A Multi-Paradigm Modelling & Simulation Approach for System of Systems Engineering: A Case Study

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Abstract - *The process of modelling and simulation (M&S) plays a critical role in system of systems (SoS) engineering, given its ability to capture and visualize the dynamic nature embedded within SoS complexity. While there are multiple M&S paradigms, currently there is limited guidance for selecting the most appropriate one(s) based on the intention of the SoS modeller, which can manifest itself through different "views" of the SoS. This paper examines three such views—social, physical, and socio-physical—and suggests an approach for matching each view with the most-suitable paradigm(s) in order to better represent the modeller's intention. A real-life case study of an emergency-response situation is presented to demonstrate the applicability of the introduced approach.*

Keywords: Modelling and simulation, system of systems, socio-physical view, agent-based simulation, discrete-event simulation, system dynamics, multi-paradigm approach.

1 Introduction

Given the rapid technological progress over the last decades across multiple disciplines, a continuously increasing number of systems interconnect in their functionality and purpose. Today, it is uncommon to see an isolated, stand-alone system, whereas the growing interdependency of such systems contributes to an ever-emerging complexity. Often, these systems do not only interface, but also share one unified goal, and such systems are referred to as system of systems (SoS). One present challenge in SoS engineering (SoSE) is how to study these systems' complexity proactively rather than reactively—that is, before something goes wrong that necessitates an examination of the SoS [1]. In this endeavour, modelling and simulation (M&S) methods show promise [2,3].

M&S is crucial in the design, development, and governance of SoSs, offering a mechanism to represent both their constituent systems and their dynamics [4]. While several M&S paradigms have been proposed and are currently used (e.g., discrete event, system dynamics, and agent-based simulation), there is no clear selection mechanism for choosing an appropriate paradigm or combination of paradigms. This process will depend on the modeller's intention in creating the simulation model—for example, is it to investigate the whole SoS or only a specific subset? Presently, M&S is also more art than science: all models are wrong, but some are useful [5]. It is in finding useful models of complexity that this paper finds its motivation. This paper proposes an approach for selecting the best M&S paradigm(s) based on the specific view taken of an SoS's architecture, which matches the characteristics of the paradigm with the inherent purpose of the view. This new approach is illustrated through its application on an emergency response and preparedness case study. In such domains, M&S can play a vital role in creating a model a priori that can be used to identify and address the weakest link, either before an incident/disaster, as part of preparedness, or during, as part of response [6]. It is critical in emergency response that a holistic picture of the SoS be taken, which perspective should also extend to emergency response's M&S practices. As such, it is important to identify and model not only the SoS's constituents, but also the interactions between them, for it is at these interfaces that complexity is created with all of its ensuing challenges [7]. The remainder of the paper is organized as follows. In the next section, a case study is presented, which will be used throughout the paper as a running example. Section 3 explores three different views of an SoS: social, physical, and socio-physical. Section 4 considers three prominent M&S paradigms that are matched in Section 5 to the SoS views described in Section 3. Section 6 revisits the case study and applies the proposed approach to an important subset of the case. Finally, Section 7 concludes the paper and offers direction for future work.

2 Case Study: A Steam Incident at a Major Canadian University

The real-world incident referred to below is not synthetic; however, for reasons of confidentiality, the description does not disclose the exact location or date when the events took place. The critical steam incident, which occurred within the past decade at a major Canadian university, initially appears innocuous, but it serves to demonstrate the complex nature of SoSs, where localized events can rapidly lead to systemic consequences.

At approximately 10:20 a.m. in early December, routine repairs at a university steam plant resulted in a water-hammer explosion (which is caused when steam comes in contact with water in the pipes). A simultaneous combination of factors including a drop in water supplied by the city and a leak in the pipes led to the explosion that ruptured the boiler releasing steam into the plant and requiring an evacuation of the immediate area. Plant operations were halted, and following a safety inspection by the local fire department, repairs to the system began shortly after 11:00 a.m., ultimately restoring normal steam levels by 5:30 p.m. The steam produced by the plant is used to heat the various buildings within the university campus. This includes the university hospital, which is not managed directly by the university, and that further uses the steam to sterilize equipment and bedding. As a result of the explosion and due to the cooler December weather, temperatures in campus buildings decreased, forcing the hospital to consider evacuating patients to the network of nearby city hospitals. While the evacuation was eventually determined not to be necessary, emergency measures within the various hospitals, as well as the city, had begun preparing for the potential transportation and reception of evacuated patients. These actions affected not only the city's transportation service, which began mobilizing buses to assist in the evacuation, but also the services within nearby hospitals, which had to cancel and postpone surgeries, the consequences of which lasted several days. The interdependency between the university steam plant and the hospital network was identified as a critical factor. However, it was not identified prior to the incident (i.e., proactively), only reactively, as a result of the incident having occurred. Because of the various unforeseen consequences and the potential for major disruption, this incident can be considered critical; it was only because other boilers could be rerouted that the incident was not more severe. This case reflects the importance of having a holistic awareness in emergency response of the SoS-of-interest a priori, and this can be supported through the use of M&S technology.

3 Three SoS Views

Partitioning is a necessary step for specifying a boundary around an SoS and for describing its complexity [8]. This is used to take what exists in the real world and encode it into a computer simulation. There are many different ways in which a system, in general, can be partitioned, which apply to SoSs as well. One natural partitioning is to consider the SoS from the social and/or physical perspective [6], and these three views—the social, physical, and socio-physical—are described below in the context of the case study.

Social View: Systems (or nodes) corresponding to the "social" view, along with the interactions between these nodes, represent one SoS partition. In this paper, social refers to the individuals within the SoS and how they interact—be it through formal, organizational policy or informal, social norms. Fig. 1 shows a portion of this view involving the most critical social nodes within the university case study. It includes the students, teachers, hospital staff, and patients, as well as the interactions between them using directed edges (bolded end represents the arrow). For example, an interaction between hospital staff and patients is "hospital staff *provides treatment to* patients." (Note that due to space limitations, these relationship labellings have been omitted from the figure.)

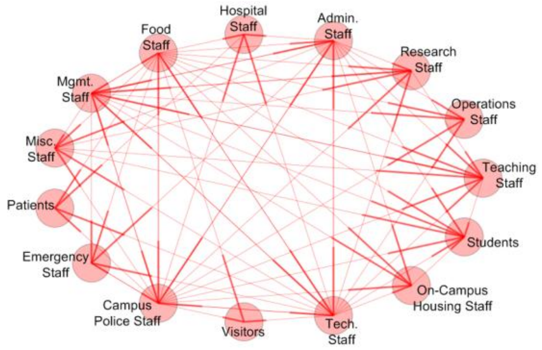

Figure 1. Partial social view of the university SoS.

Physical View: On the other hand, systems (or nodes) corresponding to the "physical" view (i.e., the remaining nodes), along with their interactions, represent another SoS partition. Physical refers to the geography and structure of the SoS (e.g., buildings and roads), which pertain mainly to engineered systems—as is the case with the "technical" in socio-technical [9]. However, in contrast, the physical view can also include natural physical phenomena, in addition to organization-related systems, which are highly relevant in emergency response and have been extensively modelled [10], such as the spread of smoke plumes and fire. Fig. 2 shows a portion of the physical view nodes within the university SoS. This includes all the "critical infrastructure" nodes, as well as their interactions. For example, "electricity *provides power to* steam plant." With respect to the teaching system and research system, these correspond to the various classrooms and laboratories within the campus.

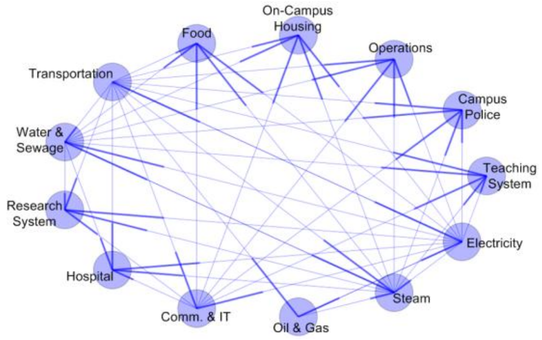

Figure 2. Partial physical view of the university SoS.

Socio-Physical View: Lastly, these two views, the social and physical, along with their interactions, and those interactions between the views when considered together, comprise the third SoS view: the "socio-physical" view. This represents a more comprehensive view of the SoS and inherently seeks to examine questions related to the interaction between humans and their environment. Whereas the social view might be considered mostly by social scientists and the physical view by engineers and (traditional) emergency response M&S practices, the socio-physical view is very much that view taken by modellers interested in socio-technical research [11].

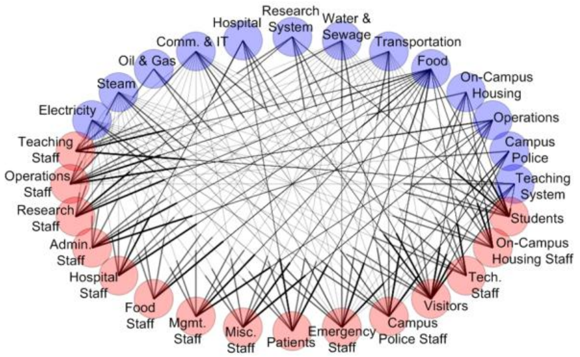

Figure 3. Partial socio-physical view of the university SoS.

Fig. 3 shows the social and physical nodes together in one network for the university SoS, along with the interactions between these two classes of nodes. In reality, all nodes and interactions are accounted for in this combined view, though for clarity the intra-view interactions of the social-to-social and physical-to-physical nodes have been omitted from the figure. Once again, interactions take the form **Node A** *provides* [some service] *to* **Node B** using directed edges. For example, "the hospital *provides facilities to* hospital staff"; and it is known from Fig. 2 that electricity, water & sewage, and steam (among other nodes) provide specific services to the hospital. All such interactions are considered in this view.

4 Modelling & Simulation Paradigms

As discussed in the introduction, the goal of this paper is to map the relevant M&S paradigm(s) to a particular SoS view based on the similarity of their inherent properties. In this section, the three main paradigms for modelling and simulation are described: discrete-event simulation, system dynamics, and agent-based modelling [5,12].

Discrete-Event Simulation: First established as a simulation technique at IBM in the 1960s, this paradigm is characterized by its use of flowcharts to control how entities (i.e., resources) move through the system [5,12]. While its representation is static, its inputs can be randomized to explore the effect of various perturbations on the system. It is well-suited to a variety of domains, including manufacturing, logistics, and business process modelling [12], and due to its flowchart-like design, it is easily understandable and is particularly useful as a performance analysis tool for identifying process bottlenecks and collecting statistics on process performance [5]. The main drawback is its inability to adapt its structure at runtime, which makes it useful only when the governing rules in the flowchart blocks are known in advance [12]. Moreover, the entities are described as passive objects with no autonomy, simply following a process, which results in limited capabilities to adapt and learn [5,12].

System Dynamics: System dynamics, developed by Jay Forrester at MIT in the late 1950s, is characterized by stocks, representing the items moving in the system (e.g., knowledge, people, or money), and flows, representing the interconnections between the stocks [5,12]. In addition, the causal diagram depicting the stocks and flows also shows the causal variables that influence the flows and any delays associated with these variables [5]. The power of this paradigm is in its ability to abstract from the effect of a single entity and focus on the aggregate effect (i.e., on the global structural dependencies) [12]. Thus, the impact of various policies on the system, for example, can be examined. The main drawback of system dynamics is its difficulty in modelling low-level systems because it focuses on modelling the high-level structure of a system using aggregate items [12]. Further, since the flows describing the causal dependencies in the system must be expressed mathematically, the modeller must have a firm grasp of the mathematics underlying these relationships [5]. However, this is becoming increasingly less of an issue as some software tools (e.g., VenSim) automatically generate the equations based on the diagram created by the modeller [5].

Agent-Based Modelling: Agent-based modelling is composed of agents that are autonomous with their own internal set of rules that govern their behaviour. This behaviour can be both reactive (e.g., responding to an event) and proactive (e.g., pursuing a goal). The value of this paradigm is that from the behaviour defined at the individual level, global behaviour emerges, which is only observable during runtime [5], and unlike the other two paradigms presented which focus on either the lower-level or higher-level aspects of the system, agent-based modelling can span the entire spectrum of abstraction [12]. Because heterogeneous agents can be added to the system and modelled individually, multi-agent systems have been gaining acceptance in the social science community. In fact, varying internal agent rules during simulation can emulate and even increase understanding of social phenomena [13]. The main drawback is that, for modelling routine and deterministic processes, agent-based modelling may require more effort than other paradigms [5]. Also, it is difficult to verify and validate the emerging behaviour of the model, which makes the deterministic nature of discrete-event simulation and the mathematical rigour of system dynamics appealing [5]. Nevertheless, this method provides increased flexibility in that specific interactions between system constituents are not required to be specified (or even known) ahead of time. Instead, an agent can respond to other agents or objects in the environment based on its internal rules, which may be very general.

5 A Multi-Paradigm Approach for the Modelling & Simulation of SoS Views

Having reviewed the three M&S paradigms, it is time to consider how these can be used to model and simulate the SoS views outlined in Section III. The underlying thesis is that these paradigms can be matched to the three views by virtue of their shared inherent properties. In doing so, it is expected that a more accurate representation of the SoS can be achieved based on the modeller's intention as the selected paradigm(s) will be better able to capture the specific characteristics of a particular view than will the other paradigm(s).

Social M&S Paradigms: Recall that the social view is characterized by decentralized, heterogeneous entities, and bottom-up/emergent behaviour (i.e., human social interaction). Of the three M&S paradigms considered, the agent-based simulation approach is the closest match. It is well-suited for capturing the dynamic nature of social interaction and the effect of individual behaviour on the SoS [13]. The discrete-event simulation approach is limited as its structure cannot be changed at runtime, while the system dynamics approach finds its limitation in not being able to represent individual entities. However, if only system-level attributes are being considered (and this is the explicit intention of the modeller), then system dynamics can be used for this view provided all important interactions are known. Thus, for the purely social view, the modeller can use either the agent-based or system dynamics paradigm; the latter focuses on the top-down, system-level, while the former focuses on the bottom-up, individual level.

Physical M&S Paradigms: The physical view relates most closely with engineered systems. In contrast to the other views, it is generally characterized by a more centralized, top-down organization of SoS constituents, where the discrete-event simulation paradigm is the closest representational match. It is appropriate for engineered systems, with known constituent inputs, normally fixed structure, and generally passive objectives, which are all characteristic of the physical view. The system dynamics paradigm suffers from an inability to represent low-level system entities, while the agent-based approach may require unnecessary effort when considering deterministic physical constituents (it is more suited to autonomous entities), in addition to being difficult to validate. It is our contention that with engineered systems being able to verify and validate system properties is a key benefit that should not be ignored. However, in cases where the physical constituents have different properties—for example, in a decentralized, prosumer energy SoS—rules can be used to describe the dynamic interactions between entities using an agent-based approach. Thus, for the purely physical view, there are two possible paradigms that can be used to model the entities and interactions of the constituents of interest: either discrete-event simulation or agent-based modelling.

Socio-Physical M&S Paradigms: When both the social and physical views, along with their intra- and inter-view interactions, are considered, there is an inherent requirement that all levels of the system be represented—from low-level to system-level. Agent-based modelling is the only single paradigm presented that is able to satisfy this requirement, as it is the only valid paradigm for both the social and physical views in isolation. If instead multiple M&S paradigms are considered, then different combinations exist. For example, the physical view could be modelled using a discrete-event simulation and then "wrapped" within an agent model that could subsequently interact with the other social agent models. In this case, the inter-view interactions between physical and social constituents (i.e., the socio-physical interface) would be represented using an agent-based model. Alternatively, a system dynamics model could also be used to represent this interface: system dynamics is well-suited to high-level modelling, which can include both social and physical constituents provided the system-level interactions are known in advance. In contrast, discrete-event simulation would not be applicable in this context, as this interface requires the ability to model both high-level, deterministic and high-level, non-deterministic interactions, neither of which is characteristic of discrete-event simulation. Therefore, for the combined socio-physical view, the modeller can choose agent-based modelling—if only a single paradigm is being implemented—or a combination of paradigms—if a multi-paradigm approach is being implemented. However, in the case of the latter, the paradigm for the social and physical view must be suited to that view and the socio-physical interface must be represented by either agent-based modelling or system dynamics. Which combination of paradigms is most appropriate can be argued to be case-specific, as different modellers will have different intentions.

6 Revisiting the Case Study: Applying the Multi-Paradigm M&S Approach

This section considers an important subset of the case study that proved critical on the day of the incident: the interaction between steam and the hospital staff and patients. Here the modeller will be interested in the following: for the social view, the attributes of individual patients and hospital staff; for the physical view, the engineered systems, which, in this case, exhibit known/deterministic interactions; and for the socio-physical interface, the aggregated, system-level interaction between the steam (physical view) and the social view. Accordingly, the three M&S paradigms described above will be used to model the social, physical, and socio-physical-interface partitions of the SoS to achieve a single multi-paradigm simulation.

Social Agent-Based Model: Because the modeller is interested in individual attributes and because the interactivities at a given time within the social level are unknown, the modeller should select the agent-based modelling paradigm for this partition. Fig. 4 shows a possible multi-agent model having two agent types, with the first providing a service to the second (directed edge). The first type is the hospital staff agent, whose key activities include the following: treating the patient, which itself can include a subset of activities, such as walking to the patient's room, examining the medical chart, and assessing the patient's vitals; waiting (e.g., when steam prevents certain treatments from taking place); and ordering the evacuation, which would involve assessing suitable evacuation sites, patient health projections, and the means available to carry out an evacuation. The second type is the patient agent, whose primary activities include recover—a response to the hospital staff's treatment, hospital conditions, and the passage of time—and whose main attributes includes the current health level of the agent, which can be accessed by the hospital staff. Importantly, each agent type can have multiple instantiations, and while each would share the same activities and attributes, the values of the attributes can be modified, thus enabling each agent to represent a distinct individual.

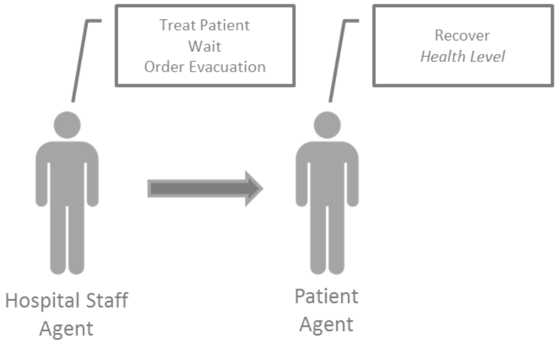

Figure 4. Key agent activities and properties (italicized).

Physical Discrete-Event Model: For this partition, the modeller is interested in engineered systems with known interactions. As such, the discrete-event simulation paradigm should be used, which would satisfy all the model requirements, in addition to facilitating verification and validation of the model. Fig. 5 shows a portion of the university SoS physical model for a specific moment in time. It captures the major systems of interest: water & sewage, along with its pipes and distribution points; the steam plant, along with its pipes and distribution points; the hospital, which is receiving both water and steam in this snapshot (blue and grey lines); the research and teaching systems, which are receiving only water (the input lines from the steam plant are empty); and, lastly, the on-campus housing system, which is also receiving both water and steam. In addition, three external factors are shown in the model. The first relates to water supplied by the city, which impacts the university water & sewage system and, consequently, the output of the university steam plant. The two other factors—room availability in city hospitals and city ambulance and bus availability—refer to physical realities which can be taken into account by the hospital staff agents when determining whether or not to proceed with the university hospital evacuation. The logic for the physical model (which is not shown in the figure) results in decreased steam output when the water supplied by the city remains sufficiently low for a sufficient amount of time that the water supply on campus (including within the water & sewage system's reservoir) is unable to satisfy the water demand of the steam plant.

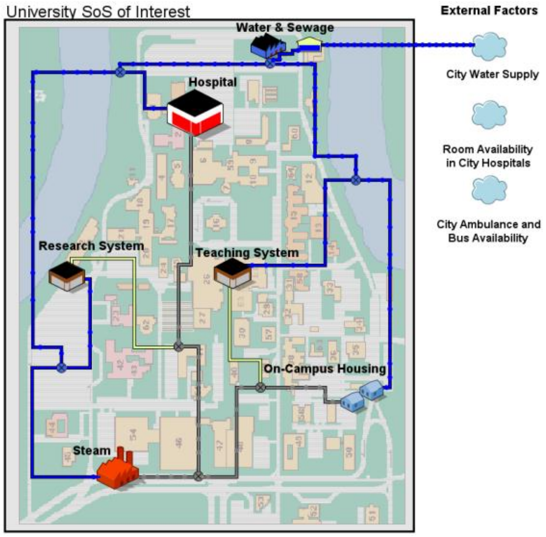

Figure 5. A screenshot of the SoS-of-interest showing key physical constituents and external factors, governed by discrete-event simulation.

Socio-Physical (Interface) System Dynamics Model: For the socio-physical interface partition, the modeller is interested in examining known system-level interactions between the physical and social constituents. As such, the system dynamics paradigm is most-suited for this intention. Fig. 6 depicts a system dynamics model, showing how the amount of steam within the hospital can impact both the hospital staff treatment and health level of the patients. As shown in the model, the rate of incoming steam is positively correlated ("+") with the amount of steam entering the hospital, which in turn affects the sterilization process, as well as hospital staff treatment (both indirectly through providing access to more sterilized resources and directly by providing better conditions—i.e., sufficient warmth in winter). Together with the natural healing rate of the patient, these factors work to increase patient health. However, a decrease in hospital steam level, which is reduced within the hospital by both its sterilization and heating requirements—the larger the building ("+") and the lower the external temperature ("-"), the greater the heating requirement—will reduce (if this demand is not matched by the rate of incoming steam) hospital staff treatment, affecting patient health oppositely to that described above, in addition to failing to reduce patient health condition severity, which contributes to the declining health of patients. The interaction dynamics within this model are considered at the system-level; however, the results of these interactions can be included within the agent-based model to affect individual hospital staff and patient agents. For example, if patient health at the system-level is decreasing, this may contribute to a reduction in recovery by the patient agents (and to differing degrees based on individual attribute values). This in turn will impact the amount of time hospital staff agents must treat patient agents. With the help of recent advances in simulation software, such multi-paradigm simulations can be created using a single tool (e.g., AnyLogic) or a combination of software tools, enabling the modeller not only to use the most appropriate M&S paradigm(s) for different SoS partitions, but also to combine them into a single simulation.

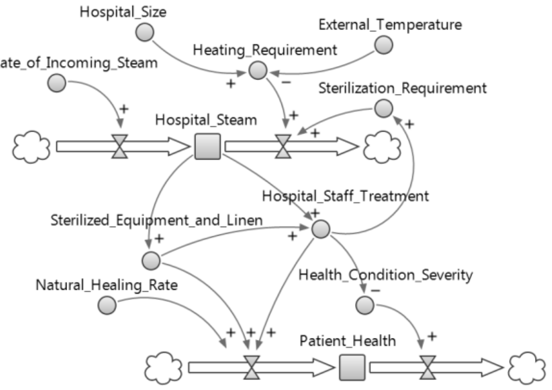

Figure 6. A system dynamics model of a possible interface between the physical view (hospital steam stock) and social view (patient health stock).

7 Conclusion and Future Work

Using computer simulation offers promise in assisting researchers and practitioners in being better able to represent, explore, and understand the complexities inherent within SoSE. In this paper, it was argued that different M&S paradigms are better suited to specific SoS views by virtue of their shared characteristics. Moreover, it was shown how naturally the different paradigms—agent-based modelling, discrete-event simulation, and system dynamics—correspond to the different views—social, physical, and socio-physical. This may be because the paradigms were developed in isolation to investigate different aspects of the SoS: agent-based for the social, autonomous aspects; discrete-event for the engineered, deterministic aspects; and system dynamics for the known, system-level aspects. Arguably, in applying multiple M&S paradigms, the SoS can be better represented and, thereby, investigated when these models are synergistically combined into a single simulation. Such efforts can assist many domains, including assisting emergency response and preparedness in more proactively preparing for potential incidents and disasters. As part of future work, the application of different combinations of M&S paradigms to additional SoS case studies will be considered to further explore the benefits and limitations of applying a multi-paradigm M&S approach to SoSE research.

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