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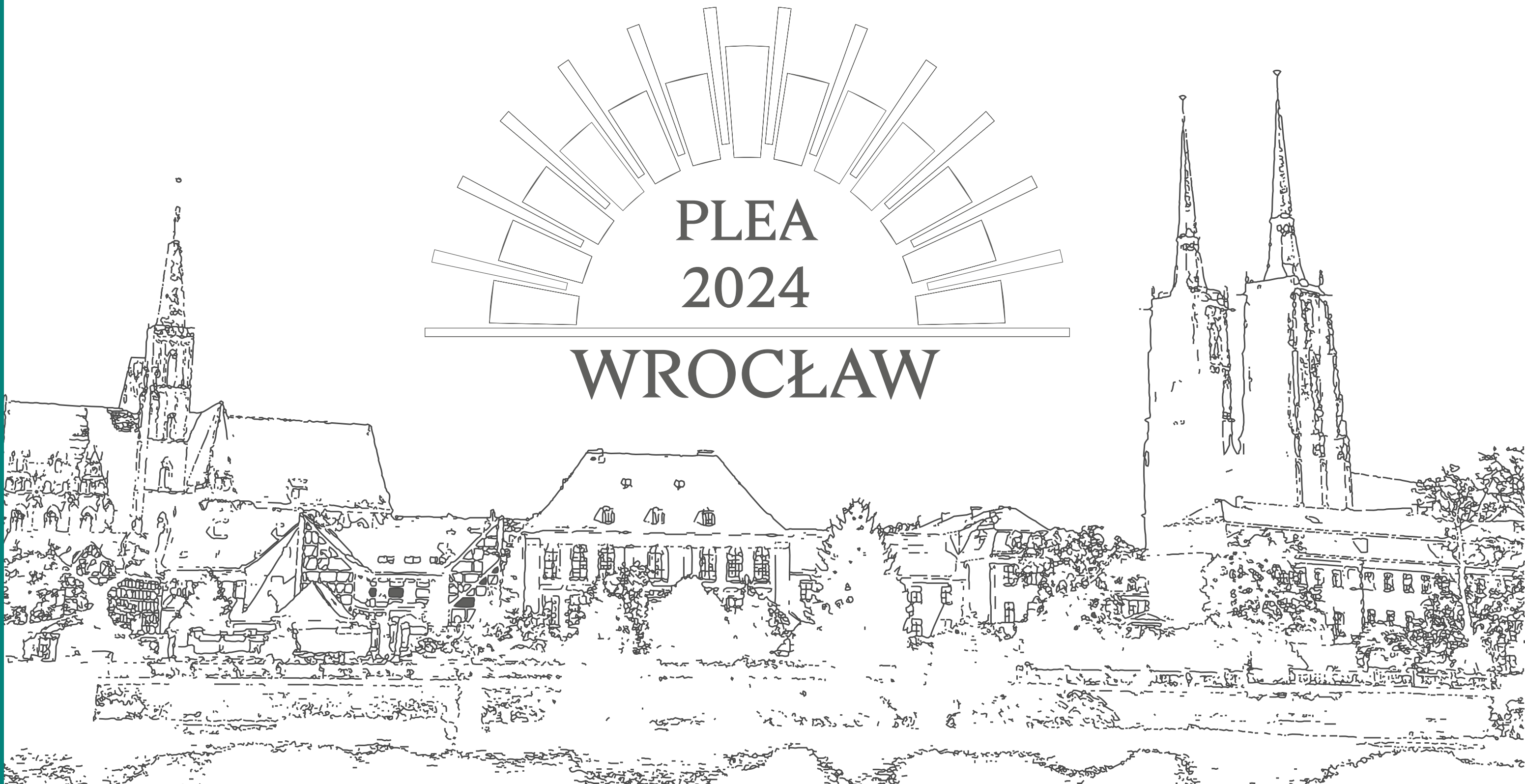

Urban Green Infrastructure for Resilient Urban Transformations:

A System Dynamics Modelling Approach for Streets as Multifunctional Spaces

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ABSTRACT: In pursuing resilient urban transformations, streets must be transformed into multifunctional spaces integrated into the urban green infrastructure (UGI), but there is a lack of systemic understanding of synergies and trade-offs of UGI in streetscapes. System dynamics (SD) modelling is a method to better understand complex interconnections between indicators in a multidisciplinary context and, therefore, can help achieve multifunctional streets. We propose here a SD model focusing on four sub-projects of a Research Training Group (active mobility comfort, private yard morphology, bird community composition, and tree canopy growth) and centred around two urban planning goals, i.e. enhancing Active Mobility Comfort (AMC) and increasing Bird Biodiversity (BBD). The resulting model allowed us to exemplify relevant indicators, synergies and trade-offs of UGI elements, indirect paths to reach urban planning objectives and high-impact indicators serving as a lever for street transformations. Through this endeavour, we gained a more holistic understanding of street UGI interactions, which is beneficial for interdisciplinary research and effective decision-making.

KEYWORDS: Streets, Multifunctional, System dynamics, Modelling, Multidisciplinary

1. INTRODUCTION

In the face of current climate change projections, Urban green infrastructure (UGI) is seen as a critical component in creating resilient and sustainable cities [1]. More than just the ecosystem services that UGI provides, its multifunctional character makes it a central component of resilient urban spaces [2]. For this reason, developing UGI demands a multi-scalar and multidisciplinary approach [2]. This is the challenge that the Research Training Group (RTG) “Urban Green Infrastructure – Training Next Generation Professionals for Integrated Urban Planning Research” at the Technical University of Munich aims to address since its start in 2022. The RTG comprises 14 departments from the natural sciences, engineering, and planning disciplines. We strive to address part of this challenge here.

Streetscapes, defined here as the areas between building facades that include public streets and adjacent spaces, represent a convergence point of the research projects of the RTG as they are increasingly recognised as pivotal components within urban ecosystems to achieve a continuous UGI in densely built areas [3]. Moreover, they are already undergoing transformations around the world significantly in part due to a shift in the mobility paradigm - from car-based mobility towards active mobility, i.e. walking and cycling [3]. These current transformations can be an opportunity to integrate more elements of the UGI, therefore becoming multi-functional spaces and helping to achieve resilience and sustainability goals. Nonetheless, these transformations represent a challenge because of the variety of actors involved and the lack of a multidisciplinary approach leading to a common understanding of the benefits and trade-offs of UGI in streets [4]. To contribute to this, we focused our study on urban transformations taking place in streets and considered the integration of UGI elements crucial to achieving resilient urban streetscapes.

1.1 Opportunities of a System Dynamics Modeling Approach

To achieve a better understanding of the benefits and trade-offs of UGI in streets, a method applicable to studying complex problems, such as sustainable development with a multidisciplinary approach, is needed [1]. System dynamics models (SD) do just that [5,6] by describing complex systems through time by illustrating stocks, flows, feedback loops, and time delays [5]. SD models frequently find application within the domain of urban development as a foundation for formulating policies and exchanges with decision-makers [5] and can, therefore, be a tool to facilitate the planning of multifunctional street spaces.

Our SD model aims to identify critical indicators and types of connections between the four identified project focuses to analyse synergies and trade-offs relevant to reaching two selected urban planning goals. Our model aims to facilitate a holistic understanding in the context of interdisciplinary research and pave the way for the planning of multifunctional, resilient streetscapes.

2. METHODS

2.1 Model Context and Boundaries

Here we present a conceptual framework for developing a SD model of urban streets. Our aim is to allow a systemic understanding between domains within UGI. As a lack of clear model boundaries is identified as a research gap [5], we limited our model to encompass the following domains: 1) Active mobility comfort, 2) Private yard morphology, 3) Bird community composition and 4) Tree canopy growth. These represent sub-projects focuses within the Research Training Group and are described in more detail below.

In the active mobility domain, the project focuses on the interactions of UGI with active mobility modes due to the direct exposure of pedestrians and cyclists to the urban environment, making them the group of users to profit the most from the benefits of vegetation in streetscapes. [4] Within the domain of private frontage morphology, the focus lies on the role of frontages as a buffer area between public and private urban spaces that contain a significant share of green elements and hold great potential in contributing to the integration of UGI in streetscapes. [7] The bird community composition is relevant as the complex interactions between different taxa and urban green are just beginning to be understood [8]. Birds are one of the best-studied urban taxa and are nearly ubiquitous in urban environments. Lastly, the domain of tree canopy growth is particularly relevant in streetscapes as trees are a decisive factor for microclimate [9] and bird habitat in otherwise highly sealed streetscapes [10].

To further reduce the scope of this specific endeavour, this model was developed to gain a further systemic understanding of two specific urban planning objectives which are, among others, relevant in achieving resilient cities, i.e. (1) enhancing Active Mobility Comfort (AMC) and (2) increasing Bird Biodiversity (BBD). Indeed, these two urban planning goals are two significant points defined by The New Leipzig Charter under the dimension of a “green city”, which contributes to developing resilient cities in the European context [11].

2.2 Model Development

We used a three-step process to develop the system model (Fig. 1). First, we identified relevant indicators for the four domains using relevant literature and domain expertise. To identify the influence of the indicators, we categorised them into adjustable, affected, or linked types. This facilitated result analysis for determining loops in the model. "Affected" indicators undergo changes mostly indirectly through other indicators in the model (e.g., Walking/Cycling comfort). "Adjustable" indicators represent potential levers within the system that can be changed or adjusted directly (e.g., Tree Species). Finally, "linking" indicators are crucial for illustrating indirect relationships between adjustable and affected indicators.

In the second step, we looked for connections between the identified indicators in step one. The connection between indicators could be either directed or mutual, exemplifying the causes and consequences of the model. In addition to the direction of these connections, they were categorised by the connection types, which can be ++, +-, --, and +/-. Table 1 explains all possible types and directions of connections in the model.

Type	Direction	Interpretation
++ or +-	Directed	Increasing index X will increase/ decrease index Y.
+/-	Directed	One index influences the other, but the positive or negative effect is not apparent. (e.g., categorical indicators)
+/-	Mutual	Both indicators influence each other reciprocatively, but the indicators are qualitative or categorical.
++ or --	Mutual	Both indices influence each other reciprocatively and will increase /decrease correspondingly

Table 1: Typology of connections between indicators.

In the third step, we visualised the indicators and connections through a causal-loop diagram using

"Kumu"[1]. The resulting causal-loop diagram captures the indicators' causal connections (Fig.2). We used this tool to define the causal loops by focusing on two urban planning goals: 1) enhancing Active Mobility Comfort (AMC) and 2) increasing Bird Biodiversity (BBD). To improve the readability of the model, indicators were grouped into eight thematic categories: 1) Active mobility, 2) Bird community composition, 3) Urban Typology, 4) Network Structure, 5) Vegetation properties, 6) Individual characteristics, 7) Climate conditions, and 8) Spatial conditions. The thematic categories linked to urban planning goals (AMC and BBD) were set at the two extremities of the model. This visual organisation allowed for highlighting cross-discipline connections and indirect, unforeseen relationships (Fig. 2).

The causal-loop diagram was iteratively developed, involving a continuous process of refinement based on expert assessment to ensure its accuracy and alignment with established literature. Therefore, the result of step 3 helped adjust the indicators and connections along steps 1 and 2 to increase the model's accuracy (Fig.1).

The resulting model was then interpreted by observing direct and indirect connections between indicators which are relevant to the urban planning goals (Fig.2). We also identified high-impact indicators, which are indicators that are characterised as adjustable and related at the maximum second-degree to indicators of the two urban planning goals. Each connection was backed up by a literature reference, which is cited in the interpretation of the results.

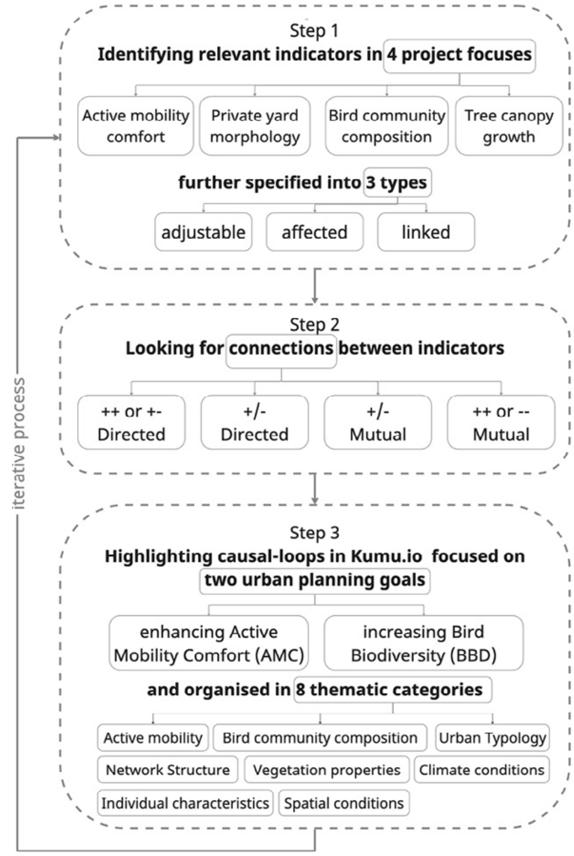

Figure 1: Flow chart of the methodological process

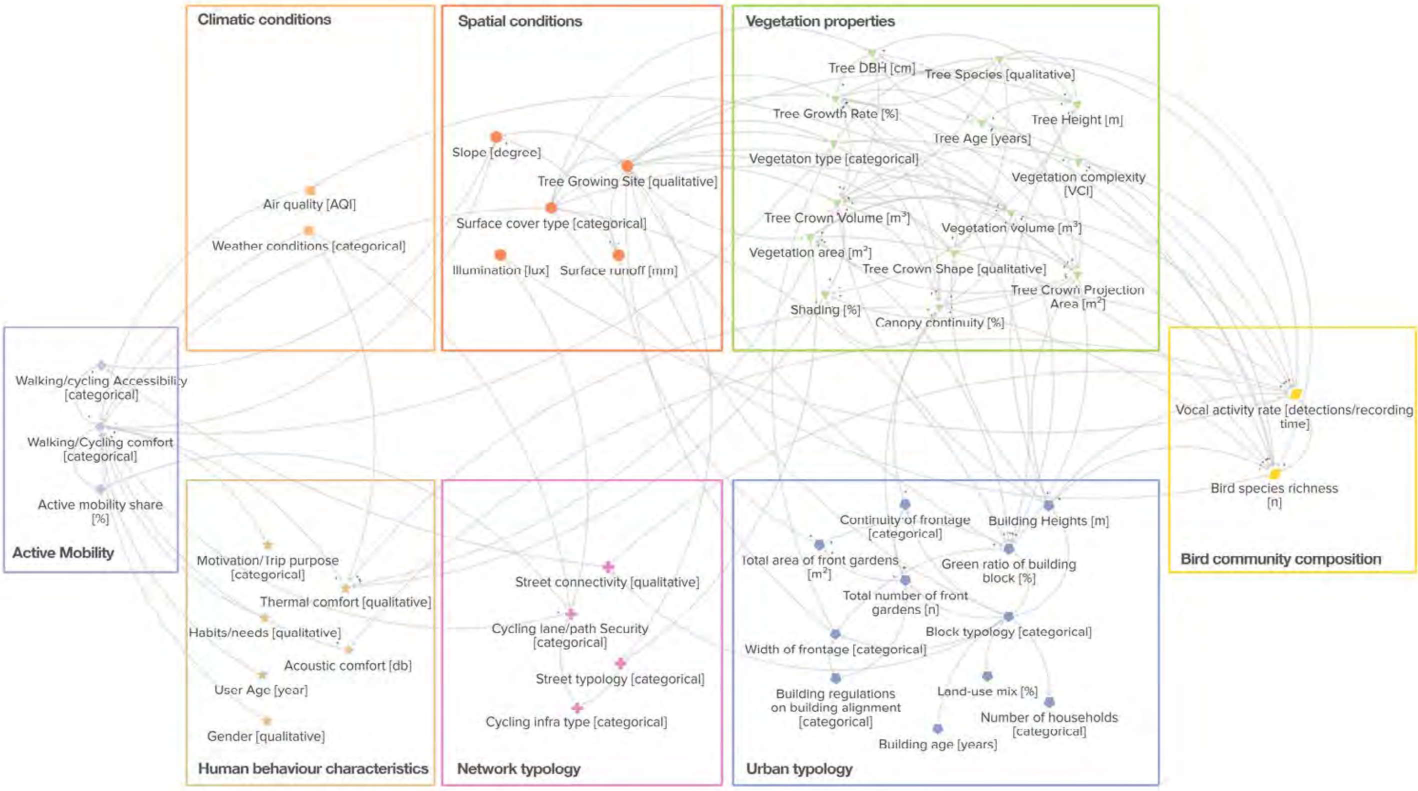

Figure 2: Visualisation of the SD model using the tool Kumu depicting the connections between indicators grouped into 8 thematic categories.

3. RESULTS AND DISCUSSION

3.1 Pursuit of Urban Planning Objectives

While The SD model illustrated known direct relationship indicators, it also highlighted indirect ones that are more surprising.

When focusing on indicators relevant to the first objective, AMC, the model illustrates indicators and relationships that are commonly described in the literature, such as the Vegetation area (Fig.3). This indicator indeed is known to participate in improving the microclimate thanks to evapotranspiration and shading [12, 9]. Our model additionally helped identify other, less obvious indirect relationships. For example, the Width of frontages is indirectly related to the indicator Walking and Cycling comfort through its influence on Vegetation type and Surface cover type (Fig. 3). Indeed, narrow frontages do not allow to plant certain tree species, and various widths of frontages allow for different usages such as parking and therefore have different surface cover types [7]. Another example of an indirect relationship is that of the Vocal activity rate of birds, which affects Active mobility comfort through its impact on Acoustic comfort (Fig. 3) [13-14].

When focusing on the second objective, BBD, the model illustrates connections between obvious indicators, also identified in the literature, such as Tree age and Species, Vegetation area, Type and Volume, and Canopy continuity. [10] Additionally to these, the results show that Building height has an unexpectedly significant relationship with Bird activity as it not only has a direct impact on bird mobility [15] but also affects Tree growth [16], which affects Vegetation volume, which then affects Bird species as identified earlier [10] (Fig.2).

3.2 Discovery of High-impact Indicators

The SD model allowed us to identify high-impact indicators that are adjustable and impact both pursued urban planning goals simultaneously. We observed ten high-impact indicators: Vegetation type, Vegetation volume, Tree species, Tree growing site, Surface cover type, Illumination, Width of frontages, Green ratio of building block, Street typology and Illumination (Fig.2). For example, the Vegetation area and the Tree growing site quality both substantially impact the Canopy continuity indicator [16, 17], which is a linking indicator related to both urban planning goals (Fig.4). Indeed, the Canopy continuity is significant for the Shading percentage and consequently affects Thermal comfort [12], which in turn affects Walking/ cycling comfort and Bird species richness by affecting their habitat [10]. This means that to achieve the urban planning goals, planners or policymakers can focus on these two adjustable high-impact indicators to achieve significant results.

Street typology is another one of these high-impact indicators as it affects the Tree growing site by changing the distance and height of the surrounding buildings [16] and the Vegetation area as different street typologies will impact the tree planting design [18]. Those indicators then have an impact on both pursued urban planning goals.

Another discovery pertains to the dual relationships of artificial light at night, represented by the indicator Illumination: it both has a positive influence on Cycling lane/path security and a negative influence on bird-related indicators, i.e. Vocal activity rate. While crucial for the safety of nocturnal pedestrians and cyclists, it represents a trade-off regarding bird habitat quality [19-20] and, therefore, requires particular attention.

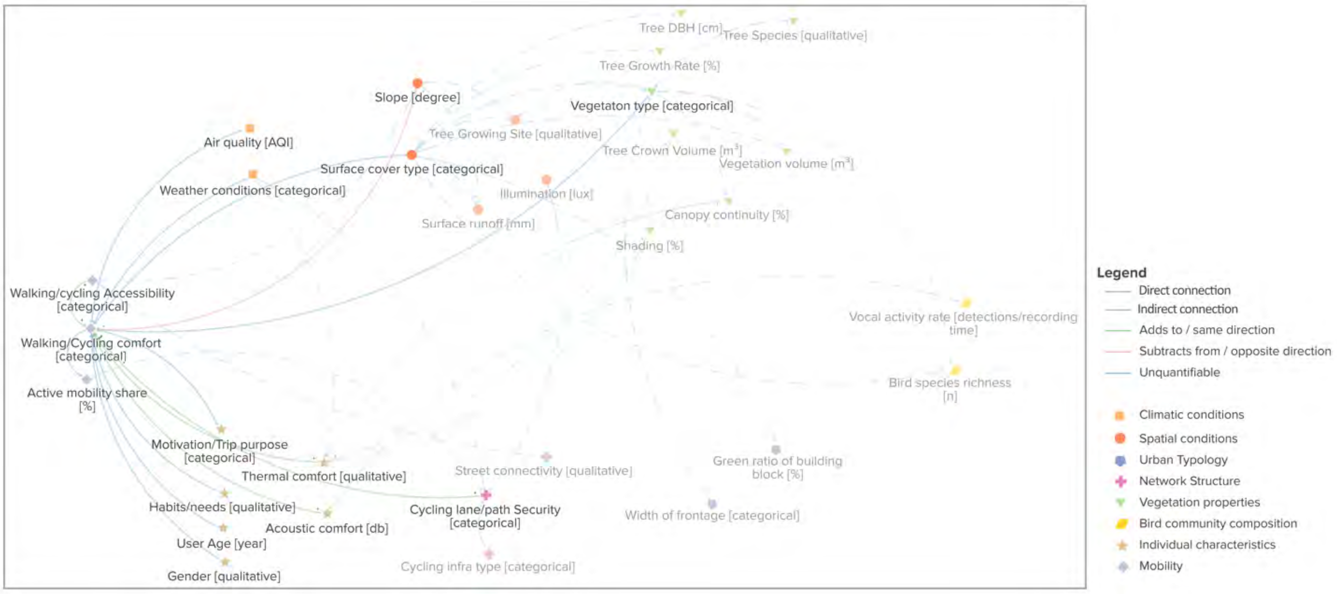

Figure 3: Direct and indirect stressors on Active mobility comfort

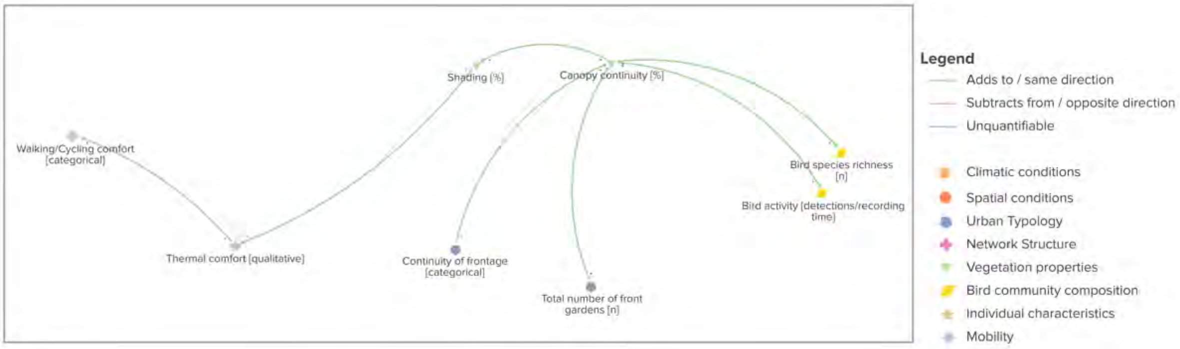

Figure 4: High impact of Canopy continuity

3.3 Implications for Interdisciplinary Research

This SD model allowed us to connect components specific to four sub-projects of a Research Training Group at the Technical University of Munich. This interdisciplinary visualisation facilitates the comprehension of correlations between research outcomes across sub-projects and scientific domains. The empirical evidence produced by each sub-project can gain meaningful interpretation through its insertion in the larger SD model, enabling the validation of anticipated correlations and the discovery of new ones. This strategic approach effectively contributes to developing a comprehensive knowledge framework specific to the interdisciplinary research group and is seen for this matter as a powerful tool for interdisciplinary collaboration. Moreover, it allows for results that are explored in a fundamental manner to be put into perspective with urban planning goals, making these results more applicable.

3.4 Process Governance

This SD model can be used as a framework for the governance of various ecosystem services that are difficult to manage by highlighting high-impact indicators that wield a substantial effect. The visualisation of the interdependencies among different indicators of the model can help decision-makers choose appropriate strategies and actions that lead to the pursued urban planning goals in practice. This is particularly important in UGI planning, where decisions can have long-term impacts.

The integrative and multidisciplinary character of the model allows for more informed policymaking, taking into consideration also indirect effects that can be overlooked in other circumstances. This aids in the effective allocation of resources to domains that may seem distantly connected to the goal but wield substantial impact. Assessing the feasibility of such changes further allows for prioritising interventions and optimising the pathway toward achieving the overall urban planning goals. Moreover, the risk of overlooking relevant actors is diminished, offering a more transparent and holistic perspective on stakeholder engagement.

3.5 Limitations and Outlook

While the proposed SD model has inherent limitations due to its scope centred around two specific urban planning objectives and four project focuses of the RTG, this deliberate framing provides clarity. It also allows the identification of potential interfaces of the model with other disciplines not presently incorporated but which can be potentially considered in the future. An illustration of this is evident in the omission of urban water systems, which would significantly impact many indicators in the Vegetation properties category. This illustrates potential connection points for further extending this model. Additionally, it's worth noting that another limitation of this system model lies in its conceptual nature. In the subsequent stage, it necessitates being populated with measurements to advance towards conducting behaviour reproduction tests, thereby verifying and quantifying the relationships between indicators within a local context.

4. CONCLUSION

In conclusion, the system dynamics model discussed in this paper proves to be a valuable tool for interdisciplinary research by elucidating high-impact indicators and highlighting synergies, trade-offs, and potential side effects of UGI in streetscapes. Focusing on two urban planning objectives — enhancing Active Mobility Comfort and increasing Bird Biodiversity — serves as a proxy to illustrate complex relationships and interdependencies between disciplines. This model can serve as a basis for further models integrating more domains and illustrating increasingly complicated relationships between indicators. The developed conceptual framework aids decision-making by identifying adjustable indicators within urban spaces and creating a baseline for interdisciplinary collaborative governance. This enhanced understanding, facilitated by system dynamics modelling in interdisciplinary research, is crucial for addressing complex challenges, such as transforming urban streets into integral components of Urban Green Infrastructure and enhancing urban resilience.

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