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Complexity and Dynamism from an Urban Health Perspective: a Rationale for a System Dynamics Approach

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ABSTRACT *In a variety of urban health frameworks, cities are conceptualized as complex and dynamic yet commonly used epidemiological methods have failed to address this complexity and dynamism head on due to their narrow problem definitions and linear analytical representations. Scholars from a variety of disciplines have also long conceptualized cities as systems, but few have modeled urban health issues as problems within a system. Systems thinking in general and system dynamics in particular are relatively new approaches in public health, but ones that hold immense promise as methodologies to model and analyze the complexity underlying urban processes to effectively inform policy actions in dynamic environments. This conceptual essay reviews the utility of applying the concepts, principles, and methods of systems thinking to the study of complex urban health phenomena as a complementary approach to standard epidemiological methods using specific examples and provides recommendations on how to better incorporate systems thinking methods in urban health research and practice.*

KEYWORDS *Urban health, Systems thinking, System dynamics, Modeling, Complexity, Dynamism*

INTRODUCTION

The world is urbanizing, and cities are the context in which a majority of us live. More than half (54 %) of the global population lived in cities in 2014, and this is projected to increase to 66 % by 2050.[1] In addition to population growth, the number of cities has grown. In 1990, there were 10 megacities (cities with populations of 10 million or more), and in 2015, there will be 29.[1] However, most (45 %) urban dwellers live in one of the 538 cities with populations of less than 500,000 inhabitants.[1] The growth of cities is a key factor in the health of urban populations, as population growth has the potential to outstrip infrastructure—which may result in the inequitable distribution of resources.[2–5]

In a variety of urban health frameworks,[6,7] cities are conceptualized as complex and dynamic. Yet, standard epidemiological approaches have failed to address this complexity and dynamism head on. Urban health research questions are often

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investigated with more traditional epidemiologic designs. Causal inference methods used in epidemiology (e.g., directed acyclic graphs or DAGs) can identify the individual levers—policy and otherwise—that drive the health and well-being of urban populations and model the relations between policies, exposures, and health outcomes. However, traditional epidemiological study designs (i.e., ecological, cross-sectional, case–control, and cohort studies) and their associated statistical methods are limited in their ability to model and appropriately analyze the effects of individual levers simultaneously and over time on multiple outcomes of interest due to their narrow problem definitions and linear analytical representations.

This conceptual essay first reviews how complexity and dynamism are defined in leading urban health frameworks. The essay then discusses the utility of applying the concepts, principles, and methods of systems thinking to the study of complex urban phenomena as a complementary approach to standard epidemiological methods, using specific examples. The essay continues with a review of the key drivers of growing interest into systems thinking and system dynamics in the field of public health. It then concludes with an initial set of recommendations on how to better incorporate systems thinking methods in urban health research and practice to effectively inform policy actions.

COMPLEXITY

In the urban health literature, the complexity of a city is usually described as having many constituent parts that are interrelated, with variables on multiple levels.[6–9] Across several leading urban health conceptual frameworks, complexity is implicit.[6] This is congruent with the perspectives of urban planners and other urban scholars.[10] The complexity is framed as both positive and negative,[6,7,9] with scholars articulating both urban health advantages and penalties,[11–15] and ordered complexity[16] and disorder and chaos.[17]

Scholars from a variety of disciplines have long conceptualized cities as systems.[18–21] The human geographer Brian J. L. Berry, writing in 1964, suggested that we consider "cities as systems within systems of cities",[18] while the systems scientist Jay W. Forrester described urban areas in 1969 as "…a system of interacting industries, housing, and people."[21] This perspective has been embraced by the Healthy Cities Movement in particular. Lawrence Duhl and Trevor Hancock described urban settings as "partly organism, partly ecosystem," both homogeneous and heterogeneous at the same time.[9] According to Hancock and Duhl, urban settings are "the example par excellence of complex systems: emergent, far from equilibrium, requiring enormous energies to maintain themselves, displaying patterns of inequality and saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient networks."[10,22]

Urban health scholars also conceptualize urban settings as systems, but few have represented urban health issues as problems within a system. Indeed, systems science is a relatively new approach in public health.[23] Many of the studies that have applied system dynamics approaches to urban health issues have often focused on urban infrastructure management such as transport,[24–26] water,[27–30] and waste management systems.[31–35] A handful of studies have explicitly focused on population health outcomes in urban settings, including oral health,[36] HIV/sexually transmitted infection (STI) prevention,[37] social determinants of health,[38] climate change,[39] and youth violence.[40] More recently, a complex systems lens was used to develop and analyze a qualitative study of a multisectoral, multiagency alliance in Adelaide, Australia, aimed at improving outcomes for disadvantaged people through the social determinants of health.[41] The complexity framework used for this analysis included factors at the micro- (i.e., individual and family), meso- (i.e., regional structures and systems), and macro-levels (i.e., federal, state, and local government policies).

DYNAMISM

By their very nature, cities are dynamic spaces that evolve and devolve over time. What does that mean to the urban health researcher? In 1969, J.W. Forrester[21] described the dynamism of urban areas, with ebbs and flows of activities and people over time, such as migration into and out of cities, housing construction, obsolescence, and demolition, and birth and death rates. Dynamic systems are characterized by interdependence, mutual interaction, information feedback, and circular causality among variables in the system. Multiple urban dimensions (e.g., ecology including physical environment and climate, politics and governance, economies, etc.) change over time simultaneously, and these changes are affected by a variety of internal (i.e., city-specific and generated) and external forces (i.e., region, state, or country-specific and generated) and interact with other phenomenon within the system. Indeed, different elements of the system may take prominence at different time periods.

The RULER group described external dynamic trends that affect cities, as well as the internal dynamics that shape them.[8] External trends may include "… demographic shifts, globalization, climate change, proximal inequities, and decentralization [of national governments]."[8] Within cities, dynamic changes occur as well. For example, the movement of different populations in and out the city can result in concentration of poor in some areas and gentrification in others.[6]

Time is a key element of urban dynamism. Phenomena occur within and external to the system over time with varying frequencies. For example, policies are often tied to legislative schedules, but resistance to policies may ebb and flow on different time scales. Further, interventions can be implemented as a package of policies that roll out at different times, and resistance may manifest for some but not all of the interventions and may evolve over time as the interventions and policies are implemented.

SYSTEM DYNAMICS AS A METHOD TO STUDY DYNAMIC COMPLEX SYSTEMS

Public health policies and interventions to improve urban health and well-being are embedded in dynamic social environments where populations, risk factors, diseases, institutions, stakeholders, and health care resources are in constant flux and interact in a complex web of relationships over time.[42] Relationships between these variables are typically nonlinear (e.g., disease prevalence and incidence rate) and involve significant time delays (e.g., disease burden and perceived health risks and actions). Further, these relationships are not necessarily unidirectional and often form circular chains of causal relationships over time, known as feedback loops, in which conditions are converted into information that can be observed and acted upon to alter undesirable dynamics. While self-reinforcing (positive) feedback loops often produce hard-to-predict path-dependent, unstable dynamics (e.g., explosive epidemic outbreaks, such as Ebola), self-correcting (negative) loops may produce strong resistance to change and intervention (e.g., stigma and discrimination). Even sophisticated statistical techniques that are designed to test complicated relationships between variables cannot be applied to the study of feedback loops or other types of nonlinearity embedded in systems or assess the impact of feedback loops on multiple outcomes simultaneously.

Feedback loops do not operate in isolation and often interact with each other, representing mutual causality embedded in social systems. The interaction of feedback loops is "the main engine of change" that produces the system's dynamic behavior.[43] This is a central notion of the system dynamics approach. For instance, the International Council for Science's (ICSU's) innovative program on Health and Well-being in the Changing Environment recognizes that health is a state of complete physical, mental, and social well-being and views the myriad proximal (e.g., individual genetic makeup, nutrition, individual behavior, living conditions) and distal (e.g., natural and built environments, food, socio-economics, governance) determinants on a continuum where they interact to increase or decrease the subsequent effects on urban health outcomes.[44] Arguably, identifying the most appropriate intervention or policy (or sets of interventions or policies) to improve the system's behavior cannot be achieved by studying the individual effects of proximal and distal determinants, which lies at the heart of commonly used epidemiological methods in urban health research. However, the knowledge generated on the relationships between determinants and outcomes using traditional epidemiological approaches is the key to the dynamic conceptualization of underlying complex urban processes. This empirical research supports the formal system dynamics model building process to study a given health problem or research question.

Social systems change over time and adapt to changing circumstances. Of particular importance in this context is the early identification of negative trends and development of adequate policies to address them. This is, however, against a background where we are limited in our ability to understand distal effects and unintended consequences of our actions because of time delays and nonlinearities within social systems. The cumulative impact of individual behaviors on macro (population) level health outcomes can be subtle and counterintuitive, particularly when diseases and risk factors are mutually reinforcing and resistant to policy interventions with limited scope given the aforementioned proximal and distal determinants of health. For instance, estimating the dynamic effects of opiate substitution therapy on the rate of HIV transmission among those who inject drugs and in the general population is an excellent example of a dynamically complex public health issue in urban settings.[45]

Prior research has shown that policymakers have difficulties in understanding and managing dynamic systems of even modest complexity,[46–49] but these individuals are expected to use resources efficiently to meet public needs and address negative trends in ever evolving environments. The system dynamics approach helps policy makers understand synergies, constraints, tradeoffs, and sources of policy resistance to change and intervention by taking "a focus inward on the inner workings of a system rather than outward on the environment of a system".[50] Such an endogenous point of view implies that "no influences from outside the system boundary are necessary for generating the particular behavior being investigated."[21] In contrast, in an extremely exogenous point of view, all dynamic variation is assumed to be caused by variables outside our purview and control.[50] Policymakers often attribute undesirable performance to exogenous rather than endogenous sources. Richardson uses the following example to make these concepts clear, "...if the dynamics of urban stagnation is assumed to be caused by external influences (e.g., whether or not the federal government provides aid), then internal tendencies that cause or exacerbate the stagnation would be missed."[50] The system dynamics approach uses computer simulation models to uncover and understand endogenous sources of system behavior and helps us explore and identify internal policy changes that can minimize emerging negative trends in a safe and inexpensive way.[50,51] Often, the insights gained from simulation modeling still need to be tested in the real world.

The system dynamics approach has a strong emphasis on group model building, where formal models are developed jointly by modelers, practitioners, and other stakeholders. The approach is best suited to public health problems whose solutions defy disciplinary boundaries and can utilize all variables that are important for the problem and policy alternatives, such as biological, medical, behavioral, social, economic, and managerial variables. Given the main objective is to enhance decision-making around the prioritization of public health policies and interventions, group model building aims to capture all the required knowledge to understand complexity and harness real learning and problem-solving capabilities by fostering a reflective attitude among stakeholders during the model building process.[52] Another unique characteristic of the system dynamics approach is that it makes full use of not only quantitative but also qualitative data available as a main source information in the model development stage.[53] The approach can also provide guidance on where to collect more data by identifying gaps in our current knowledge and lead to new research questions and hypotheses that can be addressed by more traditional epidemiological methods.

Fundamentally, system dynamics can be used to answer questions that cannot be answered with epidemiologic study designs—how do components of a complex, nonlinear system interact dynamically across time to impact health? Findings from epidemiologic studies, coupled with findings from qualitative studies and experts' opinions, are used to define the parameters of system dynamics models and are therefore essential inputs into the model. Cavana and Tobias may explain this best:

> "Traditional epidemiological methods deal with complexity by breaking the issue down into parts simple enough to be controlled (randomized control trials) or observed (cohort or case control study). System dynamics (SD), by contract, deals with complexity by abstracting key elements of the system and simulating their dynamic interrelationships (using multiple differential equations). The focus of an SD model is thus on the behavior of the system *as a system*."[54], p 676

APPLICATION OF SYSTEM DYNAMICS TO AN URBAN HEALTH PROBLEM: THE SOCIAL DETERMINANTS OF HEALTH IN TORONTO

Mahamoud et al.[38] developed the Wellesley Urban Health Model to describe the causal pathways between risk factors, social determinants, and health outcomes in Toronto. The purpose of this exercise was to identify policy interventions directed at the social determinants of health that would have wide ranging impacts on a variety of health outcomes. The model was developed by a multidisciplinary team, with inputs from key stakeholders from the community, academia, and nongovernmental organizations in addition to local and provincial policymaker and decision-makers.

Data for the Wellesley Urban Health Model[38] were provided by the Canadian Community Health Study, the Canadian Census, and mortality estimates from published reports. Health outcomes in the final model included unhealthy behavior (i.e., smoking and obesity), chronic illness (i.e., having two or more of 12 chronic conditions), disability, poor access to primary care, and mortality. Key social determinants in the model were low income, social cohesion, and adverse housing. Multiple feedback loops were modeled. For example, in one feedback loop, low income predicted unhealthy behavior, which predicted chronic illness. Chronic illness then predicted disability, which in turn predicted low income. Simulation scenarios suggested that low income and social cohesion were important drivers of health outcomes in Toronto.

While the challenges of complex and interacting social, cultural, economic, and political determinants are well established, system dynamic models make these interactions explicit and allow the evaluation of multifaceted interventions by testing the impact of different policy levers. Mahamoud et al.[38] also envisioned the model as a tool for engaging stakeholders in a discussion of how the social determinants of health interact dynamically to impact health outcomes.

GROWING INTEREST IN SYSTEMS THINKING AND SYSTEM DYNAMICS

Interest in systems thinking approaches has been growing over the past decade as evidenced by publications, funding opportunities, and programming. A cursory search of the literature in PubMed with following search terms "system dynamics" [title] OR "systems thinking" [title] OR "systems science" [title] OR "systems dynamics"[title] OR" system thinking"[title] OR" system science" [title] produced 359 articles in September 2014. Two hundred forty-nine (69.4 %) were published in the last decade, which is since 2004, and 157 (43.7 %) have been published since 2010.

There has also been a growing number of funding opportunities from leading public health agencies specifically requesting the application of system approaches to public health problems. The US National Science Foundation issued a program solicitation for Human and Social Dynamics in 2008 that explicitly mentioned systems thinking and multilevel modeling of complex systems.[55] The US National Institutes of Health also issued several funding opportunity announcements (FOAs) requesting research utilizing system science methodology between 2008 and 2013.[55–64] The first of these FOAs specifically requested grant proposals "... that propose to apply one or more specific system science methodologies to policy resistant public health problems and contribute knowledge that will enhance effective decision making around the development of and prioritization of policies, interventions, and programs to improve population health in the US and abroad."[56] Moreover, among the examples of systems science methodologies, systems dynamics modeling was specifically included.

In addition to funding opportunities, there have also been specific calls for the application of systems thinking to urban health problems in particular. For example, the ICSU initiated a program on Health and Well-Being in the Changing Urban Environment in 2011.[44] In addition, two recent urban health conferences, the *International Conference on Intra-Urban Dynamics and Health: Concepts, Methods and Applications* held in Paris (France) in

September 2013[1] and the 11th International Conference on Urban Health held in Manchester (UK) in March 2014,[2] both included systems thinking as one of the primary foci of the meetings.

DRIVERS OF INTEREST IN SYSTEMS THINKING AND SYSTEM DYNAMICS

What is driving this interest in systems thinking approaches for public health, and urban health in particular? One driver is the growing emphasis on interdisciplinary and transdisciplinary research to address public health problems.[65] This is a key feature of urban health problems, as the very nature of cities requires intersectoral solutions to complex problems that cut across sectors with respect to impact and responsibility. Trudy Harpham often refers to this as a need for "joined up government" for multisector action on urban health issues.[66]

A second driver of the interest in systems thinking is the inability of policies to alleviate important public health problems despite efficacious interventions. Policy resistance arises when policies trigger feedback from the environment that undermines the policy, such as emergence of antibiotic resistance as an unexpected outcome of an aggressive infection control policy.[49] This example illustrates how policies that intervene in complex adaptive systems often lead to unanticipated outcomes when policymakers do not account for self-correcting feedback from the environment that opposes change.

We have seen this happen with urban health policies as well. Beginning in 2002, New York City implemented a comprehensive tobacco control policy, which included increased tobacco taxes, smoke-free environments, a nicotine-patch distribution program, and intensive health education.[67] Research suggested that smoking decreased between 2002 and 2008, likely related to the comprehensive intervention.[67–69] Policy resistance emerged as trafficking of cheaper cigarettes from other jurisdictions and street sales of untaxed cigarettes.[70,71] However, economically disadvantaged individuals had higher smoking rates relative to those higher incomes, in part due to increased likelihood of purchasing cigarettes through the informal economy.[72]

Policy resistance is a common feature of complex social systems characterized by a multitude of feedback loops with long time delays between policy actions and their results. Traditional analytical methods that lack a feedback perspective may therefore fail to anticipate the best policy actions. Because of policy resistance, systems are often insensitive to the most intuitive policies.[73]

CONCLUSION

Urban areas are complex and dynamic spaces that evolve and devolve over time. Urban health as a discipline has generally coalesced around a conceptual framework[6,7,74,75] that frames the urban environment as complex and dynamic, and researchers seek to understand urban health problems and the myriad of factors influencing urban health and well-being within these frameworks. This research is in

[1] https://www.etouches.com/eselect/ColloqueInternational2013/login/

[2] https://www.icuh2014.com/home/about

service of maximizing the health and well-being of urban dwellers through the development of policies, programs, infrastructure, and other interventions. Traditional epidemiologic methods are critical to understanding the various aspects of urban health phenomena but insufficient to address the complex social determinants of current and emerging health problems in urban settings, such as the rising burden of chronic diseases in both developed and developing countries. Systems thinking is the next natural progression in methodology for tackling the policy resistant health problems that face urban communities.

System dynamics deals with the study of dynamic policy problems of feedback nature (applied or theoretical). In other words, system dynamists "do not build models of systems, but build models of selected aspects of systems to study specific problems."[43] Considering the complex, adaptive nature of urban settings, it is important to anticipate some of the unexpected and counterintuitive consequences of implementing current and new policies. System dynamics models can be used for testing the viability of policies in an inexpensive way (i.e., often with existing quantitative and qualitative data) and can illustrate the tradeoffs and unintended consequences of policy choices related to the allocation of public health resources, particularly in resource-constrained settings.

Despite growing interest in systems thinking approaches, few health scholars, officials, and professionals have been exposed to any of its concepts, principles, and methodologies.[76,77] It has been suggested that the effective integration of social and behavioral science perspectives into systems thinking approaches would be a major methodological challenge in analyzing the multiplicity of factors that shape urban health outcomes in socially complex and dynamic urban environments.[44] To this end, codesigning the research methodology is essential within a transdisciplinary mode of knowledge production,[65] rather than considering social and behavioral factors as a set of variables in system dynamics models.[23] Equally important, group model-building techniques should have special prominence and involve real-world practitioners so as to improve their understanding of the adaptive complexity of urban environments while keeping the focus on priority policy issues and integrating research and practice.

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