REQUIREMENTS FOR COMPUTATIONAL APPROACHES TO ANALYZING RESILIENCE IN HUMAN-MACHINE TEAMS

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Human-machine teams (HMTs) in complex work domains need to be able to adapt to variable and uncertain work demands. Computational modeling and simulation can provide novel approaches to the evaluation of HMTs performing complex joint activities, affording large-scale, quantitative analysis of team characteristics (such as system architecture and governance protocols) and their effects on resilience. Drawing from literature in resilience engineering, human-automation interaction, and cognitive systems engineering, this paper provides a theoretical exploration of the use of computational modeling and simulation to analyze resilience in HMTs. Findings from literature are summarized in a set of requirements that highlight key aspects of resilience in HMTs that need to be accounted for in future modeling and evaluation efforts. These requirements include a need to model HMTs as joint cognitive systems, the need to account for the interdependent nature of activity, the temporal dynamics of work, and the need to support formative exploration and inquiry. We provide a brief overview of existing modeling and simulation approaches to evaluating HMTs and discuss further steps for operationalizing the identified requirements.

INTRODUCTION

Human-machine teaming posits that novel forms of technology should be viewed as a team member or “team player” rather than a prosthesis or tool for extending human capabilities (Klein et al., 2004). From this perspective, human and machine are involved in joint activity, defined as an “extended set of actions that are carried out by an ensemble of people who are coordinating with each other.” (Klein et al., 2004). There are, however, significant challenges for designing human-machine teams (HMTs), particularly around the constraints—and often brittleness—that limitations in machine capabilities impose on the team. These limitations can hinder a team’s ability to adapt effectively to variable and uncertain work demands.

Computational modeling and simulation can provide powerful capabilities to support the design and evaluation of human-machine teams involved in joint activity, formalizing representations of work to support large-scale, quantitative evaluation. This paper presents a brief literature review of the use of computational modeling in HMTs and proposes requirements for developing computational modeling and simulation frameworks for designing and evaluating HMTs. We discuss the necessity for a novel and interdisciplinary approach to understand resilient performance in multi-agent sociotechnical systems such as HMTs.

METHOD

We conducted a review of literature on resilience engineering and the use of computational modeling in HMTs. Our aim in this review is to understand the current state of the art in using computational techniques to analyze and design HMTs, specifically focused on resilience. From an analysis of the major themes in existing resilience and HMT literature, we propose a set of requirements to lay the groundwork for future evaluative approaches using computational modeling and simulation.

Literature was found using Google Scholar, JSTOR, and Scopus using search terms such as ‘human machine teaming’ and ‘human robot interaction testbed’, and through tracing citations in the reference sections of seminal works in resilience engineering. Information about existing approaches and relevant testbeds was gathered and organized in a comparison table, where they were compared and contrasted based on aspects such as ‘difficulty of implementation’, ‘ecological validity’ and ‘hardware/software requirements’, providing a basis for further review and inquiry.

The paper first provides a brief overview of resilience in the context of human-machine teams. Second, it discusses existing computational frameworks for modeling and evaluating human-machine teams. Third, four requirements are discussed that aim to synthesize principles from resilience engineering and cognitive systems engineering into guidance for developing new computational frameworks for evaluating resilience in HMTs. Fourth and final, the paper concludes with a discussion of challenges and suggestions for future work.

RESILIENCE IN HUMAN-MACHINE TEAMS

HMTs in complex work domains (such as aviation, healthcare, emergency response, space operations) need to be able to adapt to variable and uncertain work demands. The development of systems that can extend their performance beyond traditional performance boundaries is a key goal of resilience engineering (Woods, 2019). Resilience engineering is focused on preparing systems for critical failures and providing practitioners the tools to handle novel challenges as they arise. As such, the approach is explicitly focused on understanding how architecture and governance in systems affect adaptation, recognizing that system performance is emergent, including how weaknesses coalesce in challenging scenarios to cause cascading failures (Woods, 2015). Resilience engineering is also often heavily associated with operational safety, described by Patriarca et. al (2018) as “a paradigm for safety management that focuses on systems coping with complexity and balancing productivity with safety".

Several definitions of resilience have emerged in literature, though the two manifestations most relevant to supporting adaptation in complex work domains are graceful extensibility and sustained adaptability (Woods, 2015). Graceful extensibility (or resilience as the opposite of brittleness) refers to how systems stretch to handle surprises at the edge of their performance boundaries (Woods, 2018). This concept for resilience relates closely to the interactions of agents within the system and their ability to coordinate and collaborate in real time (Woods, 2015). Engineering HMTs with graceful extensibility in mind can afford practitioners greater flexibility when facing novel and challenging work environments. Systems that support graceful extensibility can rapidly shift strategies by changing information exchange modes or the distribution of authority and responsibility, for example.

Sustained adaptability is interested in adaptation on longer time scales (e.g., a system life cycle), and in how governance and architectural characteristics affect a system's ability to manage or regulate its adaptive capacities (Woods, 2015). As all systems are resource limited, identifying tradeoffs associated with various system architectures and strengthening contextually appropriate responses can combat natural tendencies for sociotechnical systems to be brittle (Klein et al., 2004; Woods, 2015). Sustained ability then refers to control mechanisms for managing adaptive capacity relative to these trade-offs, and reconfiguring to address changes over its life cycle (such as factors that produce or erode graceful extensibility).

There are still significant gaps surrounding the operationalization of resilience. More work must be done to identify aspects of joint performance that can predict outcomes and resilience, particularly in developing new models and methods that can deal with inherent complexity and emergent phenomena (Patriarca et al., 2018).

COMPUTATIONAL MODELING OF HUMAN-MACHINE TEAMS

Novel approaches actively identifying architectural characteristics and governance protocols leading to resilient behavior could prove a powerful way to evaluate the adaptive capacity of HMTs, identifying instances of brittleness, complexities, and pitfalls occurring in joint activity. Structured approaches that support researchers and developers in operationalizing the core principles of resilience is an important step towards applying lessons-learned in resilience engineering to the design of HMTs. Computational modeling is one approach to operationalize these principles, particularly as computational power could afford the ability to test system architectures in 'fast-time' simulations and support identifying interdependencies to bolster resilience and sustained adaptivity. These postulated benefits, among others, show promise for future HMT design and evaluation using computational modeling and simulation techniques.

There are several examples of successful computational modeling frameworks for evaluating human-machine systems. We broadly see three classes of computational modeling approaches: cognitive architectures, multi-agent models, and work-centered or functional models. For each of these classes, we discuss several prominent computational frameworks that have been used to evaluate HMTs, albeit not necessarily from the perspective outlined above. We have categorized these frameworks by what we deemed are their most central foci (although many of them employ elements of all three classes). This is not meant to be a comprehensive overview, but rather an overview of the range of computational approaches that are used in evaluation of human performance and/or human-machine interaction.

The first class of computational models is cognitive architectures. Cognitive architectures are rooted heavily in cognitive science and artificial intelligence, with frameworks and underlying theory that are concerned with the cognitive properties of the human mind. They are based on theories of general intelligence and the computational structures that underlie it. Soar, one such cognitive architecture, focuses on tasks expected to be performed by an intelligent agent, exploring knowledge requirements and representations of knowledge in procedural, semantic, episodic, and iconic forms (Laird, 2012). Soar's focus is on modeling human cognitive capabilities such as decision making, situational awareness, reasoning and comprehension, planning, and learning.

Likewise, ACT-R *(*Adaptive Control of Thought-Rational*)* is a cognitive architecture that is considered hybrid in that it uses symbolic rules and declarative memory but also has activations which modify how components are related and used in a subsymbolic way. It models "the way we perceive, think about, and act on the world" (Ritter et al., 2019). ACT-R is interested in mapping capabilities such as sensorimotor control, action and decision-making, memory decay, and more.

The second class of computational models is multi-agent models, which focus on modeling and simulating the interaction between multiple agents (and often with a model of their shared environment), including how interaction and dynamics result in emergent patterns of behavior. One example of multi-agent modeling and simulation focused on human-machine systems is Brahms, which models distributed systems with a focus on capturing work as done, rather than work as imagined. Brahms favors an approach integrating multiple views (cognitive, social, physical) and aims to capture interdependent relationships within the system. Its model of work practice focused on circumstantial and interactional influences between agents (Clancey et al., 1998).

The third class of computational models is work-centered or functional modeling. Work Models that Compute (WMC) is a modeling and simulation framework that focuses on evaluating situated work in multi-agent systems (Pritchett et al., 2011). It captures the interaction between the work of multiple interdependent agents and the shared work environment (including any dynamical processes in the work environment, such as aircraft dynamics in the case of a pilot-automation system). Unlike cognitive architectures, WMC uses simple agent models, with much of the emergent patterns of behavior determined by characteristics inherent to the work.

Likewise, IMPRINT (Advanced Improved Performance Research Integration Tool) is a human-performance modeling tool that uses task network models and workload estimations to predict performance. Task network models are prescriptive task-subtask decompositions of work that aim to predict task times, accuracy, and associated mental workload (Mitchell, 2003). It uses discrete event simulation and thus is centered around individual agents and events and analyzing workloads that accompany them.

Though existing literature has articulated the need for designing HMTs for joint activity and resilience, few frameworks appear to have incorporated the concept of resilience as a key aspect of evaluating HMTs in joint activity. In the next section, we outline what a modeling and simulation framework should look like for evaluating resilience in HMTs.

REQUIREMENTS FOR EVALUATING RESILIENCE IN JOINT ACTIVITY

We propose four requirements for developing computational modeling and simulation frameworks which specifically incorporate resilience as a key aspect of joint activity in HMTs. These requirements aim to bridge gaps associated with increasing reliance on robotic/AI capabilities and facilitate the development of future computational frameworks emphasizing resilience in HMTs.

Requirement 1: A framework should focus on the joint cognitive system. Frameworks for HMT should recognize teaming as a complex sociotechnical phenomenon. This means understanding the human-machine team as a joint cognitive system (JCS), defined by Woods and Hollnagel as "an adaptive system which functions using knowledge about itself and the environment in the planning and modification of actions" (Hollnagel & Woods, 1999). Conceptualizing HMTs as JCS brings a multi-agent interaction centered perspective to HMT evaluation, positing that the configuration and organization of the broader work system is a crucial driver of its performance (Vicente, 1999). As such, evaluative frameworks should expand to encapsulate a work-centered representation of HMTs, mapping how humans and machines actively inform and support each other's work, adapt to changes in the environment, and modify activities to support tasks at hand.

A JCS focus should also enable the evaluation of teams at different levels or echelons of work, allowing multi-faceted analysis of both the bigger picture and the minutiae of work. As such, any evaluative framework should not have a predefined notion of what the system is – both in terms of the specific system composition as well as the aggregation in terms of organizational echelons. Thus, an effective framework has flexibility in scaling the system from traditional dyad to multi-human, multi-machine teams, and allows for aggregating agents into higher-echelon groups or teams (e.g., to consider interaction between teams as elements of a system). This flexible approach promotes an extendable framework that is useful even when new technology or modus operandi are introduced, allowing the modeling framework to expand or contract to varying applications or levels as necessary.

Requirement 2: A framework should capture interdependency in JCSs. As agents work toward common goals, their individual goals, limitations, and constraints coalesce, resulting in a complex web of teamwork dynamics and dependencies. A key insight gained through viewing HMTs as a JCS is a need to understand interdependencies within joint activity. Interdependence between agents is a requisite feature of joint activity, often determining the choreography of work (Hollnagel & Woods, 1999; Johnson, 2014). The incorporation of limited teammates further underscores the need to identify these connections, as brittleness or unexpected edge cases toppling a limited agent may lead to cascading failures across the JCS (Klein et al., 2004). Such concerns point to the necessity to identify emergent patterns, connections, and brittleness in HMT work that may lead to significant failures in the face of novel conditions (Woods, 2015; Ma et al., 2018). Using modeling and simulation to analyze interdependence in HMTs will provide valuable insights for supporting the adaptive capacity to respond to cascading failures.

Identifying interdependencies can support the HMT's ability to absorb perturbations and change strategies, as system design decisions could reduce the degree of reliance on a teammate that exhibits brittleness in a particular context. Several inter-team aspects influence adaptation capabilities, including initiative—willingness to adapt or seize opportunities—and reciprocity—as a commitment to mutual assistance, and the basic compact—an agreement (often tacit) to facilitate teamwork (Klein et al., 2005; Woods, 2019). Cooke et al. (2007, 2008) also explicitly highlight interactions between team members as crucial predictors of team performance, mentioning the dynamics of work as a promising approach to understanding joint activity (also see next requirement) (Cooke et al., 2007, 2008).

Requirement 3: A framework should capture the temporal dynamics of HMTs. Work within HMTs is inherently complex and dynamic. Complexities arise from the many-to-many relationships between resources, agents, task completion, communication, and other significant facets of the JCS. It is only over time that we observe how these elements interact to create emergent system behavior. This interaction includes the temporal progression of system states, as sequential actions performed by agents modify the work environment (and then the agents themselves) in a dialectical fashion; each action precedes and informs the next (IJtsma, 2019). To most accurately examine the JCS, a temporal element is necessary to capture emergent interactions. This also affords the ability to identify broader patterns within work and assess their suitability implications for joint activity in HMTs (Erik Johansson & Lundberg, 2017; Patriarca et al., 2018; Woods, 2006).

Computational simulation is particularly powerful to operationalize temporal dynamics of HMTs, which are difficult to predict from static modeling and evaluation approaches (e.g., using paper-based or conceptual models). Furthermore, with fast-time simulation, these dynamics can be explored at much larger scale than is traditionally possible with empirical research, such as observations or human-in-the-loop experiments. Examples of relevant interdependencies that can be modeled and simulated to predict dynamic effects include relationships between agents due to resource constraints, physical/cognitive load for agents performing tasks, and information exchange speed, among others (Hollnagel & Woods, 2005; Johnson et al., 2014; Klein et al., 2004).

Furthermore, in resilience engineering, JCS are considered multi-layered systems, with interdependent processes occurring at multiple levels and scales across time. Thus, an ideal computational framework recognizes that resilient behavior involves parallel and interrelated processes of sustained adaptability occurring at multiple levels of abstraction and should ideally be able to model and simulate dynamic processes at different scales of time and space. For example, adaptability in HMT can be driven by constraints best described at the level of physical forms (e.g., the geospatial configuration and dynamics of an HMT in the shared work environment) as well as by constraints best described at the level of abstract functions, such as balances and trade-offs of energy, values, and priorities.

Requirement 4: A framework should support formative exploration and inquiry. An effective framework should not only incorporate the theoretical insights that are the basis for the first three requirements; it should also provide usable and tangible insight to researchers and designers of HMTs. Vicente distinguished between two approaches to design: normative and formative (Vicente, 1999). A formative framework supports the design process through a process of exploration – supporting the identification of relevant constraints and characteristics of the work domain, the work itself, and the JCS. The understanding gained from a formative approach can then be translated into design requirements. A formative approach contrasts with a normative approach aimed at prescribing one optimal solution to a designer without necessarily supporting the designer in improving their understanding of the system and context. The complexity of JCS necessitates a formative approach over a normative approach, as normative frameworks lead to oversimplification of the complexities of actual work-in-context.

To support a formative approach, an effective framework is usable throughout a design cycle or process of inquiry, ideally starting with early discovery with a notional idea of the system, to having detailed descriptions of the JCS. To enable modeling and evaluation at various stages in a development process, a framework should afford flexibility in the level of aggregation that is necessary to generate insightful results. The scalability of the system will in large part trend with upticks in fidelity, as increased ecological validity of the simulation will come hand in hand with increased sensor inputs, new agents, and other generators of information. Thus, the framework should not have a preconceived notion of the ‘correct’ level of detail.

As a formative tool, a framework should support exploration (most likely through iteration) for discovery of potential system architectures and their subsequent evaluation across multiple levels of abstraction and scales of time. Again, the fast-time evaluation capabilities afforded by computational modeling and simulation can be a significant strength in the exploration of constraints, architectures, protocols, or operational assumptions. Yet, to best make use of these computational capabilities, a framework should be easily reconfigurable, allowing developers to explore the problem space by changing relevant parameters (for example, the system architecture, the constraints, or the demands imposed on the system). The framework should also support easy reconfiguration in terms of metrics that are deemed relevant for the problem that is being explored.

Finally, formative exploration with a computational model will likely involve multiple other methods for exploration. For example, Woods and Roth (1994) note that cognitive simulations must be part of a cycle of field research and model-based investigations. An effective framework should therefore support integration with data obtained from empirical field studies, both during model development (using empirical data as input) and as part of an investigative and iterative cycle in which insights derived from the model lead to new questions to be pursued in field research and vice versa (Woods & Roth, 1994).

DISCUSSION

The literature indicates that computational approaches to understand resilience in HMTs are needed (Patriarca et al., 2018). The requirements described in this paper outline an approach to bridge technical gaps in the integration of humans, robots, and AI in joint activity. In doing so, we lay theoretical groundwork for future quantitative analysis of HMT resilience and describe other pertinent themes relating to the evaluation of HMTs.

The computational approaches discussed in this paper are envisioned as both a method of inquiry for researchers and an engineering design tool assisting in rapid and cost-effective evaluation of HMT designs. Computational modeling and simulation offer a low-overhead opportunity to study and experiment with the complexity and adaptivity associated with HMTs and JCSs. This would be a useful tool for designers to help them understand the effects of their design decisions, but also affords significant opportunities to advance theoretical knowledge and understanding of how HMTs adapt or fail to adapt. For example, computational methods are being used as research processes in related fields such as organizational theory (Poile & Safayeni, 2016).

Challenges associated with employing computational modeling techniques include the overhead associated with model development, assuring model validity, and difficulties with operationalizing theoretical concepts. Developing a computational model typically takes a significant amount of time and expertise, which is a barrier to widespread use of these techniques during time and resource constrained design processes. However, experience shows that the initial effort can quickly pay off in time savings later, when computational affords fast-time analysis capabilities and insight at a more detailed level than one would get with traditional paper-based or static models.

Likewise, as with any model, a challenge is the assurance of model validity. Incorrect assumptions about system properties in the modeling phase has the potential to lead to poor design choices or inaccurate research conclusions. This is particularly challenging for using these techniques to analyze complexity of HMT and resilience, which will not lend themselves well for controlled validation studies. There are ways to strengthen confidence in a model, such as making minimal assumptions, verifying the model by reproducing well-known phenomena, and sensitivity analysis. An important factor in a model's validity ultimately is its utility (i.e., its ability to provide useful formative insight), with the purpose of the analysis determining what constitutes a good model.

Related to the challenge of model validity, there are significant challenges in operationalizing concepts from resilience engineering. Computational modeling is a double-edged sword in that it forces one to be articulate in order to operationalize abstract concepts, yet this is also challenging in that there might be many ways to operationalize a concept (and there might not be easy agreement on what the best operationalization is) (Poile & Safayeni, 2016). Our hope is that future work on developing a computational framework can use the requirements outlined in this paper as a guide. It is highly likely that further scoping and honing of the presented requirements is necessary. We also hope that future developments will build on what is already available in existing computational modeling frameworks, for example those described in the fourth section of this paper. For example, our own work uses the modeling and simulation framework Work Models that Compute (WMC), which has been successfully employed in investigating the dynamics of air traffic control and manned space operations (Feigh et al., 2001; IJtsma, 2019; Rosso & Saurin, 2018). By expanding its existing simulation capabilities and developing new capabilities to capture resilience engineering principles, we can begin to identify the architectural characteristics and governance protocols that lead to resilient behavior, informing the development of actionable design inputs and methodology (Feigh et al., 2001; IJtsma, 2019; Rosso & Saurin, 2018).

CONCLUSIONS

This paper provided a brief overview of literature on resilience in HMTs, the use of computational modeling and simulation to analyze human system performance and outlined requirements for using computational modeling and simulation techniques to evaluate resilience in HMTs. Increasing our understanding of resilience and resilience engineering concepts, and operationalizing this understanding into tangible design guidance, is an admirable yet—in our opinion—attainable goal for computational methods.

REFERENCES

Clancey, W. J., Sachs, P., Sierhuis, M., & Van Hoof, R. (1998). Brahms: Simulating practice for work systems design. *International Journal of Human Computer Studies*, *49*(6), 831–865. https://doi.org/10.1006/ijhc.1998.0229

Cooke, N. J., Gorman, J. C., Duran, J. L., & Taylor, A. R. (2007). Team Cognition in Experienced Command-and-Control Teams. *Journal of Experimental Psychology: Applied*, *13*(3), 146–157. https://doi.org/10.1037/1076-898X.13.3.146

Cooke, N. J., Gorman, J. C., & Rowe, L. J. (2008). An ecological perspective on team cognition. *Team Effectiveness in Complex Organizations: Cross-Disciplinary Perspectives and Approaches*, *2173*, 157–182. https://doi.org/10.4324/9780203889312

Erik Johansson, B. J., & Lundberg, J. (2017). Resilience and the temporal dimension–the chimera of timely response. *Theoretical Issues in Ergonomics Science*, *18*(2), 110–127. https://doi.org/10.1080/1463922X.2016.1154231

Feigh, K. M., Pritchett, A. R., Jacko, J. a, & Denq, T. (2001). *Decision Making During an Airline Rescheduling Task: A Contextual Control Model Description*. 1–6.

Hollnagel, E., & Woods, D. (2005). Joint Cognitive Systems. In *Joint Cognitive Systems*. https://doi.org/10.1201/9781420038194.ch6

Hollnagel, E., & Woods, D. D. (1999). Cognitive systems engineering: New wine in new bottles. *International Journal of Human Computer Studies*, *51*(2), 339–356. https://doi.org/10.1006/ijhc.1982.0313

IJtsma, M. (2019). *Computational Simulation of Adaptation of Work Strategies in Human-Robot Teams*. *August*.

Johnson, M. (2014). *Coactive Design - Designing Support for Interdependence in Human-Robot Teamwork*. Delft University of Technology.

Johnson, M., Bradshaw, J. M., Feltovich, P. J., Jonker, C. M., Van Riemsdijk, M. B., & Sierhuis, M. (2014). Coactive Design: Designing Support for Interdependence in Joint Activity. *Journal of Human-Robot Interaction*, *3*(1), 43. https://doi.org/10.5898/JHRI.3.1.Johnson

Klein, G., Feltovich, P. J., Bradshaw, J. M., & Woods, D. D. (2005). Common Ground and Coordination in Joint Activity. In *Organizational Simulation* (Issue September 2018). https://doi.org/10.1002/0471739448.ch6

Klein, G., Woods, D. D., Bradshaw, J. M., Hoffman, R. R., & Feltovich, P. J. (2004). Ten challenges for making automation a "team player" in joint human-agent activity. *IEEE Intelligent Systems*, *19*(6), 91–95. https://doi.org/10.1109/MIS.2004.74

Laird, J. (2012). The Soar Cognitive Architecture. *Computer Science*. https://doi.org/10.7551/mitpress/7688.001.0001

Mitchell, D. K. (2003). Advanced Improved Performance Research Integration Tool (IMPRINT) Vetronics Technology Test Bed Model Development. *Army Research Laboratory*, *September*. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA417350

Patriarca, R., Bergström, J., Di Gravio, G., & Costantino, F. (2018). Resilience engineering: Current status of the research and future challenges. *Safety Science*, *102*(October 2017), 79–100. https://doi.org/10.1016/j.ssci.2017.10.005

Poile, C., & Safayeni, F. (2016). Using computational modeling for building theory: A double edged sword. *Jasss*, *19*(3). https://doi.org/10.18564/jasss.3137

Pritchett, A. R., Kim, S. Y., Kannan, S. K., & Feigh, K. (2011). Simulating situated work. *2011 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*, 66–73. https://doi.org/10.1109/COGSIMA.2011.5753756

Ritter, F. E., Tehranchi, F., & Oury, J. D. (2019). ACT-R: A cognitive architecture for modeling cognition. *Wiley Interdisciplinary Reviews: Cognitive Science*, *10*(3). https://doi.org/10.1002/wcs.1488

Rosso, C. B., & Saurin, T. A. (2018). The joint use of resilience engineering and lean production for work system design: A study in healthcare. *Applied Ergonomics*, *71*(March), 45–56. https://doi.org/10.1016/j.apergo.2018.04.004

Vicente, K. (1999). *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. CRC Press.

Woods, D. D. (2006). Essential Characteristics of Resilience. In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience Engineering: Concepts and Precepts* (pp. 21–34). Ashgate Publishing Ltd.

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety*, *141*(September), 5–9. https://doi.org/10.1016/j.ress.2015.03.018

Woods, D. D. (2018). The theory of graceful extensibility: basic rules that govern adaptive systems. *Environment Systems and Decisions*, *38*(4), 433–457. https://doi.org/10.1007/s10669-018-9708-3

Woods, D. D. (2019). Essentials of resilience, revisited. *Handbook on Resilience of Socio-Technical Systems*, *January*, 52–65. https://doi.org/10.4337/9781786439376.00009

Woods, D. D., & Roth, E. M. (1994). Symbolic AI Computer Simulations as Tools for Investigating the Dynamics of Joint Cognitive Systems. *Expertise and Technology*, *January 1995*, 75–90.