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Toward Sustainability of Complex Urban Systems through Techno-Social Reality Mining

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Humanity today is experiencing a dramatic trend toward urbanization, with over half of the world population living now in cities. There is a stringent need that this global urban expansion will be accompanied by a sustainability transition, putting cities in the spotlight when trying to reduce the environmental impacts of today's and future societies.[1] This requires a profound systemic understanding of the urban metabolism, being a highly nontrivial task:

- Modern societies have become embedded in an increasingly dense and intricate web of interconnected infrastructure networks that supply water and energy, provide communication and transportation services or manage wastes. The heterogeneity and tight coupling of these systems makes a tractable description of their collective emergent performance virtually impossible.
- Cities are subject to a continuous and rapid evolution characterized by, for instance, land use and demographic changes or the spread of new technologies. We can not simply draw upon static system snapshots in order to paint a comprehensive picture of the resulting urban dynamics.
- The usage and operation of urban infrastructure networks is driving human activity and vice versa. Conventional engineering or life cycle assessment (LCA) tools need to be extended to fully capture the complexity of these techno-social interactions.

Urban infrastructures are usually engineered and operated in a rather separate manner and often evolve through socio-technological innovation under economic and sustainability constraints. So far, however, insufficient attention has been devoted to the interdependencies between them, as well as to the interplay with their social component. Therefore, little is known about how to model and eventually improve the overall systemic performance. In this context, the recent advances in the intertwined areas of network science and complex systems theory are advocated to shed light on both network dynamics and the techno-social interactions. These interactions, in turn, are becoming today increasingly tractable as individuals in urban environments leave digital footprints of their everyday activities. Large-scale data mining of the collective human activity contains information that can provide fundamental insights into the interaction of people with urban infrastructure services.[2] As sensor networks and a wave of new distributed technologies are able to constantly gather and process diverse real-time data, this overall reality mining forms an unprecedented basis for developing novel pattern-oriented modeling approaches.[3]

On these premises, we propose the following systems roadmap toward urban collective efficiency, based on measuring and predicting the urban metabolism:

1. Digital traces of anthropogenic activities provide the input for new analysis tools based on network science and complex systems theory, allowing to reveal inefficiencies and potential synergies.
2. Integrating the gained knowledge into large-scale simulation models eventually allows one to predict the complex techno-social dynamics determining the sustainability of the urban metabolism.
3. Sensor networks and novel information and communication technologies (ICT) enable the continuous measurement of aggregate human activity within urban infrastructures by "zero-delay" reality mining, thus providing vital real-time feedback information.

All these promising opportunities require intelligent feedback concepts through an urban "nervous system", linking urban infrastructures with each other, with operators and end users. Examples include cross-links between urban mobility, energy and ICT systems, and real-time carbon footprint maps, to name just a few. In this context, reality mining could also be used to create incentive schemes to encourage individual ecological behavior. Additionally, resolving a number of puzzles and knowledge gaps that currently result from the fragmentation of research communities may now be successfully addressed, providing exciting new insights into the sustainability of the contemporary urban

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environments and anthropogenic activities at large.[4] All this will pave the way for guiding the design and operation of more efficient energy networks, planning for less traffic congestion, managing scarce resources and recycling waste in better ways. It will also allow one to establish early warning systems to detect undesirable developments and emerging risks, thereby increasing the responsiveness of decision-makers. Finally, under a city-wide collaborative management, it will be possible to reduce the environmental impacts of the overall urban human activities. A more detailed description of potential applications is given in ref 4.

Obviously, the related data mining needs to be done on a voluntary basis and in a privacy-respecting way, which calls for new data mining, storage, anonymization, encryption and aggregation concepts and technologies.[5] Protecting data from misuse is a key issue that must be addressed when implementing the described roadmap. Although data anonymization is advocated to protect privacy, advanced reidentification techniques and the increasing linkability of various types of databases demonstrate the need for regulators to carefully balance the emerging risks against the expected data mining profits.

The in-depth understanding of complex urban systems remains a challenge for future research. However, the combination of such diverse but powerful concepts across sectoral and disciplinary boundaries seems to open promising new pathways for modern urban societies, allowing one to maintain a high quality of life at significantly reduced environmental impacts.

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