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Towards The Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems

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Abstract

Most recently, the COVID-19 pandemic has shown industries all around the world that their current manufacturing systems are not as resilient as expected and therefore many are failing. The workforce is the most agile and flexible manufacturing resource and simultaneously the most fragile one due to its humanity. By making human operators more resilient against a range of factors affecting their work and workplaces, enterprises can make their manufacturing systems more resilient. This paper introduces "The Resilient Operator 5.0" concept, based on human operator resilience and human-machine systems' resilience, providing a vision for the future of work in smart resilient manufacturing systems in the emerging Industry 5.0 hallmark. It suggests how to achieve appropriate smart manufacturing systems' resilience from a human-centric perspective through the means of the Operator 4.0 typology and its related technical solutions.

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Keywords: Resilience; Human Ingenuity; Operator 5.0; Operator 4.0; Industry 5.0; Industry 4.0; Smart Manufacturing Systems; Human-Machine Systems.

1. Introduction

During 2020, the COVID-19 pandemic has not only disrupted supply chains but also greatly affected shop floor operations, exposing in many cases the absence of a *resilient workforce.* The pandemic has put the spotlight on the lack of preparedness for risk and crisis management in the manufacturing industry, calling for smarter and more resilient manufacturing systems.

A *Smart Manufacturing System* – can be described as "the marriage of information, technology, and human ingenuity to bring a rapid revolution in the development and application of manufacturing intelligence to every aspect of a business" [1]. In this definition, – *Human Ingenuity* – is at the heart of such a revolution, combining in a creative and resourceful way the available information and technology to create new solutions that are adapted to face the realities of the business challenges, problems, or opportunities at hand. Hence, *Human Ingenuity* can be seen as a *frugal innovation capability,* which resides in the workforce, and that can be described as the art of doing more with less in light of difficult conditions [2]. Such *creativity* and *resourcefulness* in the workforce can allow transforming adversity into opportunity, coming up with *frugal solutions* for the challenges faced by a business.

Moreover, a *Resilient Manufacturing System* – can be defined as a "system with the ability to adjust its functioning prior to, during, or following operational changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [3]. Such *resilience* can be observed in the extent to which manufacturing activities are able to withstand and/or quickly recover from operational disruptions that pose as threats to the continuity of manufacturing operations at the desired level [4,5].

In both 'ilities' of a sustainable manufacturing system, smart and resilient, *human operators* must adjust what they do and how they do it, and what machines do and how they do it, to match current demands and available resources to the realities of the business operations at the moment. Hence, humans are indispensable in all situations involving change. Therefore, as the Industry 4.0 paradigm builds *smart* and *resilient capabilities* in the next generation manufacturing systems, it should also be doing the same for the workforce that will operate them.

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This position paper builds upon the vision and paradigm of the *Operator 4.0* [6,7], introducing the concept of the "Resilient Operator 5.0" – *as a smart and skilled operator that uses human creativity, ingenuity, and innovation empowered by information and technology as a way of overcoming obstacles in the path to create new, frugal solutions for guaranteeing manufacturing operations sustainable continuity and workforce wellbeing in light of difficult and/or unexpected conditions.* This research aims at providing a pathway towards a *Resilient Workforce,* thus approaching *Resilient Manufacturing Systems,* by making human operators – being the most agile and flexible resource in a manufacturing system while simultaneously the most fragile one – more resilient against a range of factors affecting their work and workplaces such as biological, physical, cognitive, and psychological influences having a direct or indirect impact on the "resilience" of a manufacturing system.

This paper is structured as follows: Section 2 sets the sense for the need for resilience; Section 3 discusses the engineering of smart resilient manufacturing systems – from a human-centric perspective; Section 4 addresses evolution towards Industry 5.0; Section 5 presents "The Resilient Operator 5.0" vision; Section 6 highlights the need to improve workforce resilience as shown by the COVID-19 pandemic; Section 7 suggests research domains in support of increasing workers' resilience, and Section 8 provides conclusions and outlook.

2. Setting the Scene for "The Need for Resilience"

Most recently, the COVID-19 pandemic has shown industries all around the world that their current manufacturing systems are not as *resilient* as expected and therefore many are failing. To this black swan event, other adverse realities in the global industrial landscape can be added, such as resource scarcity, climate change, skills gaps, etc. Thus, calling for new VUCA operations management models able to cope with, for example, the *Volatility* of operational changes in the shopfloor as new rules emerge for all possible work situations; the *Uncertainty* of sourcing, production, and demand management as supply chains try to find balance again; the *Complexity* of on-site, remote, and hybrid concurrent operations; and the *Ambiguity* of the "new normal" as there are no best practices that organisations can follow to manage the challenges caused by the pandemic. Hence, while implementing quick fixes to ongoing operations to "secure their continuity" in short-term, enterprises should also focus on developing *resilience capabilities* to sustain their operations in the long-term as political, economic, socio-cultural, technological, environmental, and legal forces may amend their current business and operating models in unexpected ways.

3. Engineering Smart Resilient Manufacturing Systems

According to [8], *Resilience* is a multi-faceted capability of a system that encompasses avoiding (anticipation), withstanding (absorption), adapting to (reconfiguration), and recovering from (restoration) expected and unexpected disruptions. Moreover, *Smartness* is the capability of a system to incorporate functions of sensing, actuation, and control in order to describe and analyze a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing intelligent actions both with and without human intervention [9]. Based on these two definitions, a *Smart Resilient Manufacturing System* can be defined *as an agile and flexible/reconfigurable system that uses smart sensor systems and descriptive, predictive, and prescriptive analytics techniques to collect and analyze in real-time operational and environmental data to anticipate, react, and recover from a disruption.*

The *Engineering of Smart Resilient Manufacturing Systems* can be illustrated as a digital transformation journey that implies the adoption of different smart manufacturing technologies [10] and the development of the ability to timely interpret any event or phenomenon within such systems and from their environment, which may affect their operational continuity, and autonomously react to it. Nevertheless, the *level of automation* in the reaction may vary depending on the sophistication of the manufacturing system capabilities making in most of the cases when change is needed human intervention required [11]. Therefore, the *degree of resilience* of a manufacturing system will depend on one side of the resilience of its weakest sub-system. This will in many cases be the human system due to its (human) fragility. On the other side, it will rest on its strongest sub-system, which may be also the human system because of its intuitive abilities to avoid adverse outcomes or doing better than expected when confronted with unprecedented challenges. Hence, it can be argued that in order to engineer a true *Smart Resilient Manufacturing System,* the proper balance between manufacturing activities' automation and mechanization [12], and human and artificial intelligence will be required to develop *manufacturing intelligence* [13,14] and adopt *resilience heuristics* [8] such as *human-in-the-loop* – when there is a need for rapid cognition and creative option generation [15], and *human backup* – when (human) operators should backup automation when there is a context change that automation is not sensitive to.

Moreover, [16] has identified three stops on the road to failure of any system: (i) failing to anticipate a problem before it has arrived, (ii) failing to perceive a problem that has actually arrived, and (iii) failing to attempt to solve a problem once it has been perceived. Avoiding these situations happening in the operations management of a manufacturing system requires a socio-technical strategy combing people, data, and technology. For instance, by developing *predictive capabilities* to anticipate a problem and take proactive action to prevent it (e.g., predictive maintenance strategies) or *visibility capabilities* to notify about the existence of a problem and create awareness of the given issue (e.g., *Andon* systems), or by creating a problem-solving culture in the workforce that combines creativity, ingenuity, and innovation with experience (e.g., *Kaizen* philosophy).

4. Evolution from Industry 4.0 to Industry 5.0

Industry 5.0 has its roots in the Industry 4.0 concept and aims at re-founding and widening the purpose of digital and smart technologies beyond producing goods and services for profit and focusing on creating true prosperity, which must include social and environmental gains. *Industry 5.0* – recognises "the power of industry to achieve social goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the centre of the production process" [17]. In this new quest, the *Operator 4.0 vision* [7] has already addressed the social sustainability and human-centricity requirements of the Industry 5.0 [7,18,19], and now its next-generation referred here as the "Operator 5.0" adds the resilience capability to complete the new Industry 5.0 hallmark (see Fig. 1).

Industry 4.0			Industry 5.0	
Human-Centric Technologies	Developing and Adapting Technologies for Human Collaboration & Augmentation [Operator 4.0]	►	Human-Automation Symbiosis	Harmonizing the Union of Technology with Humans for System-Resilience [Operator 5.0]

Fig. 1. Beyond Industry 4.0 towards Industry 5.0

5. Towards The Resilient Operator 5.0

The *Resilient Operator 5.0 vision* is twofold, focused on one hand on creating "self-resilience" for the workforce due to its natural (human) fragility, and on the other hand on "system-resilience" for all human-machine systems in a manufacturing system where human operators and machines cooperate to ensure the optimal operation of the overall system.

Self-resilience – is concerned with the biological, physical, cognitive, and psychological occupational health and safety as well as productivity of each operator on the shop floor. While *System-resilience* – addresses alternative ways in which human-machine systems can continue functioning by *sharing & trading control* [20] between human and machine in order to guarantee system operational continuity.

Within the scope of "self-resilience", *biological resilience* refers to the ability of an operator to keep industrial hygiene in terms of occupational health and safety, which can be aided by the use of smart healthcare wearable devices and smart personal protective equipment; *physical resilience* refers to the ability of an operator to maintain stamina and strength in face of demands, which can be aided by exoskeletons technology providing that extra needed muscle power, protection, and endurance; *cognitive resilience* refers to the ability of an operator to maintain mental ability under stress and avoid human-error, which can be aided by augmented reality technology acting as a digital assistance system, and *psychological resilience* refers to the ability of an operator to emotionally cope with a crisis, which can be aided by virtual reality technology offering a safe (virtual) environment for training for risk and crisis management.

Moreover, within the scope of "system-resilience", *human-machine systems resilience* refers to the ability of human and machine systems to demonstrate *adjustable autonomy* [21] by varying their own autonomy and *sharing & trading control* [20] to maintain the cooperative system operational performance at the sweet spot between convenience, comfort, and continuity.

5.1. Engineering Self-Resilience in the Operator 5.0

The *Operator 4.0 typology* proposed by [7] offers a framework for exploring human-technology integration, which can be aimed at addressing the multi-faceted nature of the *self-resilience of the Operator 5.0.*

Firstly, *avoiding disruption* requires *anticipation,* which goes beyond traditional occupational health and safety considerations and encompasses, in this case, the human ability to detect a drift towards his/her own system brittleness, a harbinger of potential accidents [8,22]. Such *anticipation ability* can be enabled and aided in the workforce by developing "predictive capabilities", which are showcased by the *Analytical Operator 4.0-type* [7]. This type of Operator 4.0 combines his/her own *human intuition* with the power of (big) data analytics, particularly predictive analytics, to aid his/her cognitive abilities (i.e., gut instinct) for decision-making and action-taking under uncertain situations (e.g., risk situations) or when predictions about unknown future events should be made. Hence, the combination of advanced data analytics and human intuition adds up to the *human judgement* that becomes more capable and effective with "data-informed" approaches when faced with uncertainty towards "data-based gut feelings" [23]. For instance, when managing occupational risks, workforce safety training can be aided by smart personal protective equipment [24-26], which can allow enhancing the human operator intuition and experience in occupational risks prevention and management by actively ensuring his/her safety in dangerous situations via alerting in real-time (warning signals) the worker of possible exposure to risk factors and providing him/her with relevant information to properly manage them.

Secondly, *withstanding disruptions* requires *robustness* to absorb and survive unprecedented situations without drastic system changes, and "robustness" is achieved by developing shock absorbers [8,22] to enable in this case a human system, the worker, to withstand disruption (e.g., a stressful situation). Such *robustness ability* in the workforce can be achieved by training workers in risk, crisis, and stress management, and by real-time monitoring of the operators' cognitive and physical workloads and performance under risk and stressful situations to securely manage their levels of occupational effort and stress when demanding from them an "extra" physical and/or mental effort to overcome, for instance, a crisis (e.g., an unprecedented workload or working condition). In this kind of situations, the *Healthy Operator 4.0-type* [7,27] takes advantage of biometric wearables and other types of sensors to real-time monitor the physical and mental state of the workers to determine risks and send early warning signals to prevent threats to the operator's health and safety when required to work under pressure or any other adverse condition.

Thirdly, *adapting to unexpected change* requires the ability to adjust to "new" circumstances through re-configuration and dynamic re-optimization of available capacity and resources [8, 22]. In this situation, humans are considered the most adaptable and capable system within a manufacturing system to respond to disruptions due to their creativity, ingenuity, and innovation capabilities [1,2]. In this scenario, the *Operator 4.0 typology* [7] explores different technological means for supporting and aiding the cognitive and physical work of operators in three possible ways: assisted work, collaborative work, and augmented work when faced with different and challenging tasks to be performed and decisions to be made under adverse circumstances and/or conditions. Thus, offering varying working forms that aim at, for example, satisfying needed safety and productivity levels, considering unprecedented working forms for unprecedented working conditions. For instance, the *Super-Strength Operator 4.0-type* aims at increasing the strength of a human operator by wearing "exoskeletons" for effortless manual functions when endurance and flexibility are required; the *Augmented Operator 4.0-type* aims at improving information transfer from the digital to the physical world by overlading it in real-time in the worker field-of-view by employing "augmented reality devices" such as smart AR glasses or spatial AR projectors to support complex assembly and maintenance operations even by workers with low levels of skills for conducting such intricated operations; the *Virtual Operator 4.0-type* aims at providing workers with a "virtual reality environment" to explore the outcomes of their decisions/actions without putting themselves or the workplace at risk when training for risky operations and situations; the *Smarter Operator 4.0-type* aims at utilizing "intelligent personal assistants" to avoid information and task overloads that may lead to poor (work) performance, thus employing smart AI-based interfaces to interact with machines, computers, databases, and other information systems to seamlessly execute (e.g., using voice-commands) standardized tasks and services on behalf of the worker so he/she can concentrate in more valued-added tasks; the *Collaborative Operator 4.0-type* aims at cooperating with "collaborative robots" in order to allocate to them those precise and repetitive tasks and focus on those tasks that require human dexterity and problem-solving capacity; and the *Social Operator 4.0-type* aims at connecting himself/herself to the social internet of things, service, and people [28] through the use of different "enterprise social networking services" to interact, share, and create information and knowledge for collaborative decision-making and problem-solving [7,29].

Fourthly, and lastly, *recovery from unprecedented situations* implies not only the ability to *restore* a system's pre-disruption state, which is the central focus of system resilience – but also the ability to *learn and guide proactive changes* in a system by making safety-risk trade-offs to create preparedness for future unprecedented situations [8,22]. Moreover, in a human system context, *recovery* implies a period of disruption to normal work performance for some time before the worker returns to his/her normal performance. During this (recovery) time, the worker reflects and learns from his/her newly acquired knowledge and experience and adapts himself/herself to become a smarter and more resilient operator in the face of future (similar) challenges and problems. In this scenario, the *Healthy Operator 4.0-type* [7] can help to monitor the full-recovery of the worker physical and mental health before returning to a normal workload, and the *Social Operator 4.0-type* [7] can support knowledge sharing by promoting workforce collaborative learning and adaptation without having to suffer a painful learning experience.

5.2. Engineering System-Resilience with the Operator 5.0

Furthermore, the multi-faceted nature of *resilience* can also be addressed in *human-machine systems,* for instance, in human-robot collaboration work cells. *Engineering system-resilience with the Operator 5.0* in human-machine systems [30] implies designing work cells with *adaptive automation* [31] in mind and with *adjustable autonomous human and machine agents* [32] so their unique capabilities can be leveraged at all times and situations. Hence, the main envisaged goals of *adaptive automation* are to prevent errors and to reduce out-of-the-loop system performance [31] by sharing & trading control [20] between "adjustable autonomous" but "cooperative" human and machine agents as the mean of *resilience* for the human-machine systems.

Firstly, when the objective is to *avoid disruption* in human-machine systems, both human and machine agents should aim to avoid the occurrence of undesirable events and protect the human-machine system from the consequences of such events. In this scenario, on one hand, the *Analytical Operator 4.0-type* [7] is presented as a (human) agent combing advanced data analytics and human intuition aimed at his/her self-resilience, and on the other hand, a *Smart Machine Tool* [33] as an (artificial) agent with prognostics and health management capabilities [34] aimed at its self-resilience, both creating a "joint cognitive system" [35] focused on increasing the *predictive capabilities* of the human-machine system and alerting each other of potential disruptions that may affect the other or both in support of the overall *system-resilience.*

Secondly, when it has to do with *withstanding disruptions* in human-machines systems, sharing & trading control strategies [20] will play a key role to keep the performance of the system in case of critical-events. The adjustable autonomy of the system agents [32] and the adaptive automation of the system itself [31] allows the human operator and/or the machine to modify tasks allocation by shifting control of specific functions whenever predefined conditions are met to sustain the human-machine system performance [20]. In this context, the different *Operator 4.0-types* [7] and their cognitive and physical augmentations can help make (temporarily) human operators as good as a machine in a task that was being performed originally by it, for instance, a "Load-Unload Robot" vs. the "Super-Strength Operator 4.0".

Thirdly, when it comes to *adapting to an unexpected change* in human-machine systems, while adaptive (smart) machines [36] are capable to change over on-the-fly and re-configure or re-optimize using their different available production modules, only human operators are capable of contributing to *creative response capacity* [37] by finding solutions to problems without obvious tools or materials. So, in this case, human operators provide the highest contribution to the *system-resilience* due to their agility and flexibility as well as human ingenuity to adapt and also to contribute to the adaptation of a machine to sustain the human-machine system performance. For example, when the *Social Operator 4.0-type* [7] performs creative and collaborative problem-solving in interaction with all sorts of resources [28].

Fourthly, and lastly, when *recovering from unprecedented situations* in human-machine systems, it is important to look at the progress being made in "self-healing" machine tools [38] as well as in human-machine "mutual learning" systems [39,40]. Both research streams are essential to human-machine systems resilience, particularly human-machine mutual learning systems which should allow human operators and (smart) machines to learn from each other, so human operators, for instance, can better troubleshoot the next-generation of machine tools when self-healing functionality is not possible for system recovery.

In this case, the *Augmented and Virtual Operator 4.0-types* [7] offer relevant assisting means for supporting human operators in maintenance, repair and overhaul operations (see e.g., [41]).

6. The COVID-19 Pandemic Scenario

The COVID-19 crisis highlighted the need to re-think existing manufacturing and logistics systems as well as working forms as it has put on the spotlight the lack of *resilience* of various industries, and particularly of their workforces. In this scenario, it can be possible to showcase how human creativity, ingenuity, and innovation – empowered by information and technology – were put into action to overcome the challenges presented by the COVID-19 pandemic to guarantee manufacturing operations continuity and workforce wellbeing in the "new normal" [42]. For example, different *smart wearable technologies* [42] such as smart-watches, smart-gloves, smart-glasses, smart-speakers, and smart-exoskeletons were adapted and adopted on the shop floor as "smart personal protective equipment" to empower the workforce with real-time information and hands-free tools to increase their productivity and work quality at the same time that a safer and healthier working environment was being promoted to countermeasure the COVID-19 virus effects, which require new operational safety and occupational health requirements; for instance: social distancing, low-touch, and contact tracing. Or *collaborative technologies* [42] like collaborative robots, autonomous or guided mobile robots, drones, and computer vision systems also facilitating social distancing, creating low-touch or no-touch human-machine interfaces, and contactless deliveries on the shop floor (see [42] for detailed examples).

7. Discussion

The *system-resilience* of a manufacturing system as a whole or of its human-machine (work cell) systems – is as good as – the resilience of its weakest sub-system, which in many cases may be the human system due to its inherent human fragility. Hence, when engineering *smart resilient manufacturing systems* with an *Industry 5.0 vision* [17], a *human-centric perspective* should be taken addressing human-operators' resilience as individual agents as well as cooperative agents within the exiting human-machine systems of a manufacturing system. Demonstrating in this way different working forms such as assisted, collaborative and augmented work [7,43] in which workers and automation, robotics, and artificial intelligence can operate in harmony and increasing productivity, quality, performance, satisfaction, and safety towards smart resilient human-machine systems [12,17]. To do so and addressing the three main features of *Industry 5.0:* human-centricity, (social) sustainability, and resilience [17], the following research domains can be considered as assisting means, but not limited to.

For *human-centricity, Human-Centred Automation* [44-47] – as automation, robotic, and artificial intelligence systems designed to work cooperatively with humans in support of their cognitive and physical workloads as well as the overall system performance.

For *sustainability,* particular attention should be put on the *Social Sustainability of Manufacturing* [48] – as the less addressed constituent part of three pillars of "sustainable manufacturing". Hence, detailed guidelines should be developed and provided to the industry emphasizing the design of work and workplaces that aim to empower and engage all workers, so that workers can understand and develop their own competences and take an active role in developing the manufacturing environment [49].

Lastly, for *resilience, Resilience Engineering* [3,8,22,30] – applied to human, machine, and human-machine systems at individual and systemic-bases, engineering in these systems the ability to avoid, withstand, adapt and recover from disruptions and unprecedented situations alone and collaboratively.

8. Conclusions & Outlook

This paper has reflected on the human operators' resilience as well as human-machine systems' resilience in the context of smart resilient manufacturing systems and Industry 5.0. It has provided a human-centric, socially sustainable, and resilient vision for the future of work in smart resilient manufacturing systems for the "Resilient Operator 5.0". A *Next-Generation Operator,* which evolves from the *Operator 4.0 vision* [7] that aims to build trusting relationships (interaction-based) between humans and machines (incl. automation, robotic, and artificial intelligence systems), making it possible for those truly smart resilient manufacturing systems to capitalize not only on smart machines' strengths and capabilities but also to empower their smart operators with new skills and gadgets to fully capitalize on the opportunities being created by Industry 4.0 technologies, and achieve new levels of efficiency, productivity, and resilience that neither human systems nor machine systems can achieve on their own. A paradigm which is known as "human-automation symbiosis" [50] (see also [6] & [12]).

Looking into the future, much work remains to be done, particularly when it comes to multidisciplinary research efforts, to address the multi-faceted nature of *resilience,* so industries can prepare their workforce and manufacturing systems against a wide range of factors that may affect the future of work and workplaces in the VUCA horizon.

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