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Agent-based modelling and mental simulation for resilience engineering in air transport

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ABSTRACT

Following a discussion of recent reviews, we argue that in resilience engineering (RE) there is a need for more structured modelling approaches for analysis of resilience in sociotechnical systems that can support both qualitative and quantitative studies. In this paper we present agent-based modelling and simulation (ABMS) as an approach towards this end. An agent-based model of a sociotechnical system describes the performance and interactions of its constituent human operators and technical systems in an operational context. In support of RE it can effectively be used to analyse the capability of a sociotechnical system to deal with disturbances and performance variability. We present an RE cycle, which uses qualitative and quantitative ABMS phases for analysis of the adaptive capacity of a sociotechnical system. The focus in this paper is on the qualitative ABMS phase, including the development of a qualitative model and mental simulation using the qualitative model. The model development is supported by a set of model constructs, which represent key aspects of evolution of agents' states and agents' interactions. The mental simulations use reasoning on the basis of the qualitative model to structurally analyse the interactions and dynamics of the performance in the agent-based model. Results of the qualitative ABMS phase can be used to improve the resilience of operations or they may be followed by quantitative ABMS. The approach is presented in detail for aircraft runway approach operations using conventional systems and an advanced aircraft surveillance application system.

1. Introduction

1.1. Resilience engineering

Following the origins of the resilience perspective in ecological studies on prey-predator populations (Holling, 1973), the resilience concept has been adopted in a large number of domains. Various review studies (Francis, 2013; Francis and Bekera, 2014; Hosseini et al., 2016; Martin-Breen and Anderies, 2011) discuss resilience in domains such as ecosystems, socio-ecological systems, socio-economic systems, institutions and governance, social innovation, climate, economy, individual trauma response, psychology, psychiatry, infrastructure, safety management, and organizational science. The resilience concept was introduced in the safety science domain by Hollnagel et al. (2006). For this they coined the term resilience engineering (RE), indicating the ability of a sociotechnical system to adjust its functioning to sustain required operations notwithstanding changes and disturbances, and the 'engineering' of the sociotechnical system to achieve such ability. RE stresses the key role of performance variability by human operators to adjust for changing demands and conditions in the working context. Safety management that uses an RE perspective leads to what Hollnagel (2014) calls Safety-II, entailing a focus that includes everyday actions and outcomes, which can be contrasted with a Safety-I focus on accidents and incidents only. Bergström et al. (2015) studied a selection of 86 peer-reviewed safety-oriented resilience papers along three questions: why do we need resilience, what is resilience, and who realises resilience? It was found that the need for resilience is typically addressed by referring to the complexity of modern sociotechnical systems and their inherent risks. The object of resilience is the capacity to adapt, so as to keep the complex and inherently risky system within its functional limits. The subject of resilience typically is the individual, either at the sharp end or at higher managerial levels.

In a recent RE perspective paper, Woods (2015) discusses four concepts of resilience:

(1) Resilience as rebound, expressing how a system rebounds from disrupting or traumatic events and returns to previous or normal activities.

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(2) Resilience as robustness, expressing the ability of a system to absorb perturbations.
(3) Resilience as graceful extensibility, expressing how a system extends performance when surprise events challenge its boundaries.
(4) Resilience as sustained adaptability, expressing the ability of a system to adapt to future surprises as conditions continue to evolve.

Woods argues that the rebound concept as such provides limited added value, since it needs to be understood what produces a better rebound. For this it needs to be known first what capacities are present before a surprise event arises and how such a surprise event challenges the base capabilities of the system. Woods argues that this implies a shift in focus from the rebound concept to the graceful extensibility and sustained adaptability concepts. With respect to the robustness concept, Woods refers to robust control engineering and indicates that robustness considers a particular system property that is able to withstand a particular perturbation in some sense. As argued above, system brittleness arises when the set of disturbances is not in the system's base capabilities, setting a need for resilience as graceful extensibility and sustained adaptability. In addition, Woods argues that systems that become more optimal in responding to some disturbances tend to become more brittle to other disturbances, addressing the need for system architectures that can sustain the ability to future surprises. In support of graceful extensibility, indicators of system decompensation should be tracked and anticipation of bottlenecks ahead should be stimulated. Sustained adaptability is supported by understanding the effects of changes in a system's life cycle and providing sufficient flexibility to continue to adapt over such longer time scales. In conclusion, a main principle is that a resilient system should be able to well handle surprise events that are outside its design base. How such ability can be achieved is still largely a research subject and new methods are needed for analysis and engineering towards such resilience.

1.2. Modelling for resilience engineering

As ways to assess resilience in various domains, qualitative and quantitative approaches can be distinguished, following a review in (Hosseini et al., 2016). The qualitative approaches include conceptual frameworks and semi-quantitative indices. The conceptual frameworks provide guidelines and best practices for studying resilience in various domains. The semi-quantitative indices are based on expert assessments of different qualitative aspects of resilience, for instance by structured sets of questions that are scored on a Likert scale. The quantitative approaches include general measures for resilience quantification and domain-specific structural-based modelling approaches. As general measures, a broad range of deterministic and stochastic measures are presented in Hosseini et al. (2016), which all somehow describe the decline and recovery of system performance following a disturbance. The structural-based models include optimization models, simulation models and fuzzy logic models, which mostly describe the vulnerability and recovery for disturbances in networks (e.g. transportation, power transmission, communication) and supply chains. Such models tend to describe system performance at relatively high and aggregated system levels, such as network nodes and average consumption, rather than at the level of interacting humans and technical systems in a sociotechnical system. As such they remain at a distance from RE needs.

In RE, typically qualitative approaches are used to assess resilience, and to improve resilience on the basis of such understanding. The results of such studies include guidelines for performing resilience research, qualitative insights into safety occurrences, or qualitative recommendations for design. Typically these studies discuss sociotechnical systems in detail, including interacting humans and technical systems. A well-known qualitative approach is the Functional Resonance Analysis Method (FRAM) developed by Hollnagel (2012). It uses a functional analysis-based approach, wherein functions (e.g. activities, tasks) in an operation are described by six aspects, performance variability of functions is identified, relations between functions and propagation of performance variability that may lead to functional resonance is analysed, and these analysis results are linked to the consequences for the operation. FRAM has been applied for retrospective analysis of incidents and accidents (Herrera and Woltjer, 2010; Paulo Victor Rodrigues, 2011) as well as for prospective analysis in system design (Macchi et al., 2011; Praetorius et al., 2015). It is recognized in Praetorius et al. (2015) that notwithstanding the potential of FRAM to uncover operational complexity given particular events, it is difficult to analyse and model everyday operations that do not include such events, and it may be hard to convey field data into functional models. Also other RE studies often use incidents, accidents or some kinds of non-nominal events as basis for their analysis. Thus, it is often still hard to use RE approaches productively for understanding everyday actions and outcomes, such as advocated in the Safety-II perspective of Hollnagel (2014).

We argue that there is a need in RE for more structured modelling approaches for analysis of resilience in sociotechnical systems that can support qualitative as well as quantitative studies. Support of qualitative studies is needed to align with customary approaches for studying sociotechnical systems and with the vocabulary of their practitioners, such that multidisciplinary contributions to the analysis can be achieved. Furthermore, there are cases in which a qualitative study provides sufficient results and no further detailing towards quantification is needed. Prime reasons for structured modelling and quantification in RE are to better understand complex sociotechnical systems' behaviour, and to develop more specific design requirements. Relations, events and dynamics of sociotechnical systems can be manifold and they can be hard to analyse and understand without structured means. Modelling and simulation provide such structured means for attaining deepened understanding of sociotechnical systems. Given the key contributions of human behaviour and performance variability for resilience (Hollnagel et al., 2006), it is essential that human roles and performance variability are well represented in such modelling and simulation.

1.3. Agent-based modelling and simulation

In this paper we present agent-based modelling and simulation (ABMS) as a structured approach for RE of sociotechnical systems. ABMS is an approach for modelling complex systems by describing the behaviour and interactions of a collection of autonomous decision-making entities, called agents (Bonabeau, 2002; Macal and North, 2010; Van Dam et al., 2013). The overall system behaviour emerges as a result of the individual agent processes and their interactions. ABMS provides a highly modular and transparent way of structuring a model, thus supporting systematic analysis, both conceptually and computationally. ABMS has been used in a wide range of application fields, including molecular physics, cell biology, ecology, epidemiology, social sciences, economy, market analysis, archaeology, anthropology, and transport and traffic (Chen and Cheng, 2010; Macal and North, 2010). In safety studies, ABMS has been used for accident risk assessments (Blom and Bakker, 2012; Everdij et al., 2014; Stroeve et al., 2013a).

An agent-based model of a sociotechnical system describes the performance and interactions of its constituent human operators and technical systems working in an operational context. In studying resilience of a sociotechnical system it is key to understand the