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A systems approach to healthcare: Agent-based modeling, community mental health, and population well-being

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ABSTRACT

Purpose: Explore whether agent-based modeling and simulation can help healthcare administrators discover interventions that increase population wellness and quality of care while, simultaneously, decreasing costs. Since important dynamics often lie in the social determinants outside the health facilities that provide services, this study thus models the problem at three levels (individuals, organizations, and society).
Methods: The study explores the utility of translating an existing (prize winning) software for modeling complex societal systems and agent's daily life activities (like a Sim City style of software), into a desired decision support system. A case study tests if the 3 levels of system modeling approach is feasible, valid, and useful. The case study involves an urban population with serious mental health and Philadelphia's Medicaid population ($n = 527{,}056$), in particular.
Results: Section 3 explains the models using data from the case study and thereby establishes feasibility of the approach for modeling a real system. The models were trained and tuned using national epidemiologic datasets and various domain expert inputs. To avoid co-mingling of training and testing data, the simulations were then run and compared (Section 4.1) to an analysis of 250,000 Philadelphia patient hospital admissions for the year 2010 in terms of re-hospitalization rate, number of doctor visits, and days in hospital. Based on the Student *t*-test, deviations between simulated vs. real world outcomes are not statistically significant. Validity is thus established for the 2008–2010 timeframe. We computed models of various types of interventions that were ineffective as well as 4 categories of interventions (e.g., reduced per-nurse caseload, increased check-ins and stays, etc.) that result in improvement in well-being and cost.
Conclusions: The 3 level approach appears to be useful to help health administrators sort through system complexities to find effective interventions at lower costs.

1. Introduction: community health promotion and quality of life

Social and human ecologic determinants of health and health differentials have recently risen in the political agenda of the US and other societies leading to renewed interest in disease prevention, in health promotion, and in the systems approach [1] to improving quality of life (QoL) in order to reduce reliance on sick care. We view the management and promotion of health as a complex systems problem. It is a system of systems since it has numerous layers from the biologic to the cultural and many of its layers are themselves networked systems (e.g. human physiology, a family, a community). Further it is a complex system since many of its parts are purposeful, have their own (often hidden) motivations, and behave probabilistically often leading to unexpected, emergent patterns.

One of the best tools for attempting to understand and better manage complex systems is modeling and simulation. Our goal is to place a decision support tool into the hands of health administrators. Ideally, this decision support system (DSS) includes an agent-based model of various stakeholders' motivations and micro-decision making – like a Sim City for health – that allows users to easily simulate and visualize all of the interacting parts and thereby confront costs, outcome improvements, and benefits of alternative health promotion projects in different regions. By using systematic modeling that incorporates the most salient aspects of social determinants of health and systems science, the DSS will help administrators standardize assessment and decisions about

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programs and expenditures and thereby manage scarce resources more efficiently and effectively and achieve desired outcomes.

But what exactly should be modeled? How do we know what to model and what to leave out? After all modeling is expensive and simulation is time consuming (though not modeling can be far more costly). Fortunately, systems science suggests that to understand any system, it is important to represent its three levels – how its parts work (humanization problem), how the whole works (control problem), and how it interacts with its containing system (environmentalization). If we model a community, the parts might be the individual residents and the various practices that serve the community; the whole would be all the practices and health system services available to community residents, and the container would be the community including its population groups and members, organizations they belong to, and society at large.

We hypothesize that a DSS is useful for studying how to improve operations at all three levels. First, since the traditional fee-for-service business model of healthcare is unsustainable over the long haul, it is important to understand how policy changes impact the redesign of a given practice. A DSS allows decision makers to use systems thinking. Systems' thinking is foreign to most US-trained doctors and the medical system with its traditional focus on pathogens, risk factors, treating disease, episodic care, and on running clinics as a transactional fee-for-service business. One needs a systematic way to evaluate the plethora of disruptive innovations proposed for fixing the situation: e.g., medical homes, retail medicine, nurse practitioners providing primary care, reimbursable self-run support groups, health club activities, etc.: e.g., see Christiansen et al. [2]. Which alternative interventions yield the greatest savings and the greatest improvement in health status? What are the tradeoffs? How sensitive are overall results to changes in particular features that might be implemented? How long will it take for the interventions to begin producing net savings? How might screening programs that identify these illnesses at an earlier stage improve outcomes?

Making decisions about resource utilization became a high priority with the 2010 Affordable Patient Care Act that mandates accountability for quality of care while reducing costs [3]. Multiple chronic illnesses and mental health conditions place the highest burden of cost on health care budgets and these costs are mostly shouldered by public payment systems. DSS are needed to assist health care administrators improve quality at reduced costs. However, few studies have used agent-based modeling despite advantages of accounting for complex social determinants in the analysis.

In short, this paper reports on results to date of our investigation of the usefulness of three levels of models of a community – the overall healthcare "system", the various practices and services that comprise its "parts", and the key stakeholders (organizations, groups, individuals) in the overall "containing society". Over the past 15 years, we have successfully applied this 3-level systems modeling approach for the US Department of Defense and State to analyze societal instabilities overseas and how to influence them for the better [4–6]. The current paper examines a prototype and its validity and usefulness in addressing instabilities in a large urban healthcare system. We named the model *Simulating Urban Mental Health Operations* (SUMHO) and we model health systems of the city of Philadelphia.

1.1. Case study: community mental health in Philadelphia

The population with serious mental illness (SMI) with comorbid medical problems represents one of the most complex resource allocation problems for public health administrators [7]. People with chronic mental and physical illness have great need and are associated with some of the highest costs of health care and the worst outcomes. For the SMI, rehospitalization rates and medication errors elevate the cost of care by $44 billion dollars a year [8]. Certain conditions in the social construct of the overall health care delivery system make individuals with SMI extremely vulnerable. The delivery systems for mental health, substance and physical health care operate independently, communicate with one another inefficiently and often have different financing arrangements and policies [8]. These systems are virtual silos. Patients negotiating these fragmented health care systems find them not only burdensome but perilous and result in exacerbation of symptoms and rehospitalization. For example, these challenges ignite problems following discharge from a hospitalization for a psychiatric condition and result in striking statistics: 38% of clients with serious mental illness relapse within 30 days of discharge and must be rehospitalized; 48% show high utilization of emergency services [7]; and people with SMI die 25 years earlier than those in the general population [9]. DSS could improve the effective and efficient management of this population.

Urban behavioral health systems have long been a safety net for people with serious mental illness, caring for some of the sickest and poorest individuals. Just in the city of Philadelphia alone, community mental health care is an $850 million dollar annual industry that supports up to 500,000 Medicaid beneficiaries; of these beneficiaries, approximately 100,000 are individuals with multi-complex mental and medical health problems and consume nearly 75% of the resources [7]. These systems rely on federal and state funding and have experienced deep budget cuts as states close their budget deficits. Now more than ever, public health administrators must spend resources efficiently, reducing costs while still providing essential services. Because of the complexity of the system, however, there is great need for tools to guide administrators' resource utilization decisions.

1.2. Why agent-based modeling (ABM) and modeling challenges

ABM is a new way of understanding social systems that grew out of complexity science and artificial intelligence. When equations and principles cannot adequately describe and predict a complex system's overall macro-behavior, analysts can use a mixture of quantitative and qualitative methods to construct agent-based models of key stakeholders and their micro-decision making. Initially, these start out as simple rule-based models, which grow more sophisticated as they are validated and details are added. When these models are run, one can observe synergies that emerge, study new equilibria that arise in response to policy variables, and explore the causes of micro and macro-behavior patterns that have been observed in the real world.

A system is a whole that cannot be divided into its interdependent and interacting parts without losing the essence (synergy). Further, the micro-decision making of each of its parts has an effect on the macro-behavior of the whole (emergence). A unique challenge of social systems is that there are many sub-systems that are themselves purposeful systems – many levels of self-determining functionality, from the depths of the cognitive up to the heights of the economic institutions and political strategies – and one must find ways to encapsulate them in hierarchies or networks, so that different levels may be meaningfully studied. This network of teleologic sub-systems, this independent purposefulness of the parts, is the distinguishing trait of social from other types of systems. It means that social systems are the hardest ones, the most complex – what are referred to as ill-structured and having "wicked" dilemmas.

ICSU [1] also points out that "Systems analysis involves the use of mathematical modeling to represent processes and relationships and how desirable end points may be achieved." To pursue a systems approach to inform city (health and quality of life) planning,