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Transforming resilient healthcare systems: Mapping the pathway forward with Healthcare 4.0 technologies

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Traditional approaches to healthcare service design usually seek resilient healthcare relying on social interactions between care providers. The current growth in the adoption of digital technologies in healthcare systems, usually grouped under the acronym H4.0 (Healthcare 4.0), calls for the integration of Resilience Engineering (RE) principles and Information and Communications Technologies (ICTs) in the design of healthcare services. This paper offers an expert-based mapping of how H4.0 technologies may impact four abilities that characterize resilient healthcare systems, namely: monitor, anticipate, respond, and learn. Based on our findings, we propose how specific ICTs may be used in service design to positively influence each of the abilities of resilient systems. Two topics for future research are presented, namely, the design and allocation of teams of professionals and the development of a roadmap for adopting ICTs in healthcare systems.

Keywords: service design; healthcare services; healthcare 4.0; resilience engineering

1 Introduction

The Fourth Industrial Revolution (Industry 4.0) has been promoting the use of technologies in various ways. Prospects brought to organizations through new Information and Communication Technologies (ICTs) enabled systems to operate differently (Liao et al., 2017). Among the types of organizations positively impacted by new technologies, the healthcare industry stands out, with related systems moving towards a Healthcare 4.0 (H4.0) era (Sultan, 2014; Yang et al., 2015; Vassolo et al., 2021). Here, healthcare organizations are viewed as complex systems with different departments that need resources for infrastructure and information, which are often shared (Dautov et al., 2019).

H4.0 makes it possible for the hospital staff to offer and benefit from internal and external services more efficiently and effectively (Alloghani et al., 2018). The use of ICTs in healthcare treatments brings positive consequences for hospitals' outputs in the short term and leads to incremental changes in administrative and supporting processes in the long run (Das et al., 2011; Tortorella et al., 2020a).

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Several ICTs integrate the H4.0 portfolio, most notably Internet of Things (IoT), Machine Learning, Cloud Computing, and Big Data. In a comprehensive literature review, Tortorella et al. (2020c) divided H4.0 ICTs into two categories, according to their primary purpose: sensing and communication, and processing and actuation, as shown in Table 1. They also list several contributions derived from adopting H4.0 ICTs in healthcare systems and identify electronic health record systems and mobile health applications as the ones most frequently cited. It is important to highlight that even though some researchers may not recognize 3D printing as an ICT, Tortorella et al. (2020c) found in their study that this is one of the most frequently cited digital technology. In this paper, we explore the role of H4.0 as a potential booster of resilience in healthcare systems.

Table 1. ICTs clustered according to purpose

H4.0 technologies	**Role**
Biomedical/Digital sensors	Sensing-Communication
IoT	
Big data	
Cloud computing	
Remote control or monitoring	
3D printing	Processing-Actuation
Collaborative robots	
Machine/Deep learning	
Augmented reality/simulation	

Resilient healthcare is defined as the system's ability to adjust its functioning before, during, or after changes and disturbances to deliver the required performance under expected and unexpected conditions (Hollnagel, 2011). Resilient systems may also respond to changes by setting new operational standards that lead to better performance. Interactions between healthcare professionals have the potential to enhance resilience, particularly by involving individuals with different perspectives and backgrounds in the healthcare decision-making process.

Since 2011 when the I4.0 concept was announced as one of the ten future projects of the High-Tech Strategy 2020 by the German government, researchers worldwide have been focusing on the topic and its influence in organizations from different sectors. Regardless of the increasing number of studies on I4.0, there is still a lag concerning Healthcare 4.0, with a lack of academic alignment and practical orientation founded on grounded theories (Yang et al., 2015; Tortorella et al., 2020c).

Note that the concept of Resilient Healthcare, due to Hollnagel (2011), was created in parallel with that of I4.0, although evolving separately in the literature. In this paper, we explore the role of Resilience Engineering (RE) in the design of healthcare services supported by H4.0 ICTs. RE is a systems-oriented discipline concerned with finding, assessing, and influencing resilience in socio-technical systems through design (Nemeth and Herrera, 2015). The integration of H4.0 to enhance Resilience Engineering is vastly absent in the literature, with few exceptions (e.g., Tortorella et al., 2020b; Tonetto et al., 2021; Rosa et al., 2021).

The use of ICTs in healthcare service design enables not only planning for gathering and analyzing patient and process information but also mapping the connections among professionals in the hospital that could maximize the quality of the service provided. Such mapping is essential since hospital workers tend to be closer to individuals in their unit without interacting with other departments, potentially harming the system's resilience (Braithwaite et al., 2017; Bertoni et al., 2021). For the healthcare system to be in a state where it can provide quality care to patients, the design of associated services must consider ways to boost the system's resilience.

In this paper, we explore the results of an expert opinion assessment on the potential role of H4.0 ICTs as promoters of resilient systems' abilities (i.e., monitor, anticipate, respond, and learn) and discuss how the integration of ICTs into healthcare may impact the design of healthcare services. We also propose a research agenda on the joint analysis of Resilience Engineering and H4.0 in healthcare service design.

2 Literature Review

2.1 Healthcare 4.0

Industry 4.0 (I4.0) derives from digitalization and automation trends currently present in the manufacturing environment (Tortorella et al, 2022a). I4.0 promotes the use of new Information and Communication Technologies (ICTs) in organizations, enabling and supporting more effective and adaptable processes, services, and products (Liao et al, 2017). One of the contexts in which I4.0 technologies have been used is healthcare, leading to Healthcare 4.0 (H4.0). The H4.0 trend encompasses the use of I4.0 innovative technologies to customize in real-time the type of healthcare provided to patients (Thuemmeler & Bai, 2017). H4.0 promotes a focus shift from a hospital-centered to a patient-centered perspective, with different units, roles, and responsibilities working together to achieve the best possible patient health outcome (Alloghani et al., 2018).

In the Healthcare 4.0 context, systems are characterized by interconnected ICTs, electronics, and microstructure technology that are used to create more effective therapeutic models and auxiliary processes (Sultan, 2014; Yang et al., 2015). For example, cyber-physical systems such as sensors, robots, and three-dimensional printers are used in Smart Pharmaceutical apps (Alloghani et al, 2018). The use of ICTs in healthcare systems has been extensively investigated, which may be explained by significant investments in new medical and information technologies reported in the healthcare industry (Byrne et al., 2010). Healthcare technologies include procedures, equipment, and processes used to deliver medical care (Ancarani et al., 2016). ICTs applied in healthcare usually encompass computer hardware and software that handles the storage, retrieval, sharing, and use of healthcare information, data, and knowledge for communication and decision-making (Tortorella et al., 2022b). Integrating ICTs into healthcare services potentially reduces errors, waiting times, and costs, while maximizing patient welfare, staff motivation, and productivity (Behkami and Daim, 2012).

According to Anyanwu et al. (2003), healthcare processes involve clinical and administrative tasks, which may be supported by a diversity of digital applications and information systems. For ICT adoption to properly facilitate those tasks, it is necessary to understand the dynamics of patient interaction with all components of the care delivery system and their interdependencies (Oueida et al., 2018).

The integration of disruptive technologies derived from I4.0 into healthcare systems aims to achieve virtualization to provide care in real-time (Sannino et al., 2018). Big data, the Internet of things, cyber-physical systems, and cloud computing, among others, are combined and incorporated into healthcare processes, services, equipment, material, and people, building smart systems that monitor, track, and store patient records for continuing care and analysis (Elhoseny et al., 2018).

According to Aceto et al. (2018), four types of interrelated subsets of ICTs may be found in healthcare organizations, being possible to categorize ICTs in more than one according to their role in the system. The first one, communication, congregates ICTs that promote diverse ways of interacting and disseminating health-related information, establishing patient-professional relationships, and cooperative care (i.e., ICTs that help intensify accessibility, exchange, and sharing of information). The second one, sensing, comprises ICTs intending to collect information, i.e., data on patients, equipment, materials, or processes, without necessary physical contact with the source. The third one, processing, concerns ICTs able to modify or process the collected data turning it into information. The fourth one, actuation, comprises ICTs able to move and control a system, mechanism, or software based on the information received. The same types of ICTs were rearranged into two categories by Tortorella et al. (2020c), as shown in Table 1. The set of ICTs used in this study are based on Tortorella et al. (2020c), who listed nine types of technologies. They are summarized, along with their healthcare applications, in Table 2.

Table 2. Definition of ICTs used in this study and their applications in healthcare

H4.0 technologies	Definition	Application
Biomedical/Digital sensors	Conjunction of biosensors, wireless communication, and network technologies into a group "of wireless networked low-power devices that work together to integrate an embedded microprocessor, radio and a limited amount of storage" (Ren et al., 2005, p. 483).	Used in the medical sector as body sensors, helping to sample, process, and communicate vital signs or environmental factors. They are usually placed on patients' bodies as small patches or even hidden in their clothes to allow health monitoring in their natural environment (Otto et al., 2006).
Internet of Things (IoT)	The term IoT refers to one of the many networks connected to the Internet, e.g., sensors, actuators, processors, and computers (Laplante & Laplante, 2016). IoT connects physical devices and objects to the Internet, enabling communication and interaction with others and assisting with remote monitoring and control (Alhamid, 2017; Onasanya & Elshakankiri, 2021).	IoT may help deliver comprehensive patient care in various settings, such as hospitals, nursing homes, and homes. As proposed by Laplante and Laplante (2016), "an IoT has the potential to accurately track people, equipment, specimens, supplies, or even service animals and analyze the data captured" (p.02).
Big data	Understood by Boyd & Crawford (2012) as the interplay of technology, analysis, and mythology, it maximizes "computation power and algorithmic accuracy to gather, analyze, link, and compare large datasets" (p.663) and takes information from them to find patterns. The mythology comes from the fact that these	According to Dash et al (2019), analyzing big data can help provide insights for the improvement of procedural, technical, medical, and other procedures in healthcare. By enhancing the patient-specific medical specialty or personalized

	sets can offer more knowledge and generate new, trustful, objective, and accurate insights.	medicine, big data analysis can help build a better prognostic framework for patients.
Cloud computing	Groups of computers that serve as data centers, providing "on-demand resources and services over a networked medium (usually the Internet)" (Sultan, 2010, p.110). It is an application service that uses omnipresent resources to be shared by its users (Low et al., 2011).	Used in the healthcare industry to receive and store big data from patients and manage their health records, i.e., a secure storing and sharing system of patient data (Regola & Chawla, 2013).
Remote control or monitoring	Remote controlling and monitoring are done through IoT technology, allowing users to monitor their daily activities.	In terms of healthcare, small things such as monitoring steps, using smartwatches and other gadgets can help monitor health and fitness activities (Oresko et al., 2010). It can "remotely monitor the user's physical condition and physiological parameters" (Luo et al., 2009, p. 485), not needing to be connected to them.
3D printing	It joins materials, layer-by-layer, to create artifacts from 3D model data (Wan et al., 2015) using computer-aided design software or by scanning real objects.	It may help in personalizing healthcare treatments and drug delivery. Devices and objects such as medical prosthetics and implants can be created according to each patient’s needs (Sahlgren et al., 2017). Smart drugs can be developed and personalized for each individual, providing prolonged and localized medication delivery (Trenfield et al., 2019).
Collaborative robots	It is a type of ICT that inserts robots in operational contexts, making them work alongside humans in organizations (Paxton et al., 2017).	According to Holland et al. (2021), service robots can help in a variety of ways when it comes to healthcare. They can assist the staff with daily activities, help sterilize hospital environments to prevent diseases, deliver medical supplies, laboratory samples and food, and test and sort blood samples. Furthermore, they can keep company to isolated patients as well as help monitoring their health.
Machine/Deep learning	It is a form of analyzing and interpreting data (Cruz & Wishart, 2006). According to Mitchell (1997), this type of artificial intelligence research uses various statistical, probabilistic, and optimization tools to learn from the past and	Machine and deep learning in healthcare can be applied to fields such as electronic health records, imaging, and genetic engineering. It can focus on supporting the

	then use this information to classify novel data, detect new patterns, or predict innovative trends. It uses statistical techniques to generate knowledge from specific datasets, creating predictive or descriptive models from features of a dataset, making it possible to generalize those features to similar datasets (McCarthy et al., 2004).	medical staff's ability by providing more effective treatments with better quality, speed, and precision (Habehh & Gohel, 2021).
Augmented reality/ simulation	This kind of system comprises virtual, computer-generated artifacts which coexist with the real world, i.e., the surrounding environment continues to be real, with new virtual elements being added to it (Azuma et al., 2001).	It may be used as a teaching tool for medical and surgical education, helping practitioners to enhance their technical and non-technical skills, and evaluate users while performing these activities (Viglialoro et al., 2021). Spatial abilities, as well as the strengthening of cognitive-psychomotor ones, can be some of the skills learned by students in a faster way and with more knowledge retention (Zhu et al., 2014).

2.2 Resilience Engineering (RE)

As defined by Hollnagel (2011), resilient healthcare relates to a system's ability to adjust its functioning prior to, during, or following changes and disturbances, so that it may be able to sustain a required performance level under both expected and unexpected conditions. Individuals in resilient systems present four main abilities (Hollnagel, 2017): monitor (knowing what to focus on, such that it does not become a threat in the future), anticipate (knowing what to expect), respond (knowing what to do) and learn (knowing what has happened in past successes and failures, taking lessons from the experiences). Social interactions between stakeholders may contribute to these four abilities and improve the system's resilience.

The subject of Resilience Engineering (RE) is the modeling of interactions in socio-technical systems, with characteristics that may vary according to the system's complexity. These characteristics may be described as follows: (i) interactions occur mostly between neighboring components (Cilliers, 2001), with neighboring referring to physical or intangible (e.g., shared professional or cultural background) proximity (Perrow, 1984); (ii) interactions are non-linear, meaning an asymmetry between input and output, and the occurrence of small events producing large effects in the system (Dekker & Breakey, 2016); (iii) interactions may also occur with the environment, which represents a permanent source of variability (Cilliers, 2001); (iv) interactions are path-dependent, i.e., past performance influences current behaviors (Cilliers, 2001); (v) interactions are dynamic with intensity varying over time (Cilliers, 2001); and (vi) interactions happen between a large number of diverse actors (Page, 2010).

In RE, failure is understood as a maladaptation, in which the system was unable to perform necessary adaptations to handle real problems. Thus, failure is not seen as a breakdown or a malfunction of the system, with the individuals or organization's performance needing to constantly adjust to the prevalent conditions (Madni & Jackson, 2009).

3 Methods

The research method consisted of an online survey sent to different researchers, where they were asked to assess the potential impact of nine Information Communication Technologies on the four basic resilience abilities (monitor, anticipate, respond, and learn), using a 0 (no impact) to 3 (maximum impact) scale. The respondents received an online survey with a short description of the ICT and the resilience abilities, being asked to evaluate their potential impact.

Our sample of experts was determined by convenience through the authors' networks, comprised of 10 individuals with the main characteristics given in Table 3. They hold academic positions and are experienced authors in I4.0 and H4.0, Resilience Engineering, and the intersection of both areas. Works based on highly qualified yet small samples of experts are not uncommon in the healthcare domain, e.g., Johnston et al. (2019); Tortorella et al. (2020b). Ten data tables were considered, one per respondent. We calculated the mean and standard deviation of each table entry and sums of scores in rows and columns, which were used as indicators of the importance of ICTs (rows) and resilience abilities (columns).

Table 3. Information on panel experts

Expert	Years in Academia	Background	Area of Expertise	h-index (Google)
1	20	Engineering	I4.0	22
2	25	Ergonomics	RE	34
3	27	Engineering	RE / I4.0	32
4	6	Ergonomics	RE	5
5	14	Management	I4.0	12
6	25	Management	I4.0	19
7	18	Engineering	I4.0	30
8	7	Design	RE / I4.0	5
9	19	Design	RE	13
10	13	Engineering	RE	10

4. Results and discussion

Table 4 presents the mean and standard deviations (in parentheses) of scores obtained from the respondents. Table entries in bold correspond to evaluations with a coefficient of variation smaller than 20%, which denotes strong agreement among respondents. It is noteworthy that bolded cells also correspond to the largest mean scores in the table, i.e., respondents agree on ICTs that are most likely to have a large positive impact on resilience abilities, indicating consistent responses in more important impacts.

Row and column totals were obtained by adding the mean scores in their respective table rows and columns. Row and column totals are not directly comparable, but the comparison between row totals and columns totals is valid and may be used to rank ICTs and resilience abilities in terms of perceived impact. We note a larger variation in row totals than in column totals.

Results show that Machine/Deep Learning was the ICT with the highest score, with the respondents perceiving this as the one with the most potential impact on the four basic resilience abilities, closely followed by Big Data and the Internet of Things.

Table 4. Mean and standard deviations of scores obtained from respondents

	Monitor	**Anticipate**	**Respond**	**Learn**	**Total**
Biomedical/digital wireless sensor	2.5 (0.85)	1.8 (0.79)	1.5 (0.71)	1.1 (0.99)	6.9
IoT	**2.8 (0.42)***	2.2 (0.63)	2.3 (0.95)	1.9 (1.10)	9.2
Machine/Deep learning	1.8 (1.03)	**2.9 (0.32)***	2.5 (0.53)	**2.9 (0.32)***	10.1
Big data	1.9 (0.99)	**2.6 (0.52)***	2.1 (0.57)	**2.7 (0.48)***	9.3
Cloud/Fog computing	1.3 (0.67)	1.3 (0.95)	1.7 (0.95)	1.9 (0.74)	6.2
Augmented reality/simulation	1.4 (1.26)	2.2 (1.14)	1.6 (1.07)	2.1 (0.88)	7.3
Remote control/monitoring	**3.0 (0.00)***	2.1 (0.74)	2.0 (0.67)	1.1 (0.88)	8.2
3D printing	0.2 (0.42)	0.6 (0.97)	1.4 (1.26)	1.2 (1.03)	3.4
Collaborative robots/robotics	1.5 (1.08)	1.4 (1.26)	2.1 (1.29)	1.6 (0.97)	6.6
Total	16.4	17.1	17.2	16.5	

** Evaluations with coefficient of variation smaller than 20%.*

If, as Arafah & Winarso (2017) proposed, the resilience of a system helps it deal with challenges by dealing with pressures, shocks and threats and ultimately surviving, the adoption of ICTs may significantly help organizations achieve that. More specifically, Machine Learning can help healthcare service professionals to learn from what has happened in the past and apply this knowledge to future circumstances. It is, by definition, an ICT that, through statistical, probabilistic, and optimization tools, uses data from past occurrences to *anticipate*, *respond* and *learn*, potentially improving the entire system's resilience.

Even though Machine Learning presented the highest score in total, other ICTs scored higher in individual resilience abilities. IoT and Remote Control/Monitoring scored the highest in *monitoring,* with Remote Control being the only ICT that had a perfect score out of all the results. Therefore, these two ICTs could be used in healthcare contexts to help professionals understand what to focus on in the present so that it will not become a problem in the future. In addition, similar to Machine Learning, Big Data may be used to *learn* from past happenings to redesign work practices in the future.

For healthcare organizations to work, different actors need to interact. In healthcare contexts, for example, different professionals from various units need to align strategies and courses of treatment, keeping each other in the loop about patients. In this sense, as Page (2010) proposed, for hospitals to give the best possible care to their patients and be resilient, interactions should involve many actors. In connection to the ICTs, the more experts feed the datasets with information, the more accurate the ICT's contributions will be, leading to a more resilient system.

As Bertoni et al. (2021) demonstrated, collaborations from healthcare organization professionals show that each actor has a different resilience ability. Such knowledge may help design the healthcare system, positioning each expert where they may contribute the most, benefiting from the professional's resilience abilities.

When designing a healthcare service, the knowledge that specific ICTs may help a system be more resilient and that different professionals within it may display a different set of resilience abilities is key to building both lean and safe services. The design team should be able to visualize the network of connections between professionals from different areas of the organization. They should map the experts' interactions and design workflows that explore them to promote resilience, making intelligent use of ICTs to expedite communications and decision-making. Results in Table 2 give an overview of how H4.0 and RE experts envision the role of ICTs in the design of resilient healthcare systems. The overall goal is to improve system performance through technology, providing the best possible care to patients.

To better understand the resilience abilities of the system, ICT experts should also work with the design team and healthcare professionals knowledgeable of the organization to identify the best use of ICTs to promote resilience. For example, ICTs that stand out in the *learn* ability should be considered in the design and implementation of training programs. In contrast, those that stand out in the *anticipate ability should* be considered in the medium and long-term planning of the healthcare service.

ICTs with a high impact on *monitor* and *respond* abilities should be considered when redesigning current work processes to promote resilience. As digital technologies became affordable, smaller, and capable of managing large quantities of data, H4.0 implementation has become more feasible (Prieto González et al., 2016). Thus, the increased level of automation and information exchange inherent to H4.0 not only leads to more qualified, faster, and cheaper health services (Ayer et al., 2019) but also allows physicians, nurses, and other hospital staff to benefit from internal and cross-hospital services more efficiently (Alloghani et al., 2018), responding more rapidly and assertively to signals from monitoring devices. The inclusion of ICTs in healthcare systems does not always occur in parallel with the revision of workflows that could benefit from them, opening several improvement opportunities.

5. Conclusions

Experts were asked to individually assess the potential impact of nine Information Communication Technologies on the four basic resilience abilities (monitor, anticipate, respond, and learn). Based on the top three rated ICTs in each ability, it was possible to draw some service design recommendations, which are summarized as follows:

- To increase the ability to know what to focus on (monitoring), the recommendations are (a) design artifacts to remotely control healthcare data, (b) use IoT technologies that allow monitoring service performance. It is also recommended (c) to invest in biomedical/digital wireless sensors to track individual responses to be used both by patients (e.g., to evaluate physical activity) and healthcare workers (e.g., to assess the time spent performing different types of tasks).
- To foster the ability to understand previous successes and failures (learning), the recommendations are (a) adopt machine/deep learning as a systematic tool to learn how to respond to predictable situations, (b) use big data to assess previous good practices and hardships. It is also suggested (c) to design augmented reality/simulation tools to facilitate

learning processes (e.g., technologies for beginners to rehearse medical procedures before applying techniques in human bodies).

- To boost the ability to know what to expect (anticipating), the most relevant recommendations are (a) use machine/deep learning and (b) big data to identify situations that are likely to behave similarly to past ones (e.g., evaluating clinical conditions of new patients at emergency rooms to predict their likelihood of hospitalization). It is also suggested (c) the design of IoT artifacts with the ability to gather information to allow such predictions.
- To increase the ability to know what to do (responding), the recommendations are (a) design machine/deep learning tools based on (b) big data to understand how to apply what was learned in the past to new or improved services. The experts' assessment also indicated that (c) IoT artifacts and robots may be designed to help provide services, applying what was learned.

As future research derived from our findings, two stand out. The first, associated with the Resilience Engineering dimension, concerns teams' design and allocation of professionals across shifts in healthcare services, aiming at groups of professionals with complementary strengths and evenly distributing key resilience players across work shifts. For that, professionals would have to be evaluated regarding their resilience role in the system. The second, associated with the H4.0 dimension, concerns the development of a roadmap to the adoption of ICTs in healthcare systems aiming at supporting the decision on which technologies to prioritize to minimize costs and maximize benefits. The third is to increase the sample size of experts to give the study more generalizability.

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