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The influence of digital technologies on resilient performance: contributions, drawbacks, and a research agenda

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The influence of digital technologies on resilient performance: contributions, drawbacks, and a research agenda

Abstract

The growing use of digital technologies (DTs) has a myriad of implications to socio-technical systems, which are not yet fully recognised. This paper investigates the contributions and drawbacks of DTs to resilient performance (RP), an aspect that so far has received less attention in comparison to others such as efficiency. To this end, a survey questionnaire was applied to 79 academics and practitioners linked to resilience engineering. Data analysis involved descriptive statistics and a thematic analysis of the open-text responses to the survey. Mixed impacts were identified, with 10 themes related to contributions and 16 to drawbacks. Regarding the contributions, the results highlighted the use of DTs for monitoring and anticipating system performance. Machine learning seems to be the most promising approach for this purpose. The main drawback is the need for developing new skills across the workforce so that they can make sense of the outputs of DTs and are aware of their strengths and weaknesses. The human role is expected to remain crucial for RP, despite the coordination difficulties with DTs. A research agenda composed of five major topics is proposed, encompassing description, prescription, and assessment. The agenda emphasizes the need for mapping the attributes or functionalities of DTs onto resilience concepts, models, and frameworks.

Keywords: digital technologies, resilience, socio-technical systems, complexity, human factors.

1. Introduction

Digital technologies (DTs), now an inescapable element in workplaces and everyday life, consist of software and hardware that leverage information technology to process data in digital format. More and more, socio-technical systems are cyber-socio-technical ensembles constituted of DTs that provide and use data-accessing and data-processing services, demanding new types of human contribution and skills (Patriarca et al., 2021). Moreover, the complexity of socio-technical systems has increased, owing to larger and more interconnected supply chains, uncertainty from the external environment, efficiency pressures, and, perhaps most importantly, the growing use of DTs (ElMaraghy et al., 2012). Such technologies tend to make processes more tightly coupled as variability propagates at the speed of electronic signals. Complexity driven by DTs has also made systems opaque as users rely on indirect sources of information and do not fully understand how certain systems function and why they occasionally fail unexpectedly (Hollnagel, 2021; Dekker,

2011). This undesired complexity is exacerbated by design processes that do not effectively support joint human-DT activity (Rayo et al., 2022). Conversely, DTs can amplify desirable complexity attributes – e.g., electronic platforms for collaborative work enhance dynamic interactions between actors holding diverse perspectives.

Thus, the complexity implications of DTs are multi-faceted. Human factors and ergonomics (HFE), and socio-technical systems theory in particular, have a history of investigating these implications (e.g., Clegg, 2000). A frequent HFE research approach is the investigation of the new vulnerabilities introduced by DTs and their contribution to accidents (e.g., Nakajima et al., 2017; Meeks et al., 2014). These studies also describe how people carry out their activities regardless of technology-imposed constraints (e.g., Patterson, 2018). While these perspectives are and will remain relevant, they have concealed the benefits of DTs and have provided relatively little guidance to work systems designers (Rosa et al., 2021).

This paper explores how DTs influence resilient performance (RP), which is crucial for coping with complexity. The notion of RP is used to describe how well a system adjusts its functioning prior to, during, or following changes and disturbances, thereby sustaining operations under both expected and unexpected conditions (Hollnagel, 2014). Resilient systems withstand shocks small and large, rebound from them, and might display an enhanced performance in the post-recovery phase (Grøtan et al., 2022). In resilience engineering, four systemic potentials, namely anticipating, monitoring, responding, and learning, are often adopted as a basis for resilience assessments (Hollnagel, 2017). This categorization can be used to explore how DTs influence RP. For instance, sensors can monitor hazardous conditions in real-time, while machine learning algorithms use historic data to predict system performance. Industry 4.0 (I4.0) maturity models implicitly recognize these relationships. The ACATECHS maturity index posits that the levels of I4.0, from lowest to highest, correspond to digitalization that enhances visibility (what is happening?), transparency (why is it happening?), predictive capacity (what will happen?), and adaptability (how an autonomous response can be achieved) (Becker et al., 2017). Similarly, the model by Hochreiter (2022) poses adaptability and robustness as high-level stages of artificial intelligence (AI). The AI definition by Wang (2019) is also clearly connected to resilience. This author defines AI as "the capacity of an information-processing system to adapt to its environment while operating with insufficient knowledge and resources". These relationships have also been acknowledged by the concept of Industry 5.0, which expands the I4.0 approach by putting research and innovation on new technologies at the service of a sustainable, human-centric **and** resilient industry (European Commission, 2023; Xu et al., 2021).

Although prior studies suggest relevant relationships between RP and DTs, it is not yet clear how they play out, nor how they can be articulated within a HFE framework. Against this background, the following research questions are addressed in this study: what are the contributions and drawbacks of DTs to RP? What are the main research needs related to DTs and RP? The aims that stem from these questions are, respectively, the identification of contributions and drawbacks of DTs to RP - such results are informative to work system designers; and the proposal of a research agenda. To this end, a survey was carried out with academics and practitioners linked to resilience engineering, including both multiple choice and open-text questions.

2. Digital technologies and resilient performance: what we know so far

This section presents an overview of the current knowledge on the relationships between DTs and RP. Insights into the relationships between DTs and RP can be obtained from two main types of studies: those that explicitly refer to the relationships; and those from which the relationships can be inferred. In the former group, the investigation of the workarounds carried out by workers to cope with the shortcomings of DTs is a common approach. Alter (2014) defines a workaround as a deviation from an intended work process, which is used to overcome an obstacle. Patterson (2018) reviewed studies of workarounds to the intended use of information technology in healthcare, concluding that they were employed to enable interdisciplinary communication, coordinate activities, and have real-time portable access to summarized information. Barrett (2022) uses the term healthcare information technology resilience to describe situations when professionals circumvent DTs issues that impede patients' or workers' information needs – e.g., a nurse borrows a physician's login credentials to access a patient's electronic health record data that she needs, but does not herself have access to. Barrett (2022) adds that if DTs are not designed with flexible features (e.g., multiple routes to achieving one objective, open comment boxes wherein users can input information that does not have a designated field), workers will adapt the system to accommodate their needs.

These behaviours, despite their short-term effectiveness, run the risk of depleting long-term adaptive capacity stores, which threatens sustained adaptation (Woods, 2018). Along with repeated workflow deterioration, it is unsurprising that DTs act as stressors to workers, hindering their individual resilience (Mueller et al., 2023). These authors concede that DTs can compensate for the scarcity of resources (e.g., understaffing), potentially creating slack to cope with the unexpected. However, if DTs create chronic low workload, they can reduce workers' situational awareness. This risk is anticipated by Stathis et al. (2022) in the realm of AI applications to air traffic management. In this domain, the growing use of AI is a response to efficiency pressures – e.g., allowing only one pilot at the controls during the cruise flight phase (Stathis et al., 2022). Cyber-physical systems that enable

critical infrastructures also bring their own vulnerabilities to intentional attacks, which has been studied in the emerging field of cyber resilience. Pettersen and Grotan (2024) present a rich description of cybersecurity practices in the Norwegian oil and gas industry, analysing them in light of resilience engineering.

Some functionalities of DTs supportive of RP can be identified from the literature, although this relationship is usually implicit. For example, Ferrand et al. (2018) argue for DTs that allow for the dynamic prioritization of orders or patients, based on real-time data from operations. Moreover, DTs themselves can increase the requirements for RP, such as health information systems during transition periods (Fuller et al., 2023). Scallan (2017) further discusses how to develop resilience capabilities to cope with changes and failures in DTs, such as understanding downtime thresholds, backups for DTs outages, and identifying staff to facilitate DTs configuration.

The implications of emerging DTs from the industry 4.0 movement to RP have also been addressed, although mostly at a conceptual level. Tortorella et al. (2021), based on a survey with experts, identified 4.0 technologies (e.g., digital non-invasive care) that have a stronger theoretical connection with the four previously mentioned resilience potentials. Depending on the potential to be improved, different DTs may be prioritized, while the implications to RP are moderated by contextual factors such as system complexity (Tortorella et al., 2022). The role of moderators has also been pointed out by Furstenau et al. (2022). These authors proposed a framework that describes how DTs influence the resilience potentials in health care supply chains, indicating moderating factors (e.g., alliances between suppliers, based on trust and shared goals).

Tonetto et al. (2021), in the context of emergency care during the COVID-19 pandemic, make a similar systems-oriented point, arguing that the DTs most supportive of RP (e.g., remote consultations) reduce undesirable interactions (e.g., dangerous physical proximity between caregivers and infected patients) and amplify desirable ones (e.g., interactions that support knowledge sharing). Still in a survey-based study, Rosa et al. (2021) found that RP in emergency rooms and intensive care units, due to their high complexity, tend to benefit from 4.0 technologies. Regardless of these promised benefits of DTs, Fleuren et al. (2020) found that the vast majority of machine learning applications in healthcare is still at a low level of technology readiness.

Next, exemplar studies that allow inferences regarding the relationships between DTs and RP are presented. Karnehed et al. (2022) present the consequences of systems that allow for nurses to remotely monitor the performance of healthcare assistants that provide on-site daily care to patients. Transparency meant that the nurses could develop shared situational awareness with the worker at

the patient home. Zhang et al. (2023) conducted a literature review of how DTs can enhance situational awareness for construction safety, identifying several applications for the monitoring and anticipation of hazards, often in real-time.

Mental model sharing is crucial for RP as it allows synchronized performance adjustment of team members. However, Smith and Koppel (2014) highlight that the mental models of DTs by their users can be widely different. Hence, it can be inferred that DTs supportive of RP should account for a variety of users' mental models. The diversity of such models is likely to increase in face of recent AI developments, which have been debated by the HFE community. According to Salmon et al. (2023), there is little evidence that HFE is currently influencing programs of artificial general intelligence; nor is it clear what activities are required to exert such influence. Such type of AI will possess the capacity to learn, evolve, and modify its own functional capabilities, undertaking tasks beyond its original design specification (Salmon et al., 2023; Kaplan and Haenlein, 2018).

Sujan et al. (2022) offer eight HFE principles for the design of AI, involving: situational awareness, workload, automation bias, explanation and trust, human-AI teaming, training, relationships between people, and ethical issues. There are logical associations between these principles and the resilience potentials, e.g., situational awareness benefits from monitoring; and training enhances learning. Furthermore, these principles are underpinned by the proposition that AI design should consider the performance of the overall socio-technical system. Lyell et al. (2023) lend empirical support to this proposition, based on their analysis of adverse events related to AI in healthcare. Although issues with data acquisition were the most frequent, problems with the way in which devices were used and for what purpose were more likely to result in patient harm. Thus, safety of AI requires a shift of focus from algorithms to the human-device interaction (Lyell et al., 2023).

Concerns with explainable AI have also received attention as machine learning algorithms are not human verifiable. Weld and Bansal (2019) define explainable AI as a social process and a dialogue that allows the user to explore AI decision-making by interacting with and interrogating AI decisions. This definition resembles adaptive behaviour, a core idea of RP. Lyell et al. (2023) remind us that clinicians are responsible for decision-making even if the AI provided information is wrong. This suggests a need for developing individual and organizational resilience capabilities for interpreting decisions made by AI.

Research on human-robot interaction is also relevant for understanding the relationships between RP and DTs, although they are often focused on workstation design. Collaborative robots assist the user in physically or mentally demanding activities, allowing the worker to concentrate on tasks that

require high dexterity, adaptability, and decision-making abilities (Gualtieri et al., 2024) – i.e., tasks in which RP is paramount. These authors also argue that the design of collaborative robots can support RP by acknowledging human operators' diversity in terms of their cognitive capabilities, learning styles, and physical attributes, allowing the absorption of a wider range of skills and perspectives. Murphy and Woods (2009) highlight that adaptive behaviour is a property of the human-robot ensemble as the roles of both, humans and robots, should change in a coordinated manner depending on the nature of the disruption or opportunity encountered. Finally, 3D printing is another emerging DT that can influence RP. For example, Shahrubudin et al. (2019) describe the use of 3D printing to produce customized tools in manufacturing plants as well as personalized assistive devices to disabled patients in healthcare, enhancing the capacity to cope with non-routine situations.

3. Research method

The survey questionnaire was composed of 16 questions, divided into four sections (see Appendix). In the first section, there were six questions to characterize the respondent's profile and familiarity with RE, encompassing topics such as main occupation (academic or practitioner), domain of activity (e.g., energy, healthcare, aviation, etc.), number of years working with RE, extent to which RE was part of the respondent's professional practice, and number of attended RE symposia.

The second section had four questions related to the respondent's use of DTs in their research or practice - e.g., extent to which DTs were a priority theme, DTs most used, whether RE had been used as a lens for the investigation of DTs, and whether DTs had been used to support RP. The two initial sections of the questionnaire, when jointly considered, indicated the extent to which the respondent was acquainted with the two main issues under investigation.

The third section had three questions aimed at exploring general relationships between DTs and RP; two of these were open-text questions. One of them addressed how DTs could contribute to RP, while the other focused on drawbacks, trade-offs, and pressures to RP. Finally, in the fourth section there were three questions, including an open field for general comments and feedback as well as the respondent's name and e-mail. Response time was expected to range from 10 to 15 minutes. A pre-test was conducted with four senior researchers, one from each of the authors' research labs. As a result, there were some adjustments in the wording and sequencing of some questions.

The target respondents were both RE practitioners and RE researchers. Thus, there was a convenient opportunity for promoting the survey during the 10th Symposium of the Resilience Engineering Association, held in Sophia Antipolis (France), in June 2023. During this symposium, the authors of this study coordinated a plenary panel on DTs and RP and, as part of this activity, the survey was

administered to an audience of approximately 120 attendees, most physically present at the venue and some attending remotely. Although survey participation was anonymous, respondents were given the option to provide their email address for follow-up clarifications, if necessary.

A descriptive analysis of the multiple-choice survey questions was conducted to identify frequency distributions. Additionally, a thematic analysis was carried to analyse the free-text responses, which offered rich information and totalled approximately 4,000 words. This thematic analysis followed the recommendations of Pope et al. (2000). Then, we initially read the textual data several times in order to get familiar with the data. Then, two themes were defined a priori, corresponding to the two open-ended questions of the survey (i.e., contributions and drawbacks of DTs). Following, coding involved highlighting excerpts of text related to the themes and grouping them according to their similarity. Each group was labelled with a specific code and presented in a tabulated format. Coding was carried out separately by two of the authors of this paper who then met to reach an agreement.

4. Results

4.1 Characterization of the respondents

The 79 survey respondents had a diverse profile. Regarding their main occupation, 39.2% were academics, 30.1% were both academics and practitioners, and 30.1% were practitioners (Figure 1). This Figure also presents the frequency of using RE as part of professional practice, according to the respondent's main occupation. The majority of the participants applied RE either in most to all of their projects (43%) or in some of their projects (38%). Only 11.4% were limited to theoretical knowledge without any practical application.

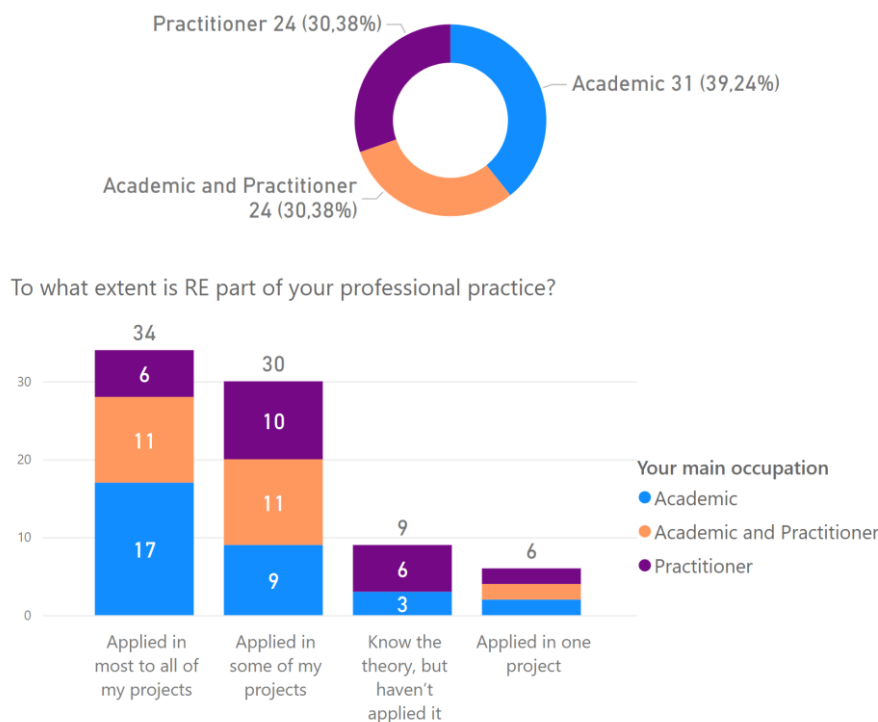


Figure 1. Respondents' main occupation and experience with RE.

The respondents represented various industry and service domains (Figure 2), reflecting the wide applicability of RE. Several respondents reported experience in two or more sectors. The higher incidence of aviation and healthcare (21% of the respondents were involved with at least one of these industries) is aligned with prior studies that pointed out these two sectors as of high interest to RE (Patriarca et al., 2018; Righi et al., 2015).

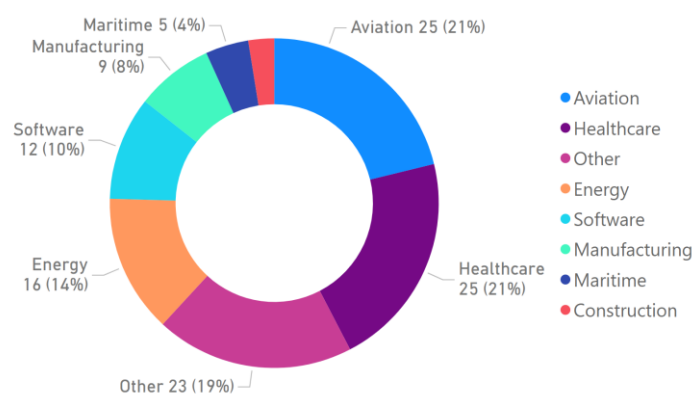


Figure 2. Respondents' domains of research or practice.

As for the respondents' experience with RE concepts and methods (Figure 3), 54.4% had more than five years, 17.7% had from 3 to 5 years, 22.8% had less than two years, and only 5.1% had less than a year. Putting this information into context, the birth of RE as an academic community and field of

practice and research can be traced back to 2004 when there was the first resilience engineering symposium, at that time a closed meeting for invited participants. The first publication that contributed to the wider dissemination of RE was the corresponding edited book, published in 2006 (Hollnagel et al., 2006). Despite the significant experience of most respondents, this was not necessarily associated with their frequent participation in the REA biannual symposia (Figure 3). Indeed, 58.2% of the respondents had attended either one or none symposia, 27.8% attended two or three symposia, and only 13.9% had attended four or more symposia.

Overall, this characterization suggests that the panel of respondents was a reliable source of information to investigate the research question. Although a minor portion of them was less experienced with RE, their perceptions were still of interest as all respondents had some degree of interest and knowledge on human factors, and the RE relevance of their responses in the open text fields was checked during data analysis.

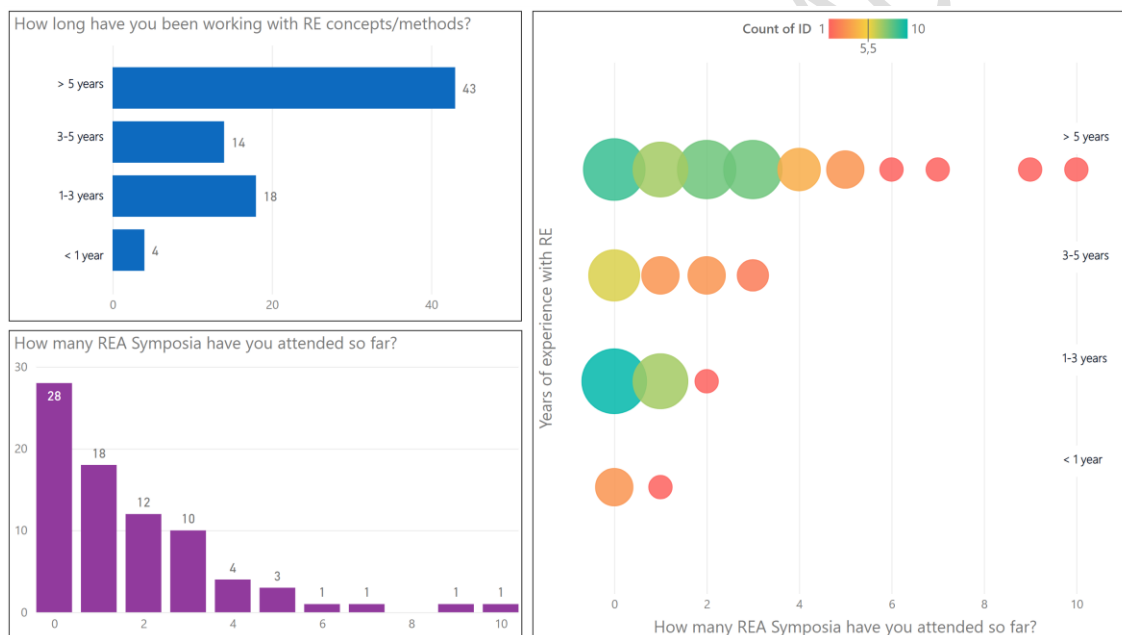


Figure 3. Frequency of using RE as part of the respondent's professional practice and attendance to REA symposia.

4.2 Contributions and drawbacks of digital technologies to resilient performance

Figure 4 shows the responses to the question on the DTs that stood out in the respondents' projects. Machine learning was the technology most frequently used, being cited by 41.8% of the respondents. This can be due to its character of base technology that provides connectivity and intelligence to the front-end technologies (Frank et al., 2019). A similar reason can explain business intelligence and visual analytics as the second best ranked (cited by 35.4% of the respondents), in addition to their use

to explore the outcomes of machine learning algorithms and disseminate them in customized formats. The top two DTs are supportive of decision-making, anticipating, and monitoring, all crucial for RP. By contrast, DTs with a narrower scope ranked lower such as 3D printing (3.8%) and collaborative robots (12.7%), which feature as front-end technologies according to Frank et al. (2019). These technologies can also support RP as presented in the literature review section. Other technologies narrow in scope, such as autonomous vehicles, ranked higher (21.5%) possibly as a consequence of current intense research efforts in contexts like self-driving cars, unmanned aerial vehicles, and autonomous vessels. Flohr et al. (2024) offer an example of explicitly discussing RP in shared automated mobility, stressing trade-offs between resilience, privacy, and security.

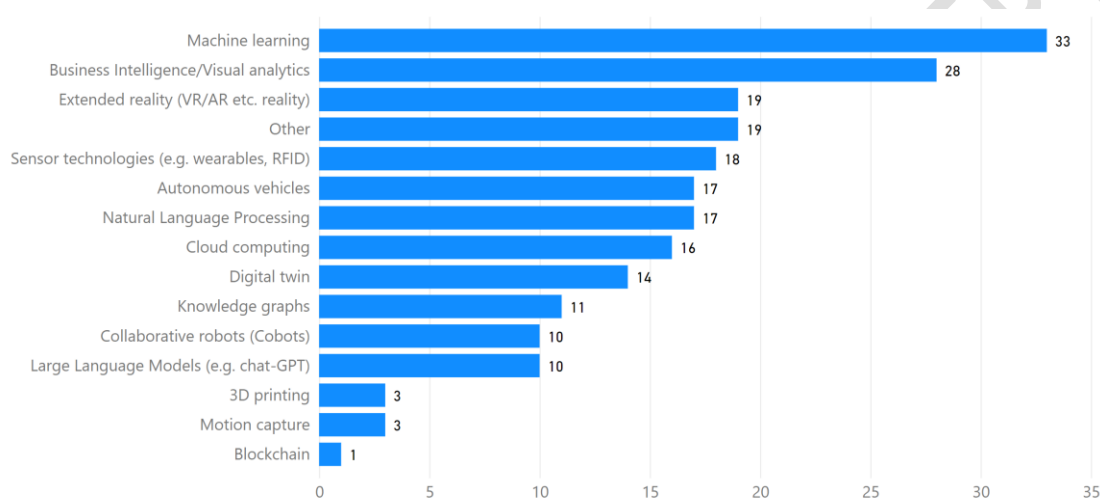


Figure 4. DTs' most frequently used in the respondents' projects.

Figure 5 presents the extent to which several RE concepts and tools are applicable to the design and use of DTs. Three concepts stood out as highly applicable: the four potentials of resilient systems (58.2% of highly applicable), adaptive capacity or performance adjustment (53.2%), and systems thinking (51.9%). Possible reasons for these findings are: (i) the over-arching nature of these concepts, which makes them relevant to any RE project; it also suggests that the respondents are aware of general principles rather than being overly focused on specific tools; and (ii) these concepts are likely to be more disseminated than others, being selected because the respondents are more familiar with them.

By contrast, three concepts and tools obtained the highest percentages of either low or no applicability: FRAM (27.8%), resilience assessment grid (26.6%), and reciprocity (21.5%). In particular, results related to FRAM appear misleading as the understanding of work-as-done, a strength of FRAM, has been recognised as crucial for the design of DTs that fulfil requirements of users (Barrett, 2022). To confirm this statement, one can mention studies that explicitly use FRAM

in the context of DTs development and use such as: Carvalho et al. (2021) used FRAM for the elicitation of users' requirements in software development; Ferreira and Canas (2019) used FRAM to understand the operational and training impacts of new automation features in air traffic control; and Grabbe et al. (2020) used FRAM to assess automation's contribution to the safety of the driving task. Regardless of these examples, the findings suggest that there is a need for making it clearer how FRAM can contribute to the development of DTs, along with practical examples of use, possibly demonstrating its effectiveness.

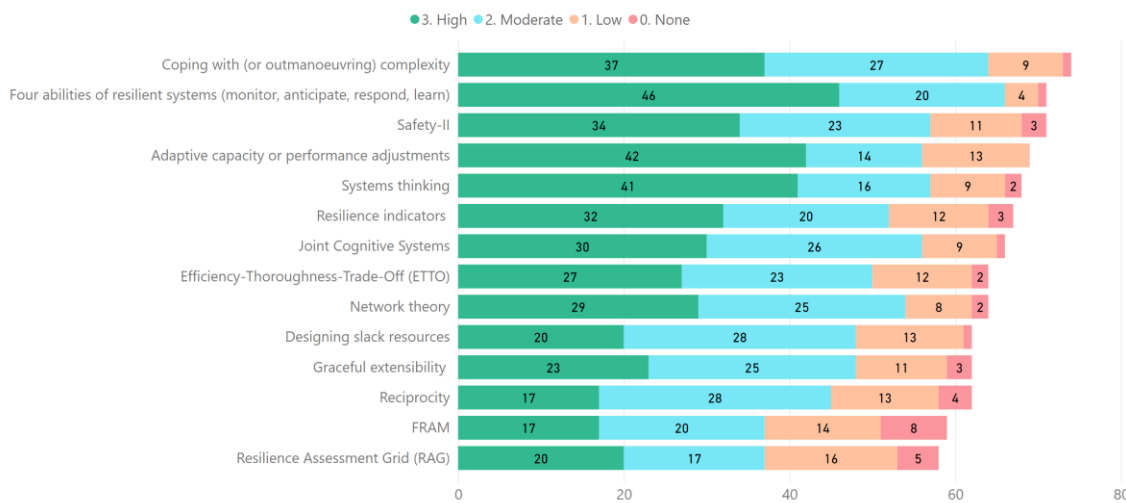


Figure 5. RE concepts and tools and their applicability to the design and use of DTs.

Table 1 presents the results of the open text question related to how DTs can contribute to RP, along with the respective frequencies. Note that these frequencies refer to the number of respondents who mentioned the issue, rather than the actual frequency of occurrence of the contribution, although it is reasonable to hypothesize a correlation between both. By far, the respondents emphasized the contribution of DTs to the provision of information for monitoring and anticipating the system performance. This information should ideally reflect the system performance in real-time, and be presented in customized formats to each actor. However, respondents were aware of traps, as illustrated by the following remark: *"DTs support will be as good as the data used to train and maintain algorithms"*. Next, the contribution of DTs to coordination and synchronization across system levels appeared as an asset to RP. This is important as RP is fractal, playing out at the micro, meso, and macro level of socio-technical systems, albeit coordination across these levels is challenging (Berg et al., 2018). This coordination can benefit from the better understanding of system performance enabled by DTs as well as from the speed of information transfer to actors across hierarchical levels. The third most frequent contribution of DTs stems from their data processing capabilities, which respondents believe will be useful for the revelation of hidden patterns or signals.

This can be important for the identification of weak signals of performance deterioration, which are not captured by traditional safety indicators (Hollnagel et al., 2021).

The top three contributions, altogether, have clear implications for learning. This was explicitly acknowledged by a survey respondent from the aviation domain, in the open-text fields. This respondent pointed out that new types of data are becoming available for analysis, expanding “*the idea that data is only the numbers that come off the airplane; we can now include safety reporting, observational data, etc., because we live in a new data ecosystem.*” What is more, the respondent stressed the possibility of capturing data that reflects adaptive patterns, such as patterns of avoiding turbulence and trade-offs involved in such decisions. Availability of qualitative data that speaks to the context of everyday work could potentially be leveraged for more proactive learning of adaptive patterns.

Table 1. Contributions of DTs to RP.

Contributions of DTs to RP	Frequency
(1) Provision of real-time data-driven perspectives to support anticipation of system behaviour and decision-making, including the presentation of customized information to each actor.	22
(2) Coordination and synchronization across system levels, through the provision of transparent information on the system performance status.	8
(3) Monitoring system performance and identification of hidden patterns or signals, by capturing and storing large amounts of data from sensors, telemetry, and other sources.	7
(4) Improved safety such as by alerting humans of hazards of autonomous vehicles	3
(5) Teaching and developing competence through simulations, encompassing various skills and attributes beyond technical expertise	3
(6) Reduction of repetitive work, releasing cognitive resources to cope with the unexpected.	2
(7) Better capabilities for promoting and practising learning in multiple languages.	1
(8) Schedule attainment in manufacturing, offering resilience to rush orders.	1
(9) Flexible and new styles of work representation useful for graceful extensibility in new situations.	1
(10) Provide separate backup capacity in cloud computing.	1

Table 2 presents the results of the open text question related to drawbacks of DTs, along with the respective frequencies. It is noteworthy that the list of drawbacks (16 items, 89 citations) is much longer than the list of contributions (10 items, 49 citations). Human factors experts can be wary of technological interventions as their interactions with humans are often frustrating and occasionally dangerous. The drawback most frequently cited by the respondents is related to the new competencies required by the workforce in order to effectively use the DTs. This resonates with studies on the need for upskilling the workforce in light of the industry 4.0 technologies (Tortorella et al., 2023; Ustundag

et al., 2018). A major competence refers to the critical thinking for interpreting the information or guidance offered by the DTs. The need for this stems from the opaqueness introduced by DTs as the users may not grasp the rationale underlying the information they receive. This problem is paradoxical with the respondents' expectation that DTs can offer insight into hidden patterns of the systems they are monitoring (see Table 1).

The second most frequent drawback refers to the undesired impacts of DTs on human initiative and creativity, compounding the existing problem of inadequate competencies. The fourth and sixth top ranked drawbacks are also related to the interactions between humans and DTs. The fourth issue reveals a concern with the users' lack of understanding of the limitations of DTs. This can produce brittle adaptations as a result of users who do not understand the hidden interactions between system elements, as well as users who rely on DTs when they are not appropriate for the problem at hand. Regarding the sixth issue, the respondents indicated responsibility gaps and coordination difficulties in joint human-machine activities. Such gaps may contribute to the absence (or delayed) of adaptive behaviour when it should occur. Coordination difficulties may also increase the human costs of RP, posing additional mental workload on operators. Paradoxically, respondents also expect that the coordination between human actors can be enhanced (Table 1) as a result of DTs that facilitate the sharing of the right information, at the right time, and at the right format.

Overall, it is clear that the respondents think that the human contribution must remain central to RP in face of DTs. For this purpose, investments in DTs must be accompanied by the development of new competencies in the workforce, which starts by identifying what these competencies are. However, DTs can be expensive (see items 8, 9, and 10 in Table 1), creating a trade-off between human and technologically-oriented investments.

Table 2. Drawbacks of DTs in light of RP.

Drawbacks of DTs in light of RP	Frequency
(1) Pressure for the development of new competencies in the workforce, which should be capable of identifying when guidance from DTs is not useful. There is a risk of overreliance on guidance from DTs to the detriment of lived experiences.	14
(2) Overreliance on DTs can hinder human initiative and creativity	12
(3) Commercial and government pressures to use DTs without adequate testing	12
(4) Lack of understanding of the limitations of DTs - e.g., less human autonomy; uncertainty about their impact on operations; hidden brittleness; opaque interfaces; propagation of uncertainty on a systemic level; no real need for using DTs.	10
(5) Using DTs mostly as a means of improving efficiency (in detriment to safety) and the reduction of the number of employees	8
(6) Responsibility gaps, coordination difficulties in joint human-machine activities, authority-accountability double binds, and unethical design of human-autonomy teaming	7
(7) Trade-off between data security measures and the benefits of data analysis	6
(8) Trade-off between too much data and too few resources to understand and manage it	5

(9) Trade-off between technically-oriented and human oriented investments	3
(10) Pressures for investing in cyber-resilience capabilities as well as managing DTs	3
(11) Trade-off between a technologically-based system that is reliable versus a system that is adaptable to new circumstances	3
(12) Inappropriate training sets	2
(13) Imprecise mapping of real-world systems into digital twins	1
(14) It is not yet known whether AI can learn and apply high-level goal constructs in novel and extreme situations	1
(15) Neglect of different users and stakeholders over the DTs life cycle	1
(16) Standards and guidance material development will need to catch up without losing quality	1

5. Discussion

5.1 The mixed implications of digital technologies to resilient performance

The mixed implications of DTs to RP are expected as they introduce changes in complex systems, and thus unintended consequences are inevitable. We make sense of these implications using the four questions on resilient management set out by Wiig et al. (2020): resilience *for what* (goals it is supporting); *of what* (what materials and resources underpin resilience); *to what* (what triggers and activates resilience); and *through what* (mechanisms, activities, and interactions that support resilience). These questions offer a comprehensive analytical framework, while remaining concerned with practical matters of resilience management.

The question of resilience *for what* is underpinned by the premise that RP is not the end purpose of any organization. It can rather play a moderating or mediating role supportive of goals such as the fulfilment of requirements of clients, provision of key services (e.g., electricity, healthcare, water), and profitability, which all come together as a system's ultimate goal, namely viability (Woods, 2018). Although DTs can contribute to these goals, their use is often motivated by efficiency improvement, as suggested by prior studies (e.g., Evangelista et al., 2014), and as indicated by the survey results. Efficiency gains derived from DTs release resources (e.g., people, time) that could serve as slack to cope with unexpected events and enhance RP. However, pressures for performing faster, better, and cheaper (Woods, 2006) are ever present and organizations can regard such slack as waste, inadvertently eroding safety margins.

Regarding the resilience *of what* question, the system formed by the inseparable human-machine ensemble must be the unit of analysis, consonant with joint cognitive systems theory (Hollnagel and Woods, 2006). Despite the current and promised advances of DTs, the respondents believed in the continued central role of human performance for the RP of joint cognitive systems. However, it is not yet clear what new resilience competencies will be required from the workforce, nor how DTs can be

designed to support adaptability of the joint cognitive system (i.e., what new "competencies" will be required from DTs). This last point can be exemplified by the interaction between autonomous vehicles (AV) and other road users such as cyclists during the overtaking manoeuvre (Parnell et al., 2023). These authors discuss whether AV will be able to effectively communicate with cyclists and compensate for the elimination of informal communications between them and drivers. Such issue was raised by our survey respondents: one of the drawbacks they mentioned was the trade-off between a reliable technologically-based system versus a system that is adaptable to new circumstances (see Figure 6).

As for the resilience *to what* question, there are a number of threats and opportunities that can be considered, both internal and external to organizations. DTs can be used in the first place to predict those threats and opportunities; this was the main contribution mentioned by the survey respondents. Nevertheless, emerging threats are always new to some extent, hindering the utility of existing databases for the training of algorithms. Moreover, the sheer complexity and implications of major threats such as pandemics, wars, and climate change (e.g., see implications of climate change for healthcare, according to Braithwaite et al., 2023) make it clear that DTs do not suffice as a resilient response. A tricky aspect related to this question, and also raised by the survey respondents, is that systems will be more and more required to be resilient to threats posed by DTs themselves. For example, failures that disrupt electricity supply and internet connection for long periods of time will demand a sustained change to manual modes of control, for which few organizations are likely to be prepared. Cyber-resilience is also an obvious concern in this context.

Regarding the resilience *through what* question, there is an opportunity to use DTs in the realm of designing for RP (DfRP), defined as "the use of design principles to support integrated human, technical, and organisational adaptive capabilities" (Disconzi and Saurin, 2022). DTs can play a role in practices of DfRP, which are "designed managerial processes and tools that operationalize the principles, necessarily including a human component; a technical component is useful but not fundamental for a practice of DfRP" (Disconzi and Saurin, 2024). These authors discuss exemplar practices of DfRP such as reflective meetings (e.g., safety huddles in hospitals, tool box talks in construction sites), and teams on standby to be activated in case of need (e.g., rapid response teams in hospitals, and emergency services in general). Creative designers can explore opportunities to use DTs for the enhancement of these practices. For example, there could be devised dashboards displaying performance indicators in real-time along with predictions for capacity utilization (Yigitbasioglu and Velcu, 2012), supporting decision-making during reflective meetings. In the same vein, robots are already used for rescue operations in emergency services (Delmerico et al., 2019),

which are designed structures to support RP. Overall, adaptability needs to be explicitly designed into systems, including design patterns meant to support the underlying cognitive functions required for adaptation (Cochran and Rayo, 2023).

The survey findings, along with the discussion above, point to the context-dependent nature of the relationships between DTs and RP. As a simple further illustration of this point, consider the role of DTs to the monitoring and anticipation of the system functioning. These impacts will be widely different whether the DTs are deployed to monitor workers aiming at the strict enforcement of procedures at all times or whether they are used to monitor and display indicators of weak signals of safety performance deterioration. Thus, it seems reasonable to propose that, in order to support RP, DTs could be regarded as resources for action. According to Suchman (1987) and Wright et al. (1996) people use resources in their environment (e.g., other individuals, calculators, environment cues) to extend their cognitive performance. From this view, the information and guidance generated by DTs can be used (or not), depending on the circumstances. Of course, this view does not apply to situations when the user does not have the option of choosing whether or not to rely on DTs. The resources for action perspective have been used in resilience engineering for the joint design of procedures and training (Wachs and Saurin, 2018; Carim Junior et al., 2016).

Paradox theory (Smith and Lewis, 2011) exemplifies another lens for the investigation of the complex relationships between DTs and RP. A paradox is a conflict between opposing but interrelated forces, which coexist over time and need to be jointly managed (Lewis, 2000). Prior studies have pointed out that digital transformation is both highly paradoxical and amplifies paradoxes (Menz et al., 2021; Smith and Beretta, 2021). Dieste et al. (2022) identified 23 paradoxes and related resolution strategies regarding the use of industry 4.0 technologies. The survey results pointed out to some paradoxes involving RP and DTs – e.g., DTs demand new resilience skills from workers while at the same de-skilling the workforce; DTs reveal hidden patterns of system functioning but operators should exercise judgment and critical thinking when analysing information; DTs can facilitate coordination between actors across system levels but the need for human-machine coordination is amplified; and DTs can improve efficiency and at the same time demand substantial investments in technological assets, training, and cyber-resilience.

5.2 A research agenda

Based on the survey findings, as well as on the literature review section, a research agenda is proposed. It is comprised of five major topics (Figure 6), namely: (i) mapping of the properties of DTs, (ii) reality-based adoption of DTs, (iii) development of DTs assistive of RP, (iv) explainability

of DTs, and (v) cost-effectiveness of DTs. The first two topics emphasize descriptive research and are foundational to the others as they allow understanding the nature of a DT to ensure it is used in a resilient way, i.e., not adding brittleness to the system. For example, DTs that support human decision-making under stressful conditions can enable the DfRP principle of designing for acceptable performance under degraded conditions. This example also highlights the need for identifying what DTs hold more promise to support RP during unexpected events and under time-pressure.

This mapping might also shed light on factors that moderate or mediate the relationships between DTs and RP. These factors are likely to differ across domains, and the micro, meso, and macro level of systems. Systems-oriented theories, either or not associated with HFE, should be used to make sense of that mapping. For example, based on paradox theory (Smith and Lewis, 2011), a taxonomy of paradoxes and resolution strategies can be developed. The resources for action theory (Suchman, 1987) can support the understanding of how people display RP on the spot using DTs on an *ad-hoc* manner, picking useful information and discarding what is irrelevant. Contingency theory (Donaldson, 2011), can be useful for the identification of contextual factors that influence the mentioned relationships.

Topic	Description
Mapping of the properties of DTs	Mapping attributes or functionalities of DTs onto resilience management and related frameworks such as the four potentials of resilient systems (Hollnagel, 2017), the theory of graceful extensibility (Woods, 2018), the principles of DfRP (Disconzi and Saurin, 2022), and macro cognitive functions supportive of RP (Klein and Wright, 2016). Resilience requirements of specific activities may be identified, and then the most promising DTs can be either identified or developed.
Reality-based adoption of DTs	Case studies of how DTs influence RP during everyday work, crises, and simulations, in a variety of settings, expanding studies focused on a few industries such as healthcare and aviation. As both system complexity characteristics and the nature of DTs differ substantially across industries (e.g., unmanned vehicles are not an issue in healthcare, at least so far), such studies can illuminate relationships and patterns that otherwise would remain concealed. A similar call has been made by Rae et al. (2020) for the investigation of what they termed reality-based safety science.
Development of DTs assistive of RP	This involves the design of DTs to assist people in activities and situations that are known to demand substantial RP. Three examples are presented: (i) DTs that assist workers in assessing the applicability of standardized operating procedures to a certain context, pointing out gaps in these procedures and raising questions that help humans to make decisions on the course of action; (ii) DTs that indicate the degree of novelty of a planned task from the viewpoint of an average worker, thus anticipating the need for RP; and (iii) DTs that detect in real-time that the standardized preconditions to start a task are not fulfilled – e.g., not all authorizations have been granted, not all safety measures are in place. These DTs can provide greater transparency to stop work decisions as well as prevent wasteful and risky RP.
Explainability of DTs	This refers to supporting human-DT interdependencies by designing DTs to be observable, predictable, and directable to the people around them (Jonhson et al., 2014). This is relevant as performance adjustment must play out at the joint cognitive system level rather than by either the human or the technical element. Both elements should be synchronized in terms of sharing a similar understanding of the workflow.

Cost-effectiveness of DTs	The mixed impacts of DTs on RP indicate that the introduction or revision of such technologies could benefit from a cost-effectiveness assessment. Frameworks for such assessment in light of RP can be useful (e.g., Saurin et al., 2023).
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Figure 6. Research agenda for the investigation of DTs and RP.

The third and fourth topics (development of DTs and explainability) have a more prescriptive emphasis, leveraging on the knowledge acquired from the investigation of the first and second topics. The fifth topic has a character of assessment, contributing to evidence-based improvement and dissemination of both existing or new DTs. These relationships between the research streams are schematically represented in Figure 7.

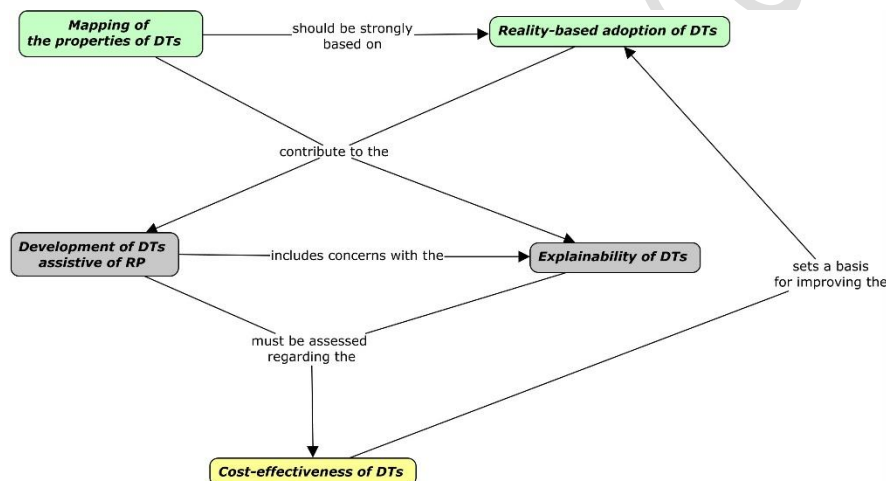


Figure 7. Relationships between the topics of the research agenda. Notes: descriptive emphasis in green; prescriptive in grey; and assessment in yellow.

6. Conclusions

This study investigated two research questions. The first question was concerned with the contributions and drawbacks of DTs in light of RP. The contribution that stood out was related to the use of DTs for the improved monitoring and anticipation of system performance. The main drawback is related to the need for enhancing the human capabilities of making sense of the outputs of DTs and being aware of their strengths and weaknesses. As a whole, findings suggest that the impacts of DTs will be contingent on their role in addressing the four resilience management questions (for what, of what, to what, and through what) as well as on contextual factors that affect digital transformations in general.

The second question was related to the main research needs related to DTs and RP. Five research streams emerged, encompassing description, prescription, and assessment. A foundational research need, which serves as a basis for all others, is the mapping of the attributes or functionalities of DTs onto resilience concepts, models, and frameworks. This mapping might benefit from a deep understanding of the real adoption of DTs, through case studies. A generic mapping might cross features of RP (e.g., dynamic prioritization of orders or products, collaborative decision-making) with their enabling DTs.

This study has some limitations. First, the survey respondents were participants from the resilience engineering symposium, not being statistically representative of the broader RE and HFE community. In this sense, the present study has an exploratory character. Larger and different samples could be used for similar investigations. However, the respondents were qualified to take part in the study, and their responses revealed critical thinking. Second, the implications of DTs, either desirable or undesirable, are to some extent theoretical given the scarcity of empirical studies and the novelty of the emerging technologies. Third, despite the counting of contributions and drawbacks of DTs, based on the thematic analysis, it is only an overall indication rather than the result of data collection purposefully designed to produce a ranking.

AUTHOR VERSION - ACCEPTED

Conflicts of interest

On behalf of all my co-authors I declare no conflict of interest related to our submission to Applied Ergonomics, entitled 'The influence of digital technologies on resilient performance: contributions, drawbacks, and a research agenda'.

CRedit authorship contribution statement

Tarcisio Abreu Saurin: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. Riccardo Patriarca: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. Sudeep Hegde: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. Mike Rayo: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing.

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Appendix. Survey questionnaire.

Section 1. Respondent profile and familiarity with resilience engineering

1. Your main occupation.

☐ Academic ☐ Practitioner ☐ Academic and Practitioner

2. What is your experience in the above occupation in years?

3. Main domain(s) of research or professional activity.

☐ Energy ☐ Software ☐ Healthcare ☐ Aviation ☐ Manufacturing ☐ Construction ☐ Maritime ☐ Other (please specify)

4. How long have you been working with RE concepts/methods?

☐ Less than a year ☐ 1-3 years, ☐ < 5 years ☐ > 5 years

5. To what extent is RE part of your professional practice?

☐ I have never heard of it ☐ Know the theory, but haven't applied it ☐ Applied in one project ☐ Applied in some of my projects ☐ Applied in most to all of my projects

6. How many REA Symposia have you attended so far?

Section 2. Respondent involvement with digital technologies

7. What is the extent to which digital technologies are a priority theme in your current research or professional projects?

☐ None ☐ Low ☐ Moderate ☐ High

8. Please select up to five DTs that stand out in your research or professional projects. ☐ Autonomous vehicles ☐ Blockchain ☐ Business Intelligence/Visual analytics ☐ Cloud computing ☐ Collaborative robots ☐ Digital twin ☐ Extended reality (VR/AR etc. reality) ☐ Knowledge graphs ☐ Large Language Models (e.g. chat-GPT) ☐ Machine learning ☐ Motion capture ☐ Natural Language Processing ☐ Sensor technologies (e.g. wearables, RFID) ☐ 3D printing

☐ Other (please specify)

9. Are you using RE as a theoretical lens for the investigation of DTs? Yes No

10. Are you using DTs in your research/practice to support resilient performance? Yes No

Section 3. Relationships between digital technologies and resilient performance

11. How can DTs support resilient performance, including capabilities such as monitoring, anticipation, proactive learning, coordination, preparedness, and cross-scale synchronization?

12. How can DTs hinder resilient performance, including drawbacks, new pressures, trade-offs and challenges?

13. Considering the RE concepts, tools, and ideas listed below, please indicate how much they can contribute to the design and operation of safer, efficient, and resilient systems using DTs and, if possible, justify your response. Use the scale as follows: None; Low; Moderate; High; N/A (mark N/A if you're unfamiliar with the topic).

() Adaptive capacity or performance adjustments () Coping with (or outmaneuvering) complexity () Designing slack resources () Efficiency-Thoroughness-Trade-Off (ETTO) () Four abilities of resilient systems (monitor, anticipate, respond, learn) () FRAM () Graceful extensibility () Joint Cognitive Systems () Network theory () Safety-II () Reciprocity () Resilience Assessment Grid (RAG) () Resilience indicators () Systems thinking

Section 4. Closure

14. Please use this field if you have any additional comments or feedback for us

15. Are you willing to be contacted for a brief discussion based on your responses? Yes No
If yes, please provide your email

16. Your Name (optional)