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Contributions of Industry 4.0 to resilience achievement in the context of COVID-19 pandemic

Saloua SAID*. Hafida BOULOIZ** Maryam GALLAB***

* *Systems engineering and decision support laboratory, Ibn Zohr University, ENSA Agadir, Morocco (Tel: +212 623407567; e-mail: saloua.said.5@gmail.com).*

** *Systems engineering and decision support laboratory, Ibn Zohr University, ENSA Agadir, Morocco (e-mail : h.bouloiz@uiz.ac.ma)*

*** *MIS-LISTD Laboratory, Computer Science Department, Mines-Rabat School (ENSMR), Rabat, Morocco (e-mail: gallab@enim.ac.ma)*

Abstract: In the totally unprecedented context of the COVID-19 health crisis, the widespread adoption of Industry 4.0 technologies, and the great interest in resilience, have been stronger than ever. Within this framework, the present paper outlines the involvement of technologies emerging from the fourth industrial revolution in the fight against the epidemic expansion, and the results of this implication in terms of strengthening and achieving resilience in diverse fields. In order to gain a fuller understanding of these points, fourteen resilience domains related to the COVID-19 pandemic are defined. On the other hand, the third section of this paper digs into the literature to expose a variety of Industry 4.0 solutions developed to cope with the sanitary crisis. Afterwards, a fuzzy cognitive map is elaborated, using mental modeler, in order to emphasize the causal links between Industry 4.0 technologies and resilience domains. Subsequently, a simulation of this model is performed to evaluate the contribution of an optimized joint use of Industry 4.0 core technologies in the achievement of resilience in its different dimensions during the COVID-19 pandemic, and to discuss how the identified gaps or weaknesses can be addressed.

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1. INTRODUCTION

Nowadays, we are witnessing what can be regarded as the most noteworthy and quickly happening series of changes in human history. This profound transformation is the result of the occurrence of great industrial revolutions during the past centuries. Currently, we are in the midst of the fourth industrial revolution, which can be considered as the greatest that humanity has been experienced, since the velocity, scope, and impact of this revolution are unprecedented (Yang and Gu, 2021). In fact, the number of things connected to the internet is substantially increasing each and every day (Kaur and Aron, 2021). Furthermore, there is a convergence of multiple new technologies (artificial intelligence, internet of things, blockchain, autonomous vehicles), which is opening up a whole new world of possibilities and ground-breaking solutions (Schwab, 2017). Nevertheless, nobody can deny that the fourth industrial revolution is behind the generation of numerous risk factors and disruptions, such as cyber and technology risks (intellectual property, data privacy, brand risk, content risk...), investment risks (cryptocurrency), environmental risks (changing weather, energy consumption...), critical supply chains disruption in case of a major outage, and this is due to the enormous dependencies created by Industry 4.0 (Gadekar et al., 2022). All these challenges lead to putting resilience in the midst of preoccupations. This is the ability of a system to adjust, decisively and effectively, its functioning before, during or

after changes or disturbances so that it can continue its operations in a disturbed context as normally as possible (Hollnagel et al., 2008). And like any other capacity, systemic resilience needs to be assessed, whether qualitatively to understand the severity and sensitivity of the situation, or quantitatively to be able to estimate the performance, time, effort, and costs at risk (Proag, 2014). The question then arises as to the role that can be played by Industry 4.0 in enhancing and reinforcing resilience in the face of crises and adverse events. As an example of the latter, the COVID-19 pandemic is selected. This crisis has emerged, without warning, shaking the whole world. It has led, in particular, sociotechnical systems to review their priorities, to redefine their working methods and even to put in the spotlight new dimensions and new criteria for surviving the fallout of the crisis (Kaye-Kauderer et al., 2021). At the top of the list is resilience, which has been named, among other things, as the word of the year 2020 (Leaver, 2020). In the literature, the cause-effect relation between Industry 4.0 and the resilience that has been, and is still eventually, proven in the framework of this sanitary crisis has been extensively investigated. In fact, exploring the improvement of supply chain resilience through Industry 4.0 accounts for the lion's share of recently published papers (Spieske and Birkel, 2021), and several points have been addressed, notably business continuity (Hussain et al., 2021), sustainable and resilient manufacturing (Lee et al., 2022), disruption management (Ivanov & Dolgui, 2020), production recovery (Cugno et al., 2022), and the list goes on. The present

work is an attempt to cover additional aspects of the impact of the use of digital technologies on the achievement of resilience during the COVID-19 pandemic. Moreover, an overall appraisal will be conducted in order to evaluate to what extent the fourth industrial revolution has contributed positively to the reinforcement of resilience in its various dimensions. For this purpose, the remainder of this paper is structured as follows: Section 2 describes the various COVID-19-related resilience domains. Section 3 digs into a set of solutions designed, with the help of Industry 4.0 technologies, to get control over the critical situation. In section 4, the chosen modeling method is revealed, namely fuzzy cognitive mapping. The resilience-Industry 4.0 map is set up and simulated. On this basis, several observations are made.

2. COVID-19-RELATED RESILIENCE DOMAINS

In the current exceptional context of the Coronavirus outbreak, resilience remains the sole and most powerful means of coping with the negative consequences resulting therefrom. All evidence suggests that human resources resilience is the highest priority (Ngoc Su et al., 2021). This resilience domain can be divided into five components (Zhang et al., 2022), which are (1) physical health resilience, including preserving and safeguarding people's health and preventing the spread and transmission of the disease, (2) mental health resilience, consisting of dealing positively with more pressure and drawing strength from it, (3) professional resilience, involving ensuring an efficient remotely work, providing adequate training, and retaining, as far as possible, employee benefits, (4) social resilience, which is about, communication and collaboration, giving and getting support, and sharing time and stories with others, and (5) creative resilience, encompassing innovation, creativity and self-experience. The second resilience domain is supply chain resilience. This integrates (1) getting into the manufacturing of elements and instruments used in the fight against the virus, such as masks and hydro-alcoholic gels, through expanding the plant by installing new production lines or migrating to new activities in order to fulfill the needs generated by the health crisis, (2) implementing smart supply chains in order to optimally manage the provision of medicines and medical devices, (3) innovating revolutionary solutions, and (4) building the integrity of supply chain through ensuring trust among the different stakeholders (suppliers, consumers...) (Ozdemir et al., 2022). The third domain is data resilience, which consists in addressing the lack of data necessary for carrying out studies, analyses, and assessments in order to be able to make well-informed and resilient decisions (Record et al., 2022). As for information resilience, it is based upon spotting and eliminating wrong and fake information and circulating reliable facts (Bin Naeem and Kamel Boulos, 2021). Financial resilience comprises effective management of assets during the crisis and avoiding bankruptcy (Danisman et al., 2021). Regarding regulatory resilience, it concerns assuring that the sanitary measures called for, are widely respected (Kaine et al., 2022). IT resilience is another important COVID-19-related resilience domain. This revolves around building cybersecurity awareness and ensuring the continued availability of digital services while reducing costs and increasing efficiency (Groenendaal and Helsloot, 2021). Traceability for resilience

is about tracking and monitoring the propagation of the epidemic, which is beneficial to the enhancement of both physical health resilience and data resilience (Georgieva et al., 2021). Moreover, reducing the harmful effects of climate change and pollution, preserving natural resources, and decreasing energy consumption, constitute the pillars of the environmental resilience (Ramanathan et al., 2021). The following illustration (Figure 1) summarizes the different COVID-19-related resilience domains.

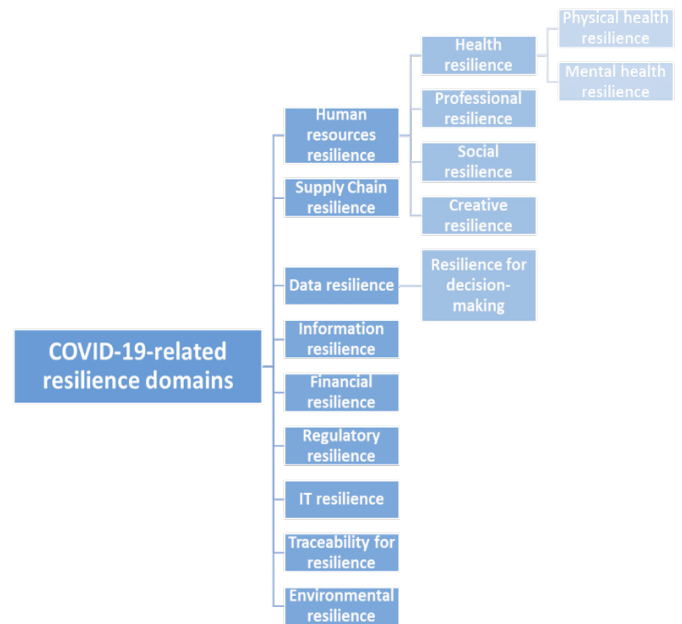


Figure 1. COVID-19-related resilience domains.

The next section will provide a brief overview of the diverse possibilities offered by Industry 4.0 technologies to reinforce the different aforementioned resilience aspects.

3. INDUSTRY 4.0 SOLUTIONS

COVID-19 pandemic can be considered as the biggest corporate stress test of all time. Nevertheless, the technological advances brought about by the fourth industrial revolution have created tremendous opportunities to overcome this difficult period. In fact, artificial intelligence was the World Health Organization's first recommendation for a computer science branch that may provide a very valuable assistance in mitigating the potentially devastating effects of the pandemic (Al-Turjman, 2021). Indeed, since the onset of the crisis, many AI-based solutions have emerged with the primary objective of strengthening physical health resilience by evaluating and predicting the contamination risks using machine learning techniques. It is also worthy of note that data resilience can positively influence the development of powerful AI-tools since the lack of data can restrict the utilization of this technology. Furthermore, artificial intelligence can make an effective contribution to boosting information resilience via detecting and removing misleading information. Moreover, the lion's share of solutions, dedicated to increasing resilience under the umbrella of crisis, accounts for the Internet of Things or IoT devices (Javaid et al., 2020). Indeed, through the use of sensors, data are collected, analyzed, and operated in order to take enlightened decisions. Therefore, resilience for decision-

making and data resilience are supported, but also supply chain resilience, thanks to automated manufacturing, and smart supply chain, made possible mostly with the help of sensors, RFID tags, and other methods serving to associate physical assets with digital mirror (Kumar et al., 2020). Internet of things helps financial institutions as well to offer consumers a better and more satisfying experience whilst optimizing costs, efficiency, and security. In addition, drones or “flying IOT” served, during the pandemic, to ensure that restrictive measures are applied properly, and thus improve the regulatory resilience, but above all, foster the physical health resilience. Traceability of the origin of the outbreak is also among the perceived strengths of this technology. Autonomous vehicles and robots have been involved in the battle to tackle the pandemic. Their mission is to promote both physical health resilience and professional resilience throughout keeping some vital occupations that cannot be practiced remotely operational without impairing the health and the safety of workers. Unsurprisingly, big data and cloud computing brought relief for further enhancing respectively data resilience and IT resilience. With respect to virtual reality, it helps to unleash the creative potential by providing attractive innovative simulations. Additionally, it facilitates communication and collaboration by means of video calls. In this case, creative resilience, professional resilience, and social resilience are emphasized. The latter two resilience domains, aside from physical health resilience, are also supported by holography. What is more, 3D printing advocates the environment protection by seeking to substitute disposable masks, which have a substantial impact on the environment, with NanoHack 3D-printed mask that is recyclable and reusable (Radfar et al., 2021). With reference to blockchain technology, it can be seen as an appropriate remedy to solve the issue of lack of mutual trust amid supply chain stakeholders, and hence deepen the supply chain resilience through the use of smart contracts as well. However, a number of studies are currently in progress to verify whether the crypto market can be a safe haven in times of crisis (Vukovic et al., 2021). Into the bargain, the environmental concerns of Proof of Work are not in favor of improving environmental resilience.

With the aim of modeling the behavior of resilience domains in the use of Industry 4.0 technologies, we opt for fuzzy-Logic cognitive mapping. This is an approach extensively used for modeling complex systems through highlighting the interrelationships between the key attributes, which are liable for the dynamic behavior of the systems (Shahid and Singh, 2019). This methodology is being more frequently employed in the scientific literature and has demonstrated its effectiveness since it combines the qualitative analysis with the quantitative one, integrates existing knowledge and experience in order to deal with the shortage of information, and ensures an intuitive interpretation of the results (Malek, 2016). In fact, several fuzzy-Logic cognitive maps have been suggested in order to assess Industry 4.0 tendency (Kiraz et al., 2019), and model (Erkan et al., 2021). This tool has been also associated with some Industry 4.0 technologies with the aim of supporting decision-making during the COVID-19 pandemic (Loia and Vona, 2021). In addition, fuzzy-Logic cognitive mapping has helped, on numerous occasions, in exploring and assessing resilience (Bottero et al., 2017).

4. FUZZY-LOGIC COGNITIVE MAP

Fuzzy cognitive maps (FCMs) form a graphical method of representing causal connections between different items. This was first introduced by Bart Kosko in 1986 (Kosko, 1986). This relies upon fuzzy logic since binary reasoning is mainly digital, whereas fuzziness closely resembles the way in which a human being makes judgements and decisions. In this particular instance, a fuzzy cognitive map is established, using mental modeler (Gray et al., 2013), with two types of components, resilience domains and Industry 4.0 technologies. This map is illustrated by figure 2.

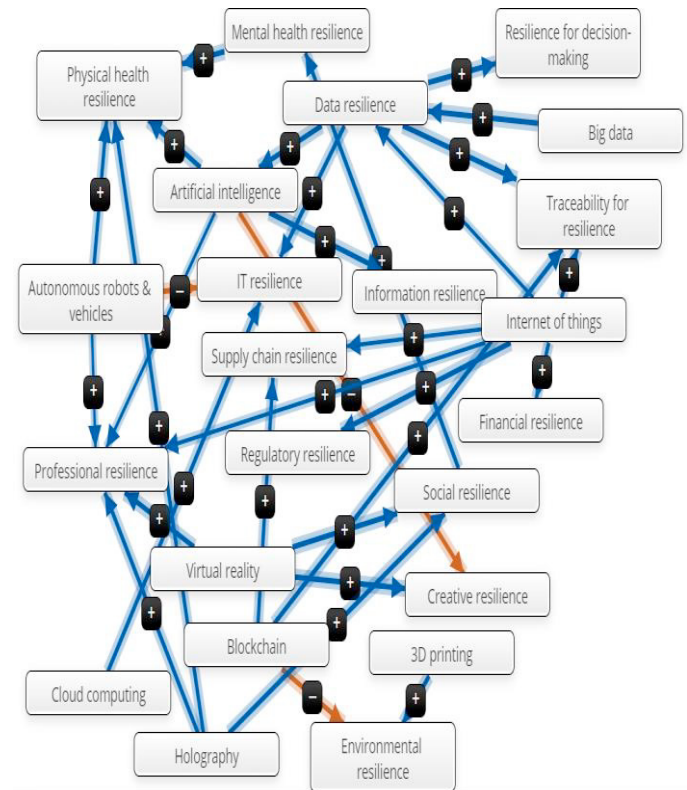


Figure 2. Resilience-Industry 4.0 map in the COVID-19 context.

According to the resilience-Industry 4.0 map, the use of artificial intelligence increases the physical health resilience with a weight of 1, the professional resilience with a weight of 0.5 because there is also a negative impact generated by this link, which is the unemployment risk (Yang, 2020). On the other side, it is well known that artificial intelligence stifles creativity (Suchacka et al., 2021), and this leads to a decrease of creative resilience with a weight of -1. As explained previously in section 2, artificial intelligence can play an important role in improving the information resilience during adverse events. Therefore, there is a positive connection between these two components with a weight of 1. On the other hand, the lack of data resilience can negatively affect the use of the artificial intelligence, hence the positive relationship between these two elements with a weight of 1 is highlighted. Regarding internet of things, the increasing use of this technology fully helps to enhance regulatory resilience, traceability for resilience, and financial resilience. Consequently, positive causal links with a weight of 1 connect these different items. Furthermore, internet of things can have

a positive effect, but also some drawbacks on professional resilience (unemployment risk), supply chain resilience (dependencies), and data resilience (data privacy issues). Out of this fact arose three positive connections with a weight of 0.5 for each of them. As for the blockchain technology, it increases, with a weight of 1, supply chain resilience and traceability for resilience. However, it decreases the environmental resilience with a weight of -1, as mentioned earlier in section 3. Unlike blockchain, 3D printing relates positively to environmental resilience with a weight of 1. There is also a positive connection with a weight of 1 between, respectively, big data and data resilience, on the one hand, and cloud computing and IT resilience on the other hand. As regards virtual resilience, it influences favorably professional, social, and creative resilience with a weight of 1 for each of them. The same thing applies to holography, which has positive links with professional resilience, social resilience, and physical health resilience as well. The latter is positively affected by the use of autonomous vehicles and robots. This is interpreted by a positive causal link with a weight of 1 between the two components. This technology also supports the professional resilience, but because of the unemployment risk that it represents, a weight of 0.5 is assigned to this positive connection. Moreover, the rising cyber-security threats generated by autonomous vehicles and robots negatively affect the IT resilience with a weight of -1. Further, it is noted that social resilience has a positive impact on mental health resilience, and the latter, in turn, contributes to the reinforcement of the physical health resilience. The weight equals 1 for both connections. For its part, data resilience has a broader positive impact on several resilience domains, which are IT resilience, resilience for decision-making, and traceability for resilience. Data resilience also helps to step up the efficiency of artificial intelligence use. This entails positive causal links, with the weight of 1, between data resilience and the other aforesaid elements.

Based on this model, we can identify the most implicated Industry 4.0 core technologies in boosting resilience during the COVID-19 pandemic. The following table (table 1) provides a classification of these technologies according to the centrality of the corresponding nodes in the resilience-Industry 4.0 map.

Table 1. Industry 4.0 technologies ranking

Industry 4.0 technology	Centrality
Internet of things	4.5
Artificial intelligence	4.5
Holography	3
Virtual resilience	3
Blockchain	3
Autonomous robots & vehicles	2.5
Cloud computing	1
Big data	1

3D printing	1
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It is clear from examining table 1 that internet of things and artificial intelligence are the most widely used technologies in the development of solutions to fight the disease. Holography, virtual reality, and blockchain come in second place, followed by autonomous robots and vehicles, and then cloud computing, big data, and 3D printing. This definitely impacts the classification of targeted resilience domains, which is shown in table 2.

Table 2. Resilience domains ranking

Resilience domain	Centrality
Data resilience	5.5
Physical health resilience	4
Professional resilience	3.5
Traceability for resilience	3
IT resilience	3
Social resilience	3
Mental health resilience	2
Environmental resilience	2
Creative resilience	2
Supply chain resilience	1.5
Financial resilience	1
Resilience for decision-making	1
Regulatory resilience	1
Information resilience	1

In the context of the present study, the established causal links, between Industry 4.0 technologies and COVID-19-related resilience domains, show that data resilience can be considered as the door to the achievement of other aspects of resilience. Moreover, it comes as no surprise that physical health resilience is the second most important resilience domain within the context of the COVID-19 pandemic. Professional resilience has also received considerable attention since the breaking out of the crisis. Traceability for resilience (tracking the spread and trend of the pandemic), IT resilience (accelerated digital transformation), and social resilience (in response to social isolation during COVID-19 lockdown) are in the fourth position, followed by mental health, environmental, and creative resilience. Then, we find supply chain resilience, financial resilience, resilience for decision-making, regulatory resilience, and information resilience.

What is crystal clear is that the ultimate objective is to ensure the enhancement of all resilience domains on the same footing

and with the same emphasis whilst taking advantage of Industry 4.0 technologies to the maximum extent possible. By simulating our model under a scenario where all Industry 4.0 technologies are efficiently implemented together, the results described by figure 3 are obtained. In fact, physical health resilience and professional resilience will be at the top of the list of boosted resilience domains. This will allow to protect the human health by limiting the spread of the disease and also guarantee a better work experience through supporting efforts to achieve work-life balance. Traceability for resilience will also be reinforced, which may shape the patterns of the future and support sustainability. Thirdly, social resilience will be further improved. Then, supply chain and data resilience, which are two interconnected resilience domains, will be strengthened and that can have a hugely positive impact on other resilience aspects, notably professional resilience.

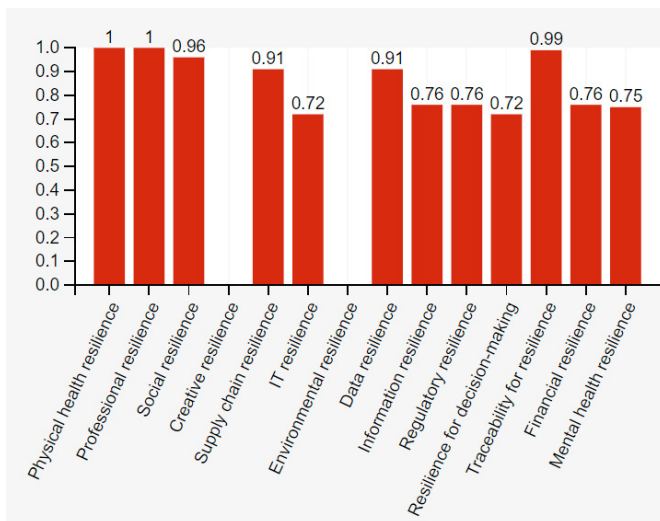


Figure 3. Simulation of the resilience-Industry 4.0 map

Afterwards, information, regulatory, and financial resilience are considered. Mental health resilience is 75% enhanced as well. Finally, resilience for decision-making and IT resilience are increased by 72%. This said, creative resilience and environmental resilience are not included in the list of fostered resilience domains. Indeed, despite the multitude of advantages associated with Industry 4.0, the latter heightens concerns regarding environment. As a consequence, more effort is required on behalf of industrial systems in order to fight against climate change through achieving carbon neutrality, increasing energy efficiency by using renewable sources of energy, and reducing greenhouse gas emissions. Natural resources should also be preserved by sustainably managing water resources and using recyclable materials. All these actions can pose significant challenges for companies since the scarcity of resources and the implementation of a transition to a low-carbon economy could increase production costs, disrupt operations, and thus adversely impact other resilience aspects, for instance supply chain resilience. On a different note, the near total dependence on modern technology today can be considered pretty alarming in terms of human creativity. In a broader context, sociotechnical systems can make use of this model to estimate the potential impact of the application of Industry 4.0 technology on the resilience of their different processes and resources, and

therefore develop the actions necessary to handle the adverse effects. Examples may include, replacing Proof of Work with Proof of Authority to reduce the negative consequences of blockchain technology on the environmental resilience, promoting innovation among employees in order to foster creative resilience and minimize human dependence on artificial intelligence, and managing the challenges associated with implementing digital and smart supply chains.

Future work concerns a deeper analysis of the role that can be played by Industry 4.0 in the improvement of critical resilience domains (IT resilience or cyber resilience, resilience for decision-making, environmental resilience, and creative resilience) through the use of other modeling methods, such as agent-based modeling and optimization algorithms.

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