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Integrating and validating urban simulation models

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1 Introduction

The integration of environmental dimensions within simulation models for territorial systems from theoretical and quantitative geography is an other important implementation project. For example, [1] use an urban growth model to evaluate the local impact of climate change, but does not make associated aspects endogenous, such as energy price or the energy efficiency of the urban structure. Negative externalities such as congestion and pollution, directly linked to emissions, have a feedback for example on the location of activities. More generally, systematic links between a precise description of urban structure and energy efficiency, in a dynamical and endogenous way, remains to be established. Similarly, numerous studies in ecology which establish the impact of anthropic habitat disturbances would particularly benefit from a coupling with urban growth models, for example for a better management of the interface between the city and nature within the new urban regimes that are urban mega-regions [2].

At the macroscopic scale, several couplings between models of systems of cities and ecological models or from environmental science are possible and desirable. In terms of territorial planning at small scales, an estimation of the impact of flows from interactions between cities on traversed areas can for example yield compromises between the distribution of flows and their environmental impact, and establish recommendations to minimise the global impact of the urban system, with. the constraint of keeping a reasonable resilience and economic performance. In the same way, the questions of production, storage

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and distribution of energy are endogenous to territorial systems, and the dynamics of infrastructures and associated entities can. be integrated within models of systems of cities. This research direction can in fact be generalised to any type of resource, and the SimpopLocal model [3] and also the Marius model family [4] have integrated these aspects without however making them endogenous nor making them a central component of models. This aspect is linked to the previous point, given the difficulty to endogenise energy within macroeconomic models.

This research project, inspired by sciences of complexity and a principally geographical viewpoint, proposes the construction of bridges, coupling, and interdisciplinary dialogues, i.e. the construction of integrated theories. A way to understand such approaches is described by the complex systems roadmap [5]. It combines horizontal integration (fundamental transversal questions at the intersection of different types of complex systems) with vertical integration (multiple levels coupled within multi-scale models).

2 Horizontal integration: coupling urban models and dimensions

3 Vertical integration: constructing multi-scale models

Finally, the construction of multi-scale models will be in itself a crucial aspect, since it is a dimension in itself of the integration expected for the theories and models constructed. Following [6], given the multiple levels of articulation and interdependency that systems of cities have reached, the management and planning must necessarily be multi-scalar in order to take into account the geographical particularities while ensuring a global consistence which yield limited inequalities between territories.

Moreover, a considerable methodological work would be necessary to elaborate coupling techniques between scales (for example as the hybrid modeling coupling agent-based models with differential equations for an epidemiological model [7]), to determine the relevance of levels to. be included and avoid "ontological dead-ends" [8], and to determine the nature of retroactions between scales and their necessity.

4 Model exploration and validation

Working to integrate models and theories necessarily necessitates a fine understanding of the modeling process itself, but also of stylized dynamics produced by simulation models. In the case of geographical models, succh a knowledge has for example been developed within the Geodivercity ERC project [9], which lead to the conception of new methods answering to specific questions coming from geographical concerns (for example necessity and sufficiency of processes in a multi-modeling context [**?**], exploration. of the feasible space of model outputs [**?**]). More generally in social sciences, modeling and simulation driven by

new practices including model coupling, the use of high-performance computing for model exploration, open science practices, could be at the origin of new types of integrated knowledge [10].

Besides, the development of methods and tools to improve the extraction of knowledge from simulation models, and an epistemological investigation on modeling practices, are crucial within this direction which can thus be understood as a theoretical and methodological direction. Indeed, methods to validate simulation models mostly remain to be developed. Methods for the exploration, sensitivity analysis, and validation, are essential for robust application of models, but also yield a better complementarity with other types of approaches since they can establish when modeling is not relevant.

5 Discussion: towards evidence-based multi-scalar sustainable territorial planning

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