A. M. Romaniuk, Student majoring in Information Systems and Technologies,

Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk

# MATHEMATICAL MODELLING FOR HEALTH MONITORING

**SYSTEMS**

*Abstract. Mathematical modelling has emerged as a crucial instrument for delving into intricate systems, particularly in advancing comprehension and optimization of health system operations. Two widely embraced approaches, system dynamics models (SDM) and agent-based models (ABM), serve as complementary methods to simulate both macro- and micro-level behaviours within health systems.*

*Keywords: System dynamics, Agent-based, Health systems, Systematic review, Modelling.*

Health systems are complex adaptive systems. As such, they are characterised by extraordinary complexity in relationships among highly heterogeneous groups of stakeholders and the processes they create. Systems phenomena of massive interdependencies, self-organising and emergent behaviour, non-linearity, time lags, feedback loops, path dependence and tipping points make health system behaviour difficult and sometimes impossible to predict or manage. Conventional reductionist approaches using epidemiological and implementation research methods are inadequate for tackling the problems health systems pose. It is increasingly recognised that health systems and policy research need a special set of approaches, methods and tools that derive from systems thinking perspectives. Attempting to evaluate the performance of such a multi-faceted organisation presents a daunting task. Mathematical modelling, capable of simulating the behaviour of complex systems, is therefore a vital research tool to aid our understanding of health system functioning and optimisation.

System dynamics models (SDM) and agent-based models (ABM) are the two most popular mathematical modelling methods for evaluating complex systems; while SDM are used to study macro-level system behaviour such as the movement of resources or quantities in a system over time, ABM capture micro-level system behaviour, such as human decision-making and heterogeneous interactions between humans. While use of SDM began in business management it now has wide spread application from engineering to economics, from environmental science to waste and recycling research. A SDM simulates the movement of entities in a system, using differential equations to model over time changes to system state variables. A stock and flow diagram can be used to provide a visual representation of a SDM, describing the relationships between system variables using stocks, rates and influencing factors. Often before the formulation of a stock and flow diagram, a causal loop diagram is constructed which can be thought of as a ‘mental model’ of the system, representing key dynamic hypotheses.

Unlike SDM, ABM is a ground-up representation of a system, simulating the changing states of individual ‘agents’ in a system rather than the broad entities or aggregate behaviour modelled in SDM. Aggregate system behaviour can however be inferred from ABM. Use of ABM to model system behaviour has been

transdisciplinary, with application in economics to ecology, from social sciences to engineering. There can be multiple types of agent modelled, each assigned their own characteristics and pattern of behaviour. Agents can learn from their own experiences, make decisions and perform actions based on set rules (e.g. heuristics), informed by their interactions with other agents, their own assigned attributes or based on their interaction with the modelled environment. The interactions between agents can result in three levels of communication between agents; one-to-one communication between agents, one-to-many communication between agents and one-to-location communication where an agent can influence other agents contained in a particular location.

Given the increasing amount of literature in this field, the main aim of the study was to examine and describe the use of SDM and ABM to model health systems. Although microsimulation, DES and Markov models have been widely used in disease health modelling and health economic evaluation, our aim in this study was to review the literature on mathematical methods which are used to model complex dynamic systems, SDM and ABM. These models represent two tenants of modelling: macroscopic (top-level) and microscopic (individual-level) approaches. Although microsimulation and DES are individual-based models like ABM, individuals in ABM are “active agents” i.e. decision-makers rather than “passive agents” which are the norm in microsimulation and DES models. Unlike Markov models which are essentially one-dimensional, unidirectional and linear, SDM are multi-dimensional, nonlinear with feedback mechanisms. We have therefore focussed our review on SDM and ABM because they are better suited to characterise the complexity of health systems. This study reviews the literature on the use of SDM and ABM in modelling health systems, and identifies and compares the key characteristics of both modelling approaches in unwrapping the complexity of health systems. In identifying and summarising this literature, this review will shed light on the types of health system research questions that these methods can be used to explore, and what they add to more traditional methods of health system research.

Djanatliev et al. developed a tool that could be used to assess the impact of new health technology on performance indicators such as patient health and projected cost of care. A modelling method that could reproduce detailed, high granularity system elements in addition to abstract, aggregate health system variables was sought and a hybrid SDM-ABM was selected. The tool nested an agent-based human decision- making module (regarding healthcare choices) within a system dynamics environment, simulating macro-level behaviour such as health care financing and population dynamics. A case study was presented to show the potential impact of Mobile Stroke Units (MSU) on patient morbidity in Berlin, where stroke diagnosis and therapy could be initiated quickly as opposed to standard care. The model structure was deemed credible after evaluation by experts, including doctors and health economists.

Of the six hybrid modelling papers, only Djanatliev et al. presented a model capable of both ABM and SDM simulation. The crucial macro- and micro- level activity captured in such models represent feedback in the wider, complex system while retaining the variable behaviour exhibited by those who access or deliver healthcare. With increasing software innovation and growing demand for multi-method modelling

in not only in healthcare research but in the wider research community, we need to increase their application to modelling health systems and progress towards the ‘holy grail’ of hybrid modelling.

Statistically-based models are usually used in quantitative data rich environments where model parameters are estimated through maximum likelihood or least-squares estimation methods. Bayesian methods can also be used to compare alternative statistical model structures. SDMs and ABMs on the other hand are not fitted to data observations in the traditional statistical sense. The data are used to inform model development. Both quantitative data and qualitative data (e.g. from interviews) can be used to inform the structure of the model and the parameters of the model. Furthermore, model structure and parameter values can also be elicited from expert opinion. This means that the nature of validation of ABMs and SDMs requires more scrutiny than that of other types of models.

We found numerous studies employing SDM and ABM methods to analyze health system behaviour, with a few employing hybrid model structures. These studies primarily focused on emergency and acute care, as well as elderly care and LTC services, examining the effects of various health policies and interventions on healthcare services and patient outcomes. While most studies concentrated on high- income countries, there's a call for more research in LMIC healthcare settings to assist policymakers and researchers. Although the use of hybrid models in healthcare is still relatively novel, the growing demand for models that can simulate both macro- and micro-level activities within health systems suggests a promising future for their adoption.

# References

1. Kitson A, Brook A, Harvey G, Jordan Z, Marshall R, O’Shea R, et al. Using Complexity and Network Concepts to Inform Healthcare Knowledge Translation. Int J Heal Policy Manag. 2017;7:231–43. https://doi.org/10.15171/ijhpm.2017.79.
2. Shepherd SP. A review of system dynamics models applied in transportation. Transp B Transp Dyn. 2014;2:83–105. https://doi.org/10.1080/21680566.2014.916236.
3. Kunc M, Mortenson MJ, Vidgen R. A computational literature review of the field of system dynamics from 1974 to 2017. J Simul. 2018;12:115–27. https://doi.org/10.1080/17477778.2018.1468950.
4. Yousefi M, Yousefi M, Fogliatto FS, Ferreira RPM, Kim JH. Simulating the behavior of patients who leave a public hospital emergency department without being seen by a physician: a cellular automaton and agent-based framework. Brazilian J Med Biol Res. 2018;51:e6961. https://doi.org/10.1590/1414-431X20176961.
5. Cassidy, R.; Singh, N.S.; Schiratti, P.R.; Semwanga, A.; Binyaruka, P.; Sachingongu, N.; Chama- Chiliba, C.M.; Chalabi, Z.; Borghi, J.;Blanchet, K. Mathematical modelling for health systems research: A systematic review of system dynamics and agent-basedmodels. BMC Health Serv. Res. 2019, 19, 845. https://doi.org/10.1186/s12913-019-4627-7.
6. Djanatliev A, German R, Kolominsky-Rabas P, Hofmann BM. Hybrid simulation with loosely coupled system dynamics and agent-based models for prospective health technology assessments: Proc. Winter Simul. Conf., Winter Simulation Conference; 2012. p. 69:1–69:12.