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A framework for model integration and holistic modelling of socio-technical systems

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A B S T R A C T

This paper presents a layered framework for the purposes of integrating different socio-technical systems (STS) models and perspectives into a whole-of-systems model. Holistic modelling plays a critical role in the engineering of STS due to the interplay between social and technical elements within these systems and resulting emergent behaviour.

The framework decomposes STS models into components, where each component is either a static object, dynamic object or behavioural object. Based on existing literature, a classification of the different elements that make up STS, whether it be a social, technical or a natural environment element, is developed; each object can in turn be classified according to the STS elements it represents. Using the proposed framework, it is possible to systematically decompose models to an extent such that points of interface can be identified and the contextual factors required in transforming the component of one model to interface into another are obtained.

Using an airport inbound passenger facilitation process as a case study socio-technical system, three different models are analysed: a Business Process Modelling Notation (BPMN) model, Hybrid Queue-based Bayesian Network (HQBN) model and an Agent Based Model (ABM). It is found that the framework enables the modeller to identify non-trivial interface points such as between the spatial interactions of an ABM and the causal reasoning of a HQBN, and between the process activity representation of a BPMN and simulated behavioural performance in a HQBN. Such a framework is a necessary enabler in order to integrate different modelling approaches in understanding and managing STS.

1. Introduction

The task of modelling modern socio-technical systems (STS) such as transportation systems, organisational systems and energy infrastructure systems is challenging due to the complex nature of these systems. This complexity stems from the interactions and interdependencies between a diverse range of social, technical and contextual elements in and around the system [1,2]. However, modelling plays an essential role in STS engineering and providing decision support as part of the design, operation and evolution of STS [3]. Even though individual models of STS and specific STS elements are well developed, integration of the different perspectives in a holistic model is a significant research challenge [2,4–6]. Specifically, an understanding of the relationships between different STS elements and how they can be captured by different modelling methodologies is essential to the development and application of holistic models that capture the different perspectives, interdependencies and ultimately the emergent behaviour of STS. Understanding emergent behaviour is integral for decision makers in the STS context.

One of the difficulties of STS modelling lies in the interdisciplinary nature of STS and the lack of consensus on issues such as the definition of STS across the different fields [3,7]. First coined by Emery in 1960 [8], STS are characterised by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society [9]. The interaction and interdependency between social and technical systems on a large scale are a discerning feature of STS [9,1,10]. Also referred to in some fields as engineering systems [9] or Complex Large-scale Integrated Open Systems (CLIOS) [11], STS need actors and some social/institutional infrastructure to be in place in order to perform their function [12]. Critical infrastructures, such as the national electricity grid, oil and gas systems, telecommunication and information networks, transportation networks, water, banking and financial systems, agriculture and food systems, and public health networks, are examples of STS [2,12].

For many real world systems, it is necessary to adopt STS approaches rather than traditional systems engineering approaches due to the interplay between the social and technical elements. It is argued that due to the human dimension of STS, existing systems engineering approaches such as IEEE 1220/ISO 15,288 are inadequate for STS [12,13]. In traditional systems engineering, humans are represented exclusively

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as fulfilling sub-functions and the social dimension (such as regulations, laws and procedures) is often ignored. A failure to incorporate social effects tends to result in unstable requirements, and poor systems design and user interfaces, thus incurring project delays and unmatched expectations [3,7]. It is argued that the human aspect is more expansive and complex than hard technologies and thus requires greater investment of time and resources in order to manage reliably (and have greater public trust) [10,14].

In addition, STS are not necessarily amenable to the reductionist approach of systems engineering due to the existence of complex relationships between system components and interdependencies [9]. Although the system can be viewed in terms of its constituent components, their interaction is non-linear, which undermines the ability to decompose the problem and specify requirements ahead of time as required in systems engineering [6]. Such non-linear interactions and dependencies lead to emergent behaviour, self-organisation, and adaptation (the system has memory) [6]. As a result, holistic modelling is necessary as modelling parts of the system in isolation is not only impractical, but often also irrational.

Modelling and simulation of STS, especially infrastructure systems, are essential to help enable stakeholders to: (i) find downstream consequences of loss events and identify the risks and vulnerabilities, (ii) predict system behaviour for extreme and rare events, (iii) assist decision making and policy development, (iv) help develop, test and validate infrastructure protection strategies, (v) perform what-if analysis, and (vi) support training via modelling and simulation [15].

However, the task of modelling STS is challenging due to the complex nature of the problem domain. There are many different dimensions to STS such as economic, legal and regulatory, technical, security and social dimensions [2]. De Rosa [6] argues, based on Ashby's law of requisite variety [16] and Bar Yam's mathematical proof [17], that the complexity of the STS requires a corresponding level of complexity in the approach and hence in the model. Therefore, it is necessary to integrate different models to capture STS as a whole. Although existing models of individual elements of STS exist, integration of these models to obtain a whole-of-system perspective is in itself challenging as it is not possible to hook-together different models [2]. In order to meet the requirements for STS engineering, it is necessary to have a holistic model that captures whole-of-system effects, and especially system interdependencies [15]. Adapting and integrating one or more existing methods to develop a holistic model is a current research challenge [3].

This paper presents a framework that categorises the different elements of STS and provides a method for drawing relationships between them to enable holistic modelling. Using the framework, a case study is developed for an airport passenger terminal socio-technical system that evaluates and integrates three different models into a holistic model. The passenger facilitation process is particularly representative of STS due to the diversity of stakeholders involved in a process with regulatory, security, business economic and time based operational constraints and objectives [18]. Such a model is integral in understanding emergent airport behaviours and whole-of-system performance as part of the design, development and operation of the airport system.

2. Background: socio-technical systems

Despite the prevalence of STS in the real world, the application of STS methodologies such as STS design (STSD) or STS engineering (STSE) is rare; instead, systems engineering methods are still the predominant approach [3,6]. Part of this can be attributed to the fundamental paradigm shift required as the system cannot be centrally designed, made and controlled [10,9]. Instead, the development of STS and the implementation of changes are enacted by actors within the STS [7]. In addition, STS are inter-disciplinary by nature and there has been very little cross-fertilisation across research fields to date [3]. Furthermore, the tools for STSE are not well developed and there is little agreement on methods for STSE [6]. It can be seen that the development of models of STS is not only an integral part of STS engineering and decision making [3], but also in the study of such complex systems.

This section briefly reviews the STS literature with regard to current high-level approaches to modelling, and the need for a framework to enable holistic STS modelling and model integration.

2.1. Modelling approaches

There are two main approaches to STS modelling especially for infrastructure: an integrated model that covers every element in one framework, or a coupled model where a series of individual models are joined together [4]. Typically, integrated models tend to be high level models and coupled models tend to provide greater fidelity [4]. The challenge with the coupled approach, however, lies in the need to interface between different models which may have different assumptions, data requirements, and other characteristics (such as the scale of the model) [2]. A structured framework that identifies the different elements of STS and their relationships is essential to enable the integration of different modelling methods. Such a structure is also applicable to support the development of a single integrated model as it provides reference guidelines regarding the dimensions and elements of complex STS. The proposed framework helps to address this need.

In recent times, there has been a trend towards data-driven computational models of STS that enable the simulation of STS processes [19]. Examples of these approaches include discrete event simulation [20,21], Agent Based Modelling (ABM) [22,23] and network models [24,19]; however, de Weck et al. [9] argue that much more research is required in order to address the challenges of holistic STS behaviour [9]. In general, it is infeasible to obtain an analytic expression of dynamic STS behaviour, even for simple systems, hence the trend towards computational models [19].

Such dynamical models of STS have been applied in social sciences and infrastructure modelling to explore and predict the emergence of whole-of-system (macro level) collective behaviour as a function of processes at the individual (micro) level and especially of individual humans. There are two major approaches for modelling human agents [10]. One is to assign behavioural rules at an agent level and simulate system behaviour via scenarios, context, roles and the like as used in sociology and social psychology. The other approach, popular in economics, is to assume rational agents who always choose the action to maximise the expected outcome at every time step.

Rinaldi [15] classifies existing STS infrastructure interdependency models into six categories: (i) aggregate supply and demand tools, (ii) dynamic simulations (e.g. system dynamics), (iii) ABM, (iv) physics based models (e.g. power flow analysis on electricity), (v) population mobility models (movement of entities through urban regions), and (vi) Leontief Input–Output Models (economic flows). Pederson et al. [4] concur and add additional categories for models based on game theory, mathematical models, and models based on risk. A comprehensive review by [25] poses a simpler classification structure relating modelling methods with usage scenarios as shown in Fig. 1.

Another key thrust of research is the development of diagrammatic models to represent STS dependencies and processes. A dependency matrix or equivalent graph, where directed edges connect dependent subsystems, is a method that has been applied in the analysis of interdependencies of critical infrastructure [4]. Unified Modelling Language (UML) diagrams are another popular approach in the study of STS and especially organisational STS as they provide a graphical depiction of system relationships and processes with respect to function [3,9]. Herrmann et al. [5] present an approach based on UML for the study and optimisation of business processes.

Regardless of the approach adopted for modelling, it is necessary to capture the uncertainty inherent in the system. Herrmann and Loser [26] provide one approach to classifying uncertainty based on whether it is deliberately introduced by the modeller (e.g. through abstraction), through vagueness (potential inaccuracy and/or incompleteness), and