven strategies, tools, digital twins, GIS, simulations, and digital decision support to help cities plan and design transformations and strategies and better understand tradeoffs between alternatives, beyond analysis of the current state or a 'static' future. Pilots include redevelopments of waterfront areas under participatory principles, including reuse of old harbour buildings, new public spaces, public transport, coastal erosion, etc. Considering temporal aspects for longer-term integrated scenarios opens a range of challenges:

- Complex integration of different simulations, tools, methods, and data sourcing. Integration of multi-faceted planning domains.
- Complex cross-domain feedback loops and inter-dependencies in simulations are difficult to model over time. Interdependencies are often not yet well understood on an implementable basis. Simulation uncertainties, especially when integrated, may need rather probabilistic scenarios; results can be difficult to meaningful visualise or interpret holistically.
- Holistic Interpretation of Data: Narrow or short-term results interpretation may lead to unintended consequences across domains.
- Temporal Granularity Mismatch: Misalignment between different modeling or data timelines, periods, or frequency; may require aggregation or transformation. For example, mobility patterns can range from few manual samples or yearly averages to real-time estimates, while energy modeling may only be available at seasonal averages.
- Time horizon mismatch: Planning and policy targets (e.g. CO_2 emissions) operate on horizons incompatible with operational data; different tools often optimise for one dominant horizon. Temporal synchronising/integration across domains: different domains operate on different horizons and rhythms (timescapes).
- Data availability, data quality, data/model interoperability, data management, sharing/access, governance issues
- Lack of Standardisation for data-driven urban development approaches. limiting transparency, reproducibility, and institutional capacity within planning authorities.
- Governance and accountability: Responsibility for short- and long-term outcomes may be unclear, feedback loops can be longer than the remaining time to reach the targets. Tools also may influence which futures are considered plausible or desirable or reinforce existing plans rather than open up novel ones.
- Participatory planning and better informed decision-making: while scenarios become more complex, they need to remain accessible for discussion and debate.

3 Conclusion

Together, these examples highlight specific temporal challenges for digital planning tools and options for improvements of tool integration for climate-neutral and liveable cities. While individual simulation tools are already quite advanced, an integration of different tools and models, temporal and forecast granularity, including cross- and inter-dependencies, side effects, and second-order effects is still a major and urgent challenge.

Temporal aspects should be embedded as core considerations into future tools, data-driven approaches, and processes. This would help further develop and co-create options and alternative scenarios and their meaningful comparison with suitable tool support for data analysis, simulations, and forecasting towards climate-neutral and liveable cities. The concept of timescapes can help us understand how the use of time-, time-horizon-, or time-frequency-sensitive perspectives influences how time is conceptualised, represented, and operationalised in digital urban systems.

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