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SIMULATION OF EMERGENCY CARE SYSTEMS: A TAXONOMY AND FUTURE DIRECTIONS

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ABSTRACT

The Emergency Care System (ECS), comprising pre-hospital and in-hospital sub-systems, is a vital health infrastructure for round-the-clock life-saving care. The ECS is one of the most modelled parts of the health system. In the process of a comprehensive ongoing scoping review of ECS simulation using the methods of Discrete Event Simulation (DES), System Dynamics (SD), and Agent Based Modeling (ABM), we propose a method-agnostic simulation process framework, and use this framework to suggest Research Questions (RQs) that will provide a state-of-the-art view of ECS simulation. Our RQs and the resulting encoding approach guide us to a taxonomy of ECS simulation. This taxonomy addresses potential gaps in understanding the systemic nature of the ECS and its linkages to other parts of the health and social services system. It also helps to conceptualize the attributes of ECS simulation models that will help them to evolve to Digital Twins.

1 INTRODUCTION

The World Health Organization's Emergency Care System (ECS) framework encompasses essential care "at the scene of injury or illness, during transport, and through to emergency unit and early inpatient care" (World Health Organization 2023). The ECS consists of a pre-hospital subsystem (often referred to as Emergency Medical Services, or EMS), including dispatch centers and ambulance services, and an in-hospital system, comprising the Emergency Department (ED). As a system that provides life-saving care round the clock in addition to being a gateway to inpatient facilities, the ECS performs vital functions for society. ED congestion is seen as a "sentinel indicator of health system functioning" (Kelen et al. 2021).

The public importance, uncertainties and heterogeneities in demand arrival and service characteristics (queueing), and clear geospatial layout of the ED and EMS (Salmon et al. 2018), the threat posed by ED crowding (Vanbrabant et al. 2019), and the critical mission of the EMS (Aboueljinane et al. 2013) are among the reasons that simulation modeling of the ECS has a rich research tradition, with the ED being one of the most commonly modeled parts of the health system. The reports of the ISPOR Task Force on Dynamic Simulation Modeling Applications (Marshall et al. 2015a; Marshall et al. 2015b) emphasize that the dynamic simulation methods of Discrete Event Simulation (DES), System Dynamics (SD), and Agent Based Modeling (ABM) are suited to addressing the inherent complexity of health systems and the need to assess the upstream and downstream consequences of interactions.

The work presented in this paper arises from an ongoing scoping review of application of DES, SD, and ABM methods to the ECS. In this project, we will perform a full-text analysis of more than 650 articles on ECS simulation, following the Cochrane methodology (Armstrong et al. 2011). The study design is summarized in Table 1. Our literature search was conducted following the "SDMO" framework recommended for reviews of current research methods (Munn et al. 2018). In this paper, we present the Research Questions (RQs) and encoding dimensions of our ECS simulation scoping review, with the aim

of seeking feedback from researchers on these. Since we have based these RQs and encoding dimensions on our proposed method-agnostic simulation approaches, the resulting table of encoding dimensions serves as a taxonomy for ECS simulation.

Table 1: Design of Ongoing ECS Simulation Review

Study Design (S)	Simulation of the Emergency Care System and its components including pre-hospital and in-hospital sub-systems
Types of data (D)	Data based on observations, Electronic Health Records, benchmarks, etc. (no exclusions)
Types of methods (M)	DES, SD, ABM
Outcomes (O)	Quantitative metrics reflecting ECS utilization, time-based metrics, mortality, morbidity, etc. (no exclusions)

2 METHODS

Our approach towards the proposed taxonomy of ECS simulation studies consists of three stages. In the first stage we briefly review past reviews of ECS simulation to identify common themes, points of divergence, and gaps in the research. Secondly, we analyze the recommended frameworks for simulation modeling with DES, SD, and ABM to design a common method-agnostic modeling process framework. Finally, we frame research questions that we will seek to answer in our scoping review, so that the main gaps identified through our review of reviews are re-assessed, and every part of the modeling process framework is covered.

2.1 A Brief Review of Prior Reviews

Table 2 summarizes ten reviews of ECS simulation. These reviews focus either on the pre-hospital sub-system or the in-hospital sub-system. We were unable to find reviews that take a view across these two sub-systems. The common themes that recur across more than one of the reviews are: (i) There is a need to appreciate the linkages beyond the ED scope within the ECS, and consider the interactions of the ED with other parts of the health system; (ii) Performance measures are dominated by time-based measures and a wider set of outcome measures should be studied; (iii) The modeling process can be made more transparent, with better reporting on validation, verification, and actions taken; (iv) The perspective is dominated by crowding and a short-term planning focus.

Table 2: Summary of Previous ECS Simulation Reviews.

#	Authors Time-frame	Theme/ Review type	Methods included	Sub-system (No. of studies)	Main Findings	Directions for future research
1	Paul et al. (2010) 1970-2006	Simulation of ED over-crowding [Scoping review or intervention with/without Meta-analysis]	Simulation	ED (43)	• Studies are motivated by cost-control, efficiency, re-engineering and quality. • Patient categorization is based on arrival mode, acuity, and case type. • Scenarios tested are resource-related, process-	• Address human beliefs and behavior. • Study ED as part of larger system. • See the patient perspective

#	Authors Time-frame	Theme/ Review type	Methods included	Sub-system (No. of studies)	Main Findings	Directions for future research
					related, or environment-related	
2	Lim et al. (2012) 2000-2010	Mathematical modelling of ED waiting times	Analytical queueing models; DES, SD, ABM	ED (29)	• Waiting time reduction strategies can be grouped into scheduling, demand management, resource allocation, process improvement, others (e.g., layout).	• Simulation optimization
3	Abouelji nane et al. (2013) 1969-2013	Simulation in Emergency Medical Services	Simulation	EMS (number not stated)	• Greater attention on dimensioning and deployment of resources; short-term decisions • Performance measures focus on timeliness	• Multi-period and dynamic redeployment • Demand forecasting
4	Delgado et al. (2013) 1966-2012	Simulation of ambulance diversion	Simulation	EMS (10)	• Ambulance diversion has minimal effect on ED waiting time. • Improvements in ED operations reduce need for ambulance diversion	• Effect of ambulance diversion on ED throughput and hospital revenue
5	Gul and Guneri (2015) 1968-2013	Simulation of EDs	Simulation modelling	ED (106)	• Developing countries under-represented • Efficiency and service quality most common aims; LOS and waiting times most common KPI. • Case novelty dominates method novelty	• Multi-method modelling • Cost outcomes • Disaster situations • Networks of EDs
6	Mohiud-din et al. (2017) Until 2016	Simulation of patient flows within EDs in the United Kingdom	DES, SD, ABS, hybrid simulation, Monte Carlo simulation, distributed simulation or stochastic modelling.	ED (21)	• 19 studies used discrete event simulation and 2 used system dynamics models. • 16 studies centered on service redesign; 19 used waiting time or throughput time as key outcomes. • Weaknesses include lacks in awareness of system complexity, quality of data, and engagement of stakeholders	• Justification of modelling method • Avoidance of selective use of data • Increased engagement of stakeholders • Transparency • Reporting on the implementation of changes

#	Authors Time-frame	Theme/ Review type	Methods included	Sub-system (No. of studies)	Main Findings	Directions for future research
7	Salmon et al. (2018) 2000-2016	English language papers on simulation modelling of EDs	DES, SD, ABM or Monte Carlo simulation/ Markov Modelling	ED (254)	• Rate of publications increasing • Majority of projects appear to be of academic origin, based on DES, and operational. • Hybrid modelling and sponsorship from HC orgs may drive strategic outlook	• Greater effort in examining external linkages (e.g. GP, inpatient); measures of ability to cope.
8	Vanbrabant et al. (2019) Since 2000	KPIs and improvement options in ED simulation literature	Simulation	ED (107)	• KPIs are grouped into (i) qualitative (ii) time-related (iii) proportion (iii) utilization and productivity (iv) budget. • Improvement options are (i) input (ii) throughput (iii) output.	• Combination of KPIs in multi-objective way • Simultaneous introduction of improvements • Budget KPIs and simulation-optimization
9	Yousefi et al. (2020) 2007-2019	Simulation-based optimization in EDs	Simulation and optimization	ED (34)	• Objective functions include (i) LOS and boarding time (ii) expenses (iii) waiting time and crowding (iv) others. • Simulation duration is 12 hours to 365 days. • Arena the most common tool	• Focus on increasing the efficiency of multi-objective optimization problems by decreasing their cost in time and labor.
10	Doudareva and Carter (2022) 1990-2020	Validation methods in ED DES studies	DES	ED (90)	• 17 distinct metrics used for validation, including % LOS, throughput time, and time to triage. • Data-led validation and face validation are used; few studies report verification	• Validation decision tree proposed, based on level of data availability

2.2 A Framework for ECS Simulation Studies

In this section, we summarize the recommendations for sound modeling practice from thought leaders in DES, SD, and ABM and synthesize these recommendations into a framework for the simulation modeling process.

In the DES method, a sound simulation study (Law 2015) starts with formulating the problem and planning the study. Then, data collection and model definition are followed by a check that the assumptions

document is valid. The next steps are model construction and verification. Pilot runs help to confirm model validity. This is followed by experiment design and production runs, leading to outputs and use of results. Law (2015) emphasizes that this is an iterative and non-sequential process. From a validation and verification (V&V) perspective (Sargent 2010, 2020), simulation modelling can be viewed as a process in which system theories underpin the representation of the real world in a conceptual model. Such a model helps to frame the real-world and will readily undergo adaptation as we accept or reject hypotheses about the system. Fidelity of the simulation model to the real-world undergirding V&V comprises conceptual validation (model representation, structure, and logic are fit for purpose), operational validation (model outputs are accurate over the intended application domain), computerized model verification (the conceptual model is correctly coded and executed).

SD also reflects on the mapping of the real world to the simulated world. Mental models, defined as "the relationships and assumptions about a system held in a person's mind" (Ford 2019) of the real world are continuously updated by information feedback from the real world, and the results of the modelling process. It is the mental models of stakeholders that drive strategy and action, and the outcomes of actions "feed back" into the mental models (Sterman 2010). The modelling process, which runs through problem articulation and boundary selection, dynamic hypotheses, model formulation, testing, and policy formulation, is embedded in the dynamics of the system. If the model fails structure tests, structure-oriented behavior tests, or behavior pattern tests, the modeling team must revise the model (Barlas 1996).

ABM follows the "usual steps" of DES but addresses the "unique twists" dictated by individual agent's behaviors (Macal and North 2005, 2009); these include identifying the agents and their interactions, and linking micro-scale to macro-scale emergent behaviors. The essential stages of the modeling process can be viewed as model design, model building, and model examination (Wilensky and Rand 2015). Model design may be phenomena-based or exploratory. In top-down design, the approach followed is more aligned to the DES approach outlined above, in that a conceptual model is produced first before any coding is done. Bottom-up design is a more iterative process in which coding and model formulation progress in parallel. The ABM design principle is to start with the simplest set of agents and rules of behavior that allow modeling of the system.

The core ideas of the three methods are well aligned. Modeling is an iterative and cyclical process rather than a sequential one. The simulation model must be the simplest possible representation of the real world that is fit for purpose. It must be validated and verified. If it is successful, the modeling process influences the mental models of system stakeholders, leading to informed actions. Such actions produce changes in the real world, which should reflect in revised mental models of system stakeholders. Our proposed method-agnostic simulation process framework is shown in Figure 1. Simulation model design is the part of the process that creates a conceptual model, informed by the mental models of the stakeholders and modelers. Conceptual validation ensures that the designed model is faithful to the real world, for the problem at hand. The built computational model should be verified as an accurate implementation of the design. Running the model facilitates operational validation and model verification. The validated model brings new insight that further informs the mental models of stakeholders, including decision-makers. The actions that are taken impact the real work system. While DES literature emphasizes robustness, the SD literature highlights unintended consequences, and the ABM literature emphasizes emergence. In any case, the actions taken change the real world, and create a new reality for subsequent use of the model, whilst acknowledging the existence of volatility, uncertainty, complexity and ambiguity (Bennett and Lemoine 2014) particularly apparent in health systems globally (Pandit 2020).

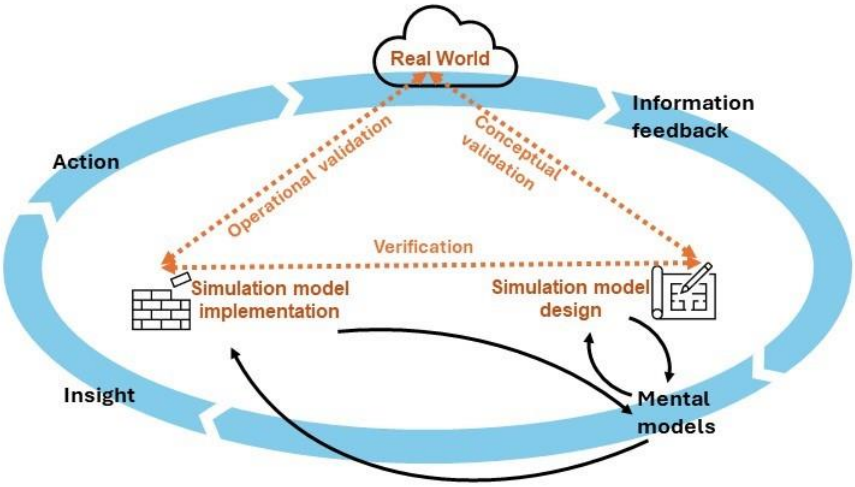

Figure 1: The Simulation Process.

2.3 Research Questions for the ECS simulation scoping review

We use the simulation process framework of Figure 1 to frame the Research Questions (RQs), summarized in Table 3, of our scoping review. While RQ1 and RQ2 relate to yearly trends and regional patterns, RQs 3 through 17 can be classified into simulation model design, V&V, and simulation model implementation stages of the simulation process.

2.3.1 Simulation Model Design

The RQs on simulation model design can be grouped into strategy and analytics RQs and ECS domain RQs. The strategy and analytics RQs are domain-agnostic, while the ECS domain RQs help to contextualize studies with respect to the concerns of ECS practitioners and researchers.

RQs 3 through 9 form the strategy and analytics group. RQ3 will allow us to uncover patterns in the research questions of the included ECS simulation studies through text analytics. RQs 4 through 6 address methods and tools. Our RQ 8 assesses whether the study is strategic, tactical, or operational, based on it planning horizon (Hans et al. 2011; Zeltyn et al. 2011). It is very common for simulation studies to refer to scenarios in their results. Being unable to find a taxonomy of simulation scenarios, we adapt a framework from futures research (Börjeson et al. 2006) for RQ8. RQ9 places the study in terms of analytics maturity (Delen and Zolbanin 2018; Lustig et al. 2010)

The ECS domain group comprises RQs 10 through 13. From a flow perspective, a study can focus on one or more of three debottlenecking approaches (Asplin et al. 2003). This is the subject of RQ10. RQ 11 and its sub-questions will help to discern how much research has been directed to a systemic issue that troubles the ECS: "The problem and therefore the solutions to ED crowding lie largely outside of the ED" (Morley et al. 2018). RQ12 provides a complete view of outcome measures, based on two earlier reviews (Aboueljinane et al. 2013; Vanbrabant et al. 2019), the well-established quadruple aim of healthcare (Bodenheimer and Sinsky 2014), and the domain knowledge of two co-authors (FJS and MO). Finally, RQ13 concerns patient categories: patient acuity and mode of arrival into the ED.

2.3.2 Validation and Verification

We use RQ14 to check the completeness of reporting on V&V (Sargent 2010, 2020). Data validation is considered a part of the four V&V steps listed.

2.3.3 Simulation Model Implementation

RQ15 assesses what types of sensitivity analyses were performed, i.e., changes in parameter value, probability distribution, simulated entity, or level of detail of sub-systems (Law 2015). RQ16 captures the extent to which policy actions are reported on, and RQ17 the extent to which models are put to repeated use and benefit from learning.

Table 3: Research Questions (RQs).

Stage	RQ	Question	Explanation and key ideas
--	RQ1	What are the longitudinal trends in ECS simulation research?	
--	RQ2	What are the regional patterns?	
Simula-tion model design	RQ3	What patterns are seen in the research questions addressed?	Text analytics will be applied to the stated research questions of the articles
	RQ4	Which simulation method(s) is/are used?	ABM, DES, and/or SD
	RQ5	What other methods are used in conjunction with simulation?	E.g., Machine Learning, Optimization
	RQ6	Which software tools are used?	E.g., Netlogo, Vensim, Arena…
	RQ7	What is the perspective of the study: Strategic, tactical, or operational?	Based on time horizon (Hans, Van Houdenhoven, and Hulshof 2011; Zeltyn et al. 2011)
	RQ8	What scenario types are considered?	Projections, explorative, or normative (Börjeson et al. 2006)
	RQ9	What is the analytics maturity level?	Descriptive, predictive, or prescriptive (Delen and Zolbanin 2018; Lustig et al. 2010)
	RQ10	Which patient flow aspects are studied?	Reducing input, increasing throughput, or increasing output (Asplin et al. 2003)
	RQ11	Which ECS sub-system(s) is (are) studied?	Prehospital (Call/ dispatch centre); pre-hospital (EMS); hospital?
	RQ11.1	To what extent are interactions between ECS sub-systems studied?	E.g., flow between ambulance system and ED
	RQ11.2	To what extent are multiple ECS systems studied?	E.g., networks of EDs
	RQ11.3	To what extent are interactions between ECS and other parts of the health system studied?	E.g., Primary care gaps and ECS use
	RQ12	What primary and secondary outcome variables are modelled?	Quadruple aim of healthcare (Bodenheimer and Sinsky 2014)
	RQ13	Which patient categories are studied?	Patient acuity, Mode of arrival
Validation and verification	RQ14	Which validation and verification types are reported on?	Conceptual model validation, specification verification, implementation verification, operational validation. (Sargent 2010, 2020)
Simulation model implemen-tation	RQ15	What type(s) of sensitivity analysis is (are) performed?	Changes in parameter value, probability distribution, simulated entity, level of detail of sub-systems (Law 2015).
	RQ16	Are the results of recommendations implementation reported?	

Stage	RQ	Question	Explanation and key ideas
	RQ17	Does the study feature use of a previously developed, validated, and verified model?	

3 RESULTS

Table 4, based on the RQs of Section 2.3, describes our proposed process-based taxonomy of ECS simulation studies. For some dimensions, we enumerate items to the best of our knowledge, and leave an "Others" item. The table below is the basis for our encoding guide, which will be used for the analysis of studies included in our scoping review. The encoding guide is available to researchers upon request.

Table 4: Proposed Taxonomy for ECS Simulation Studies.

Code	RQ	Dimension	Elements
A	RQ1	Year of publication	--
B	RQ2	Country of study setting	--
C	RQ3	Research questions/ aims	(Free text field)
D	RQ4	Simulation method	SD/DES/ABM
E	RQ5	Other methods used	Other methods used in conjunction with SD/DES/ABM
F	RQ6	Software tool(s)	--
G	RQ7	Time horizon of results	--
H1	RQ8	Scenario type(s)	Projections: Business As Usual
H2			Projections: Fundamental changes
H3			Explorative: External
H4			Explorative: Strategic
H5			Normative: Preserving
H6			Normative: Transforming
I1	RQ9	Analytics maturity	Descriptive
I2			Predictive
I3			Prescriptive
J1	RQ10	Flow orientation	Input
J2			Throughput
J3			Output
K01	RQ11	Sub-system(s) studied	Dispatch Centre/ Call centre
K02			Ambulance fleet
K03			ED
K04			Inpatient care, including ICU
K05			Outpatient care
K06			Primary care
K07			Others not included in 1-6
K08		Single or Multiple Hospital/ Single or Multiple EMS	Single or Multiple Hospital/ Single or Multiple EMS
L1.1	RQ12	Outcome measures – time	Response time
L1.2			Waiting time
L1.3			Length of Stay

Code	RQ	Dimension	Elements
L1.4			Door to doctor time
L1.5			Other time-based measure
L2.1		Outcome measures - human resource	Doctors
L2.2			Nurses
L2.3			Ambulance crew
L2.4			Dispatchers
L2.5			Other health professionals
L3.1		Outcome measures - physical resource	Ambulances
L3.2			Observation beds
L3.3			Triage rooms
L3.4			Registration desks
L3.5			Imaging facilities
L3.6			Other diagnostic facilities
L3.7			Other physical resources
L4		Outcome measures - quadruple aim	Health outcomes
L5			Cost
L6			Patient satisfaction
L7			Provider satisfaction
L8		Outcome measures – other	Outcome measures not included above
M1	RQ13	Patient categorization	Acuity
M2			Mode of arrival
M3			Other
N1	RQ14	Validation and verification	Conceptual model validation
N2			Specification verification
N3			Implementation verification
N4			Operational validation
O1	RQ15	Sensitivity analysis	Parameter value(s)
O2			Probability distribution(s)
O3			Simulated entities
O4			Level of detail of different sub-systems
O5			Other
P	RQ16	Action taken	Whether reported or not
Q	RQ17	Use of an existing, validated, verified model?	Yes/ No

4 DISCUSSION

Though the ECS is the part of the health system that is most studied through simulation, a complete taxonomy of ECS simulation studies, spanning the different parts of the ECS and taking an inclusive view of its linkages with other sub-systems, is missing prior to this work.

The dimensioning shown in Table 4 is meant to be collectively exhaustive, yet not unduly focused on mutual exclusivity across concepts. This approach will help to extract a richer picture of overlaps and patterns in the studies since the dimensions are not orthogonal by design. For example, we expect that there will be associations between analytics maturity and scenario type, or patient acuity (Table 4, code M1) and

patient arrival mode (M2). Associations across dimensions and the methods used may also exhibit trends over time.

Each ECS itself is a critical societal resource, with interdependencies between the pre-hospital and in-hospital parts. ECS are connected in networks; the phenomenon of ambulance diversion is an anecdotal reminder of these connections. Moreover, ECS are also tightly linked to the other parts of the hospital and health system; inappropriate use of ECS is driven by gaps in other sub-systems (e.g., primary and community care), exit block in ECS is driven by gaps in inpatient capacity. Reattendances in ECS may be driven by gaps in both ECS and inpatient care. The proposed taxonomy will help to establish the extent to which studies have accounted for these interdependencies.

The range of outcome measures included will help to assess weaknesses in system modelling practice and to provide directions. The Quadruple Aim (Bodenheimer and Sinsky 2014) is well enshrined in health policy research as a set of objectives that are all important and need to be assessed from the point of view of unintended consequences – does an achievement of a narrow outcome, e.g., waiting time, conflict with another, e.g. patient satisfaction? Simulation modelling is well suited to address such trade-offs. Further, reporting on the outcomes brought about in the real world by simulation studies, assessing the patient perspective, and modeling the interactions between ECS sub-systems and other health and social sub-systems are important gaps in the earlier published research (See Table 2). Our scoping review will provide an updated view of these gaps.

Reporting on the use of existing, validated and verified models has a bearing on the future use of Digital Twins (DT) in ECS. The originators of the idea of the DT (Grieves and Vickers 2017) suggest that it "started off relatively sparse as a CAD description" (CAD refers to Computer Aided Design) and has recently evolved to actionability. Simulation is an enabler of DT (Biller et al. 2022), but there are other components – chiefly synchronization between the digital and physical twin throughout the life cycle of the physical twin, enabling "active learning" – that need to be added before a simulation can become a DT (Taylor et al. 2021). Figure 2 is our depiction of the idea of active learning. Thus, the need to synchronize ECS simulation models to the real world is fundamental if they are to be true digital twins. Beginnings have been made in this area (Bouleux 2023), but ECS researchers will need to account for the sociotechnical aspects of ECS, as opposed to the engineering systems in which the DT concept originated. This appears to be an important area of future research, but as a first step, more research is needed on the continued use and adaptation of ECS simulation after the initial phase of model development.

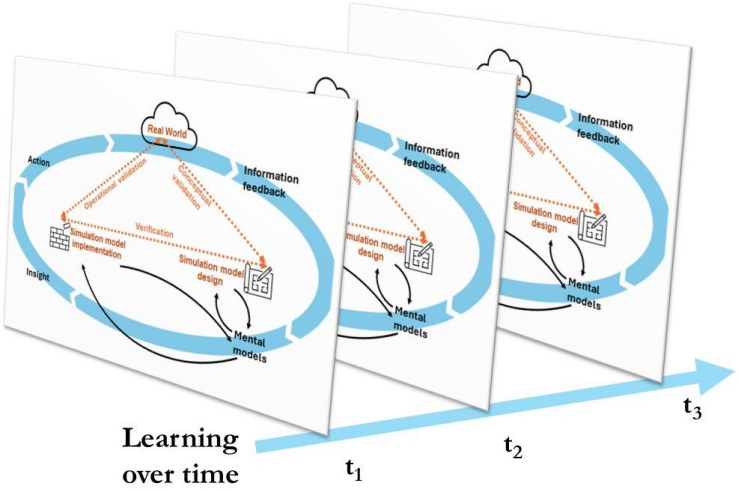

Figure 2: Model use over time.

5 CONCLUSION

Though ECS simulation has a rich research tradition, we believe that our scoping review, being grounded in the ECS simulation process framework and executed by a team including emergency medicine clinicians, will refresh and expand on the previous separate reviews of pre-hospital and in-hospital emergency service simulation reviews. We seek feedback on our approach through this paper and by making our encoding guide available on request, we believe that we foster collaboration among researchers and clinicians to advance the state of the art of ECS simulation.

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