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Workforce and supply chain disruption as a digital and technological innovation opportunity for resilient manufacturing systems in the COVID-19 pandemic

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ABSTRACT

During the SARS-CoV-2 pandemic (also known as COVID-19), workforce downsizing needs, safety requirements, supply chain breaks and inventory shortages affected manufacturing systems' and supply chain's responsiveness and resilience. Companies wandered in a disrupted scenario because recommended actions/strategies to survive – and thrive – were not available an improvised actions to keep their operations up and running. This paper analyzes the COVID-19 impacts on the workforce and supply resilience in a holistic manner. The following research questions are discussed: (i) how can manufacturing firms cope with urgent staff deficiencies while sustaining at the same time a healthy and safe workforce in the perspective of socially sustainable and human-centric cyber-physical production systems?; (ii) is remote working (cf. smart working) applicable to shop-floor workers?; (iii) is it possible to overcome supply chain breaks without stopping production?

In the first part, we propose three Industry 4.0-driven solutions that would increase the workforce resilience, namely: (i) the *Plug-and-Play worker*; (ii) the *Remote Operator 4.0*; (iii) the *Predictive Health of the Operational Staff*. In the second part, the concepts of (i) *Digital & Unconventional Sourcing*, i.e. Additive Manufacturing, and (ii) *Product/Process Innovation* are investigated from a novel business continuity and integration perspective. We ultimately argue that forward-looking manufacturing companies should turn a disruptive event like a pandemic in an opportunity for digital and technological innovation of the workplace inspired by the principles of harmonic digital innovation (that places the human well-being at the center). These aspects are discussed with use cases, system prototypes and results from research projects carried out by the authors and real-world examples arising lessons learned and insights useful for scientists, researchers and managers.

1. Introduction

Resilience was a watchword among manufacturing and supply chain researchers and practitioners even before 2019. Back then, a very small percentage of business leaders from OECD countries considered the rapid and massive spread of infectious diseases an imminent global risk, according to the WEF Global Risks Report (2019), whereas warnings from scientific and international communities to prepare for the next pandemic were largely unheard (Walsh, 2017). Since December 2019, mankind has been experiencing the extraordinary outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), also known as coronavirus disease 2019 (COVID-19). Almost all the nations of the world were affected by this outbreak; hence, the World Health Organization (WHO) declared COVID-19 as a pandemic on March 11, 2020 (World Health Organization, 2020). As a response to "flatten the curve" and reduce the growth rate of thousands of new infections per single day, challenged governments have immediately enforced border shutdowns, social distancing, self-isolation, and mobility restrictions that had a turmoil effect on production systems and supply chains across all economic sectors (Nicola et al., 2020).

In a scenario where unexpected disruptions are increasing, servitization (Kowalkowski et al., 2012), supply chain end-to-end visibility (Brandon-Jones et al., 2015) and simulation-based risk analysis (Ivanov, 2020) has traditionally helped manufacturing firms to stabilize their operations. Nevertheless, the manufacturing sector was one of the most severely affected industries by the pandemic and the stringent

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restrictions to cope with the spread of the virus (Rapaccini et al., 2020). Manufacturing systems were indeed crippled (sometimes even at the same time) by two distinct, yet complementary, problems that led to partial or full plant shutdown:

i. an *endogenous* disruption due to a ***Workforce Downsizing Problem (WDP)***. Strongly reliant on their blue-collar workforce, many manufacturers struggled to manage their workforce and keep the employees working on site all around the world – from Italy (IlSole24Ore, 2020) to UK (The Conversation, 2020), from Asia (BBC, 2020) to the United States (Chicago Sun Times, 2020) and Canada (CBC, 2020). In each of these examples, lack of employee physical distancing, scarce adoption of PPEs and failure of early containment have been identified as important contributing factors to the spread of the illness within the workforce. This was exacerbated by a high percentage of factory workers (Confindustria, 2020) who still needed to go to the workplace and increased the "domino effect". Reduced shifts, paid or unpaid temporary leave, quarantined or self-isolated workers led to a worldwide unprecedented deceleration of production volumes, with consequent negative impacts on the whole economy (Eurostat, 2020);
ii. an *exogenous* disruption, identified as a ***Supply Downsizing Problem (SDP)***. Due to the reduced productivity/availability of workers, distorted demand patterns (consider, for example, the chip shortage causing delays in 2021 for car manufacturers, among others) and uncertain freight transportation (also due to further disasters, such as the Suez Canal obstruction by the Ever Given container ship for 6 days), manufacturing companies experienced considerable material shortages and curtailed responsiveness.

This two-fold impact of a pandemic on manufacturing systems and the urgent need of executives to cope with such calamity and build resilience for future disruptive events motivated this study. First of all, Section 2 intends to fill this literature gap and to examine the impacts of a pandemic (such as the SARS-CoV-2) on manufacturing systems and supply chains, an event that is different from any other one posing the attention on the social sustainability (internal and external) of manufacturing companies.

Despite manufacturers significantly increased their investments in Industry 4.0 technologies over the last few years and digitalized manufacturing firms displayed higher resilience and adaptability than manufacturers with lower digital adoption, the pandemic revealed that production environments are still inadequate to cope with black swan events and are not as agile and resilient as expected. High levels of automation and digitalization may result into inflexible and rigid production, unable to quickly adapt to changes arising from disruptive events, such as a pandemic. In the perspective of harmonic innovation, that fosters human well-being, the capacities that a Human Cyber-Physical Production System (H-CPPS) may offer and recent societal challenges push us to re-think how to exploit the maximum potential of the arising new "cyber-physical factories" and "digital twin environments".

This paper then poses the following research questions:

- RQ#1: how can manufacturing firms cope with urgent staff deficiencies while sustaining at the same time a healthy and safe workforce in the perspective of socially sustainable and human-centric production systems?

Strictly linked to the first one and the inability of shop-floor workers to "bring their work home", we pose a second question:

- RQ#2: is remote working (cf. smart working, working from home) applicable to shop-floor workers?

And finally:

- RQ#3: is it possible to overcome supply chain breaking without stopping production?

After an analysis of current related works and identification of literature gaps in Section 3, we answer the questions above by using the methodology outlined in Section 4. In the case of the WDP, a digital toolbox is defined as a set of three technology-driven solutions that would increase the resilience and robustness of manufacturing systems, namely:

- the Plug-and-Play worker;
- the Remote Operator 4.0;
- the Predictive Health of the Operational Staff.

In the case of the SDP, the concept of *Digital & Unconventional Sourcing*, i.e. using Additive Manufacturing (AM) to produce material, is investigated here from a novel business continuity perspective. Despite AM is usually associated to higher costs, such drawbacks may be offset or even less than stopping or slowing down the production process. AM would allow to integrate some production steps within the company even if those were given to external suppliers. In other cases, as an "outlandish" outcome, sometimes the only way to overcome SDP is the *product/process innovation*, thus forcing a crisis scenario to become a land of opportunities. All these aspects are discussed in Section 5 with the help of use cases (section 6) and practical examples from R&D projects conducted by the authors providing an original and novel perspective on the workplace of the future, on the role of smart operators and on the resilience of supply chains. Lessons learned are finally provided, together with insights about how to use proposed solutions for future black swan events (section 7) and concluding remarks (section 8).

2. Manufacturing systems and supply chains in times of pandemic: the case of SARS-CoV-2

Any serious disruption (e.g., explosions or man-made disasters, natural disasters, innovation-triggered demand variations, cyber- or terrorist attacks, economic or political shocks, strike actions) affects a company's performance – whether it is measured by sales, productivity, profits, customer service or another relevant metric – according to what Sheffi & Rice Jr. call a "disruption profile" (Sheffi & Rice, 2005). However, pandemics such as the COVID-19 and other forms of epidemic outbreaks are unique due to high uncertainty of a rapidly evolving either national-level and global scenario, and limited capability to forecast "what is going to happen tomorrow" due to hasty political decisions, unpredictable spread patterns of the disease within the society, and unstable external dynamics (e.g. demand surge or drops). As a consequence, typical features – described in the following – can be identified in a *pandemic disruption profile* depicted in Fig. 1.

First, unlike other disruptive events, the pandemic does not immediately strike the company business. While warning alerts range from little or no warnings at all in the case of explosions or cyber-attacks to a time window of 15–30 min in the case of natural disasters, the spread of an infectious disease is not instantaneous. We can define the *preparation time* as the interval between the first discovery of the infectious disease in the epicenter of the outbreak (in the case of the COVID-19, most probably the Seafood Market in Wuhan, Hubei, China) and the moment the virus strikes the business (by affecting the workforce or its supply chain). The preparation time is therefore typically much larger (in the magnitude of days/weeks) in the case of epidemics compared to other disruptions. Nevertheless, in this period, a general climate of uncertainty begins to destabilize and exert pressure on the operations. In this time, the company is called to implement the mitigation measures previously planned.

Second, the spread of an infectious disease does not fully take out the business outright, but the performance of its operations (e.g. productivity) starts to deteriorate depending on the percentage of incapacitated

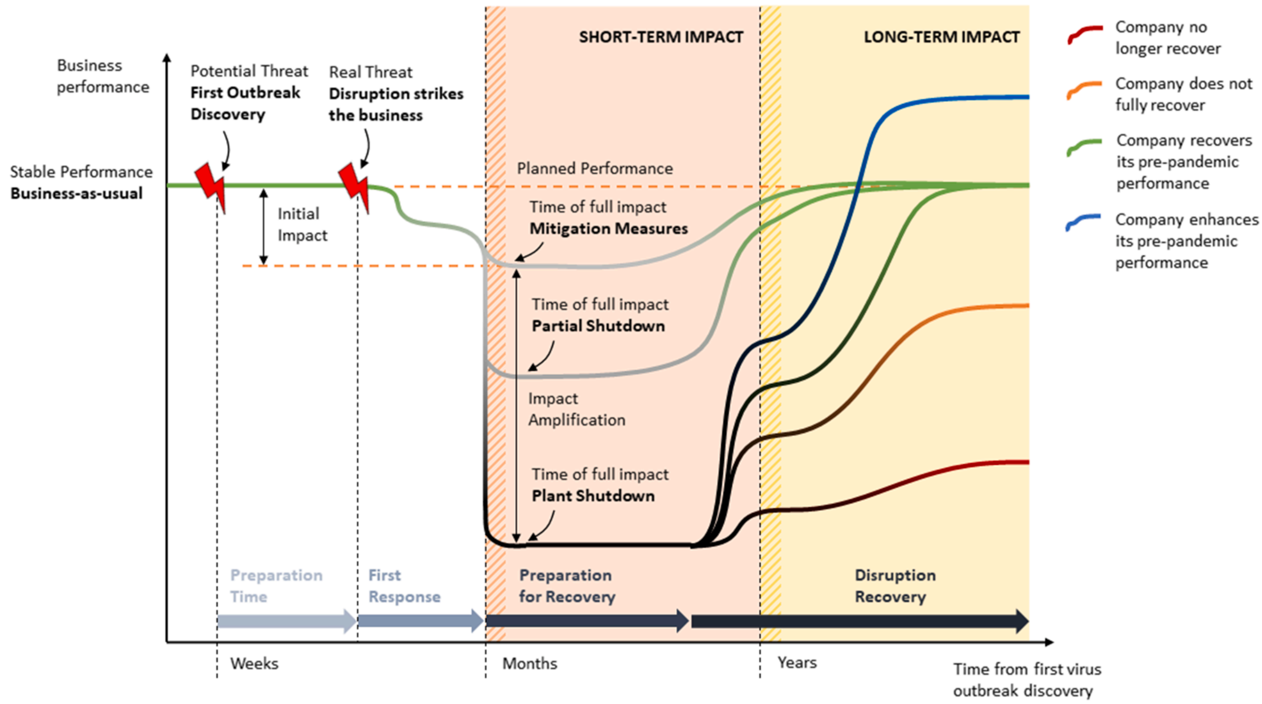

Fig. 1. Pandemic disruption profile (adapted from Sheffi & Rice, 2005).

manpower and disrupted supplies or activities. In industrial environments where the human component is still fundamental, the percentage of human labor acts as an impact amplifier of the pandemic effect (see Fig. 1), and performance often drops precipitously. If mitigation measures are not immediately adopted, partial or full plant shutdown would be necessary, whose duration is difficult to predict and may even last for months.

Third, the pandemic directly hits the human component of the enterprise – i.e. the workforce – and, indirectly, its societal ecosystem. It does not impact (at least not directly) the health of industrial assets, such as machinery, facilities or supplies. However, service operators, such as maintenance technicians, could be unable to travel to or access the factory due to restrictions. Maintenance, repairs and overhaul (MRO) plans could be then significantly delayed and asset health could be impacted to some extent.

A twofold short- to medium-term impact of a pandemic event on manufacturing systems can be identified:

- an endogenous disruption of manufacturing processes and systems, caused by the underperforming or unavailable workforce, which makes a reconversion/repurposing of manufacturing lines or personnel capability development (upskilling or reskilling) necessary to avoid to shutting down the factory;
- an exogenous supply chain disruption ascribable to two phenomena:
  - o increasing panic among consumers and firms will provoke extremely distorted demand patterns and market anomalies, with steep drops in some sectors (e.g. automobile and textile products) and skyrocketing demand for other products (e.g. thermal scanners, ventilators, face masks, sanitizers, essential food items, but also toilet paper);
  - o inventory shortages, unstable flows of material due to closed or overloaded suppliers as well as to impaired freight transport networks, mobility restrictions, and logistics bottlenecks due to a higher priority of essential items (e.g. food and medicine) led companies to stockpile and to increase their "safety stocks" (where possible), thus causing temporarily the failure of the "just-in-time" manufacturing paradigm.

In the long term, companies can ideally bounce back and fully recover their pre-pandemic performance when the virus will be finally contained. Unfortunately, others (especially those in financial troubles) might be no longer able to recover (see the red and orange line in Fig. 1). But amid this disruption, there could also be some companies and workers, who will catch the crisis as an opportunity for long-overdue upskilling or and digital transformation in the perspective of human-centered innovation. These companies will eventually outperform their expectations in the long-term (see the blue line in Fig. 1 above the planned performance).

3. Related work

3.1. Human-centered cyber-physical production systems in times of pandemics

Despite manufacturers significantly increased their investments in digitalization over the last few years (World Economic Forum, 2018) and digitalized manufacturing firms displayed higher resilience and adaptability than manufacturers with lower digital adoption (Okorie et al., 2020), production environments are still inadequate to cope with black swan events and are not as agile and resilient as expected. Over the last few years, Cyber-Physical Production Systems (CPPS) came out as a combination of technological enablers of both physical and digital nature, operating successfully alongside humans (Pinzone et al., 2020). While manufacturing is increasingly automated, there is now a greater demand for more effectively integrating, rather than eliminating, human cognitive capabilities in the loop of production related processes (Krugh & Mears, 2018; Golan et al., 2020). There is general consensus that humans have a central role, as they are the only ones who can govern production systems, address anomalous situations and can provide flexible solutions in case of need (Di Nardo, Forino & Murino, 2020;

Fantini et al., 2020). The recent trend is not creating unmanned production facilities, but building human cyber–physical production systems (H-CPPSs) where machines are not designed to replace the skills and talents of humans, but rather to co-exist with, and to assist humans in being more efficient and effective via smart tools and assistance systems (Romero et al., 2016). In this context, the "Operator 4.0" is envisioned as a smart worker, empowered with Industry 4.0 technologies, capable to control decentralized production resources, access intuitively a wealth of knowledge about the factory and receive cognitive support when needed to achieve more effective sociotechnical systems (Emmanouilidis et al., 2019). Recent research has proposed Human-in-the-Loop (HIL) integration in CPPS to empower a workbench with intelligent decision and assistant systems (Costa et al., 2019), to prevent cognitive overload for human operators and enhance decision-making capabilities thanks to a range of automated decision recommendations (Gross et al., 2017), to integrate spatial augmented reality in manual working stations to project technical information on a motorbike engine during a maintenance procedure (Uva et al., 2018). Other applications of intelligent tutoring systems integrated with natural interaction interfaces for operators' support have been also tested (Longo et al., 2019b). However, research is still primarily confined to onsite operator support and does not encompass workforce management at large or remote working. Further development of methods and technological solutions is required as humans are now being recognized to be a major enabler for the Factory of the Future (Emmanouilidis et al., 2019).

The capacities that a H-CPPS may offer and recent societal challenges of global disruptions, such as the SARS-CoV-2 pandemic, mean that we must re-think how to exploit the maximum potential of the arising "cyber-physical factories" and "digital twin environments". Two challenges can be identified:

- if not properly implemented, high levels of automation and digitalization may result into inflexible and rigid production (Frohm et al., 2008), unable to quickly adapt to changes arising from disruptive events, such as a pandemic. A corollary impact of the pandemic is the need for more flexible human resources (in terms of capabilities and requirements) and production processes to enable more resilient systems. Resilient factories and flexible H-CPPS need to bring together "human competences" and "CPPS autonomy" in order to unlock flexible problem-solving and rapid adaptation to a failure event (Ansari et al., 2018);
- the paradigm of socially sustainable workplaces (Hancock et al., 2013) and anthropocentric production systems (Rauch et al., 2020) are today compelled to develop further the topic of sustaining a competitive, healthy and safe workforce. This is particularly true if we match the ageing phenomenon and demographic trends that are affecting the manufacturing workforce (Calzavara et al., 2020) and the devastating impact of the SARS CoV-2 pandemic on older adults. However, while several manufacturers and logistics companies opted for repurposing temporarily their production processes (Okorie et al., 2020) and used Additive Manufacturing (AM) equipment to address critical product shortages (Longhitano et al., 2020; Tarfaoui et al., 2020), very few tested smart technologies to sustain a healthy and safe workforce on the shopfloor (Naughton, 2020; Vincent, 2020; Wuest et al., 2020).

As reported by Kadir & Broberg (2020), in some large companies, the health and safety departments had been involved in the design of innovative digital work, but only after the new digital solutions had been fully developed and implemented. Fantini et al. (2020) argue that emerging needs for work design are not thoroughly addressed by the available studies on CPS-enabled manufacturing.

3.2. The healthy operator 4.0

In the context of H-CPPSs, the increasing attention to digitally-enabled Occupational Health and Safety aspects (OHS) gave birth to a specific sub-type of the Operator 4.0: the *Healthy Operator 4.0 (HO4.0)*. Envisioned initially as an industrial worker using wearable devices to track health-related metrics (e.g. heart rate or posture) (Sigcha et al., 2018), the HO4.0 concept evolved today towards a holistic perspective on the workforce health management and analytics. Along with smart wearables and ambient intelligence, a new generation of smart exoskeletons, adaptive co-bots and smart personal protective equipment (PPEs) is also emerging (Romero et al., 2018). Prospectively, the integration of autonomous robots, AR and VR, simulation, I-IoT and automation technology, and novel networking technologies such as 5G, will open new possibilities in the next future to sustain a healthier and safer workforce through cognitive e-Health platforms (Zolotová et al., 2020). Sun et al. (2020) envisioned a HO4.0 that gathers the workers' and environment's real-time information and fuse them appropriately to develop a digital image of the operator's behavior, thus enabling what Monostori and Váncza (2020) call a "predictive maintenance of operational staff". This paradigm can exploit the "caregiver" functionality of a CPPS, theorized by Pinzone et al. (2020), that aims at minimizing the negative impacts of work tasks on the operators' health while improving their productivity (by providing real-time instructions and searching for information).

Despite a significant number of employees is still fighting the adoption of HO4.0 technologies for multiple reasons (e.g. limited privacy, required upskilling to master them) or their use declines after some initial enthusiasm (Mattila et al., 2013), the recent SARS-CoV-2 pandemic rekindles the concerns on the workers' well-being and safety in industrial workplaces and fosters the debate on the HO4.0. In the post-pandemic era, we feel that the adoption and acceptance of the HO4.0 technologies will receive a boost as industrial workers will raise awareness on the need to maintain high safety levels at workplaces. This paper looks exactly in this direction.

3.3. Supply chain in times of pandemic

While COVID-19 has unearthed the limitations that pandemic causes on plague the human workforce in the Factory 4.0, it has also highlighted the need for innovative solutions to cope with sudden material shortages or supply chain breaks. During the first COVID-19 wave, several supply chains highly reliant on China's economy understood the need to avoid over-reliance on any one source or geographical location and started to decouple from China and find other back-up suppliers, wholly independent from them. However, given the large scale impact of a pandemic, even back-up suppliers or subcontractors may be overloaded or unavailable. What can manufacturing firms do when supply chains are interrupted and buffer stocks are lacking?

Research on adaptability and mathematical modeling has been a topic of interest for decades, yet is more important than ever today (Bottani et al., 2019). While few computational studies started to appear in the SC theory, helping decision-makers of high-demand and essential items to make accurate and prompt decisions in designing the revised production plan to recover during a pandemic (Paul & Chowdhury, 2020), recent literature proposes that companies should conduct a comprehensive mapping of their supply chain in order to predict and prepare for disruptions like a pandemic from the supply side (Sheffi, 2020). A transition toward a "capability-based" and "technology-enabled" digital supply network (DSN) can provide the required visibility and agility to face future interruptions and unpredictable black swan events (Ivanov & Dolgui, 2020). This calls for the need of a simulation-based Supply Chain Digital Twin, that companies can use to effectively plan and mitigate risks in the event of disruptions like the COVID-19 (Di Nardo et al., 2020).

Company management can integrate within the industrial organization part of the process which is commonly externalized. In this way, although a lack of flexibility and a further complexity of the organization arises, the system results globally more resilient.

In the I4.0 paradigm technology helps the management introducing some processes which are at the same time flexible and able to substitute the conventional ones, without the need of strong workshop equipment and organization.

More in detail, when material shortages became significant, the Additive Manufacturing (AM) community stepped up and tried to fulfill local demands. Anyone with access to maker equipment, either privately or as part of an organization, contributed to the production of PPE (Mueller et al., 2020). 3D printing was validated as an efficient agile production technology in times of pandemics, supported by the fact that it is relatively cheap to adapt towards changes in design or parameters. Manero et al. (2020) have explored the feasibility of exploiting additive manufacturing, like three-dimensional (3D) printing, to overcome such issues. Utilizing various real-world examples, the authors have illustrated the hypes and hopes of 3D printing and how it can be deployed for counteracting and mitigating the burden generated by COVID-19. Similarly, Salmi et al (2020) have concluded that 3D printing represents a "promising open source solution, especially during emergency situations".

3.4. Summary of current challenges and gaps

Overall, the above-mentioned streams of literature provide different and complementary viewpoints on manufacturing systems' resilience, even in relationship with technological systems, but leave gaps. As a matter of facts, there is a lack of guidelines, methods and solutions that can drive the Factory of the Future to cope successfully with black swan events like a pandemic. In particular:

Gap 1: Research is primarily confined to onsite operator support and does not encompass a holistic view on workforce management or remote working.

The main challenge is to enable an ageing shop-floor workforce with the tools to "bring their work home" when possible and investigate work design structures in the post-pandemic era.

Gap 2: Literature on resilient factories and flexible H-CPPS lacks of technology-enabled solutions and work design strategies that are recommended to manufacturing firms to cope successfully with staff deficiencies in black swan events like a pandemic.

The pandemic showed us how companies navigated perilous waters trying to understand what to do to cope with the pandemic effects. The next challenge is not only to understand how to support onsite shop-floor operators with novel 4.0 technologies but also understand how to provide heterogeneous workers with tools and solutions that allow them to fit quickly in the production process and ramp up to their full operational productivity.

Gap 3. Literature on the Healthy Operator 4.0 is still at an early stage and should be considered from a holistic point of view.

There is a need to sustain a healthy, competitive and safe workforce, but current solutions and approaches seem incompatible with the challenges of a pandemic. Further concepts and solutions must be investigated in the perspective of an enhanced well-being and safety of the workforce.

Gap 4. Literature on SC digitalization and optimization is mainly focused on its efficiency.

Some events such as a pandemic may have, as a consequence, the supply chain breaking. In this case company have the need to redesign the SC in order to overcome the material shortage.

Gap 5. Literature on Industry 4.0 presents the main paradigm pillars allowing a firm digital transformation oriented to data generation, analysis and control.

I4.0 has within the seed to increase companies' resilience even if the literature stresses the role of pillars to increase both efficiency and control capacity. Further efforts on the use of techonologies allowed by the digital ecosystem to increase resilience are required. At the same time, company may show an antifragile behavior, according to the innovation boosting due to the difficulties to manufacture pre-pandemic products.

In the next section, a methodological contribution to address these needs is presented.

4. Methodology

In the light of the profound disruption that hit our society, future of work design is needed. Despite an abundance of works is available on the topic of resilient manufacturing systems and supply chains, the SARS-CoV-2 pandemic taught us that industries are extremely vulnerable to black swan events and that proper investigation of the phenomenon and discussion of actions is needed. This paper proposes a new evolutionary paradigm from a "pandemic society" to the so-called "super smart society" (Fig. 2) inspired by the principles of harmonic innovation and new digital humanism. This approach encourages the transition towards novel workforce management strategies (e.g. work shift flexibility, continuous training & assistance, predictive health management), work structures (unmanned remote-controlled factories) and technological innovations (digital & unconventional sourcing, product/process innovations). The ultimate aim of this work is to provide useful recommendations, principles and solutions showing the feasibility of building resilient manufacturing systems and how to turn a global disruptive event in the opportunity to increase the social well-being.

The methodology here proposed consists of an innovation design framework aimed at:

- expanding the scope of the analysis and design of human work in H-CPPSs with solutions that enable an effective workforce management in case of a pandemic event (but also for the future of work). This part addresses the challenges of the WDP in a black swan event.
- exploring an innovative manufacturing paradigm that would guarantee business and production continuity in case of interrupted or downsized supplies (SDP).

A summarizing overview of this framework is in Fig. 3. Five literature gaps have been identified in the first step of this research (see Section 3.4) that gave birth to three research questions (RQ). Thinking about the WDP, Gaps 1 to 3 generated the following RQ#1 and RQ#2:

- RQ#1: how can manufacturing firms cope with urgent staff deficiencies while sustaining at the same time a healthy and safe workforce in the perspective of socially sustainable and human-centric production systems?
- RQ#2: is remote working (cf. smart working, working from home) applicable to shop-floor workers?

On the other side, regarding the SDP, Gap 4 and 5 generated RQ#3:

- RQ#3: is it possible to overcome supply chain breaking without stopping production?

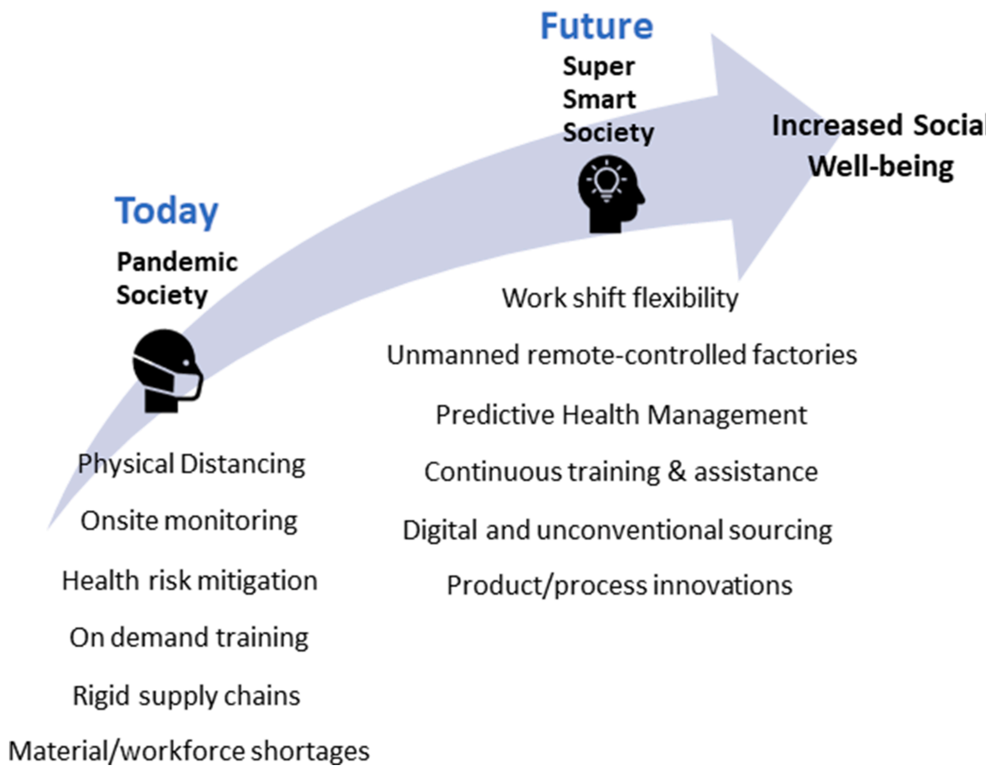

Fig. 2. An evolutionary paradigm: from a pandemic to a super smart society.

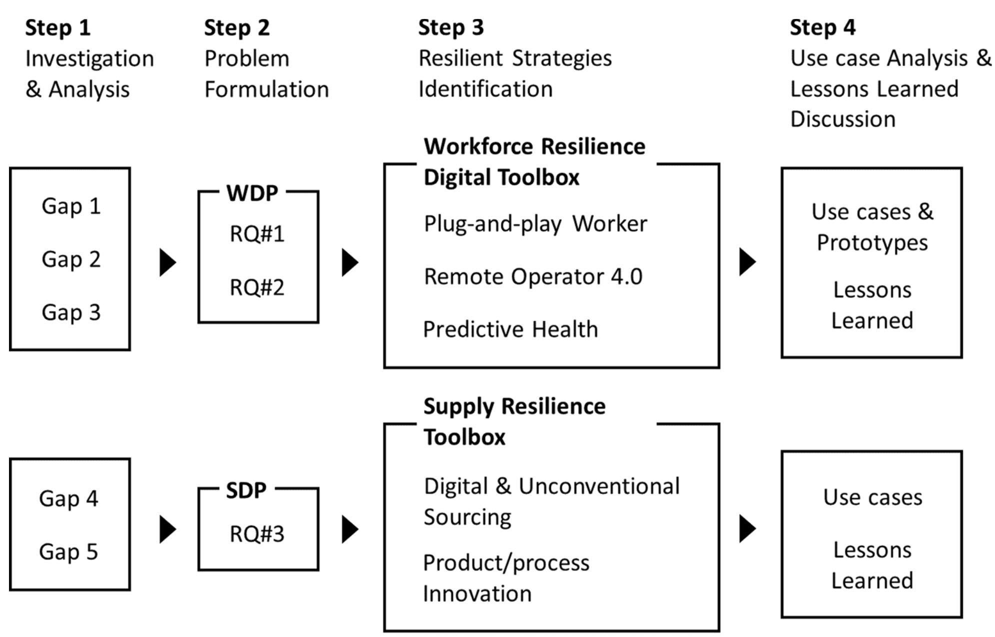

Fig. 3. An innovation design framework.

In order to answer these questions, the concept of *toolbox* has been adopted.

During the COVID-19 pandemic, companies had a reactive behavior and tried to improvise actions to keep their manufacturing operations up and running. However, they wandered in the darkness because a comprehensive list of recommended actions/strategies to survive and even thrive is not available yet. Recent events accelerated the need to have blueprints for achieving value while responding to disruptive events. For this reason, this paper looks at the COVID-19 pandemic and its impacts on the workforce and supply as an opportunity for digital and technological innovation for resilient manufacturing systems. A *toolbox* inspired by novel technology-driven manufacturing paradigm is proposed as a set of strategies and actions enabling manufacturers to prepare for and achieve higher levels of workforce and supply resilience.

Step 3 of the innovation design framework consists in identifying strategies and actions aiming at ensuring and enhancing workforce and supply resilience. In particular, three solutions are here proposed and discussed to solve the WDP and answer RQ#1 and RQ#2: (i) the plug-and-play workers, (ii) the remote operator 4.0 and (iii) the predictive health of the operational staff. On the other side, RQ#3 is answered through (i) digital & unconventional sourcing, i.e. additive manufacturing, and (ii) product/process innovations.

Use case analysis based on prototypes and real business cases will provide clear insights and lessons learned that would be useful not only to companies who are fighting the pandemic (or have to prepare for the next black swan event) but also to researchers and scientists operating in the computers and industrial engineering and human management field of study.

The results are illustrated in the Sections 5 and 6.

5. Workforce resilience digital toolbox

This section investigates the first aspect mentioned in Section 4, that is the *workforce downsizing problem*. The COVID-19 pandemic has accelerated the need to have and implement strategies to keep, sustain or rebuild quickly a safe, healthy and sustainable workforce. However, companies found themselves running around in the dark, because a comprehensive list of actions/strategies that allow to build a resilient workforce are not easy to implement in a black swan event like a pandemic and such strategies have never been matched yet with current technology-driven manufacturing paradigm. We argue that forward-looking companies should turn a disruptive event like a pandemic in an opportunity to grow in the perspective of a harmonic innovation (that places the human well-being at the center). That is why it is important on a first place to understand which are the workforce resilience strategies (see Section 5.1) that can be turned today in an opportunity to invest in the future of work. Section 5.2 proposes a **digital toolbox**, with three main solutions that finally allow the strategies to be effectively implemented: the *Plug&Play worker*, the *Remote Operator 4.0* and the *Predictive Well-being of Operational Staff*. A use case based on prototypes developed by some of the authors (described in Section 5.3) will give clear insights and paves the way for interesting lessons learned that would be useful not only to companies who are fighting the pandemic (or have to prepare for the next black swan event) but also to researchers and scientists operating in the computers and industrial engineering and human management field of study.

5.1. Strategies for a resilient workforce in a pandemic

Starting from an extensive literature review and analysis of documents, companies' reports, specialized magazines and online news, seven strategies have been identified to allow a resilient workforce in industrial workplaces. The first three strategies directly affect the *workforce capacity*:

1. *Contingent labor (S1)*

In industrial settings facing acute short-term workforce shortages, manufacturers may employ contingent labour to *increase their workforce capacity*. This is a growing trend as companies worldwide expect to rely much more on individual freelancers or temporary workers from the gig economy to cover production and working capacity in the next future (McKinsey Global Institute, 2020). This includes not only agencies providing temporary workers but also cross-industry talent exchange, which means redeploy temporarily select talent with similar competences from external industries facing reduced demand or shutdown to those facing a shortage of workers. However, getting any temporary workers up to speed quickly comes at a major risk of them not being sufficiently trained. Temporary workers are not familiar with processes and procedures of the "hiring" industry/firm and the learning curve would not be compatible with the need to have the perfect person, made to order, ready for their position and ready to go.

2. *Personnel flexibility (S2)*

In case of disruptive events, specific work cells, departments (e.g. purchasing, logistics, production) or facilities may be hit more than others. In this case, firms could redeploy temporarily experienced internal staff from low- to high-burden processes to stem worker shortages arising from COVID-19. This solution would allow the company *to rebalance the workforce capacity* and cope with delays on some urgent due dates and important customers' orders. However, even in this case, redeployed workers would need training or upskilling to familiarize with different processes, different materials, different machine tools, etc.

3. *Workforce reduction (S3)*

Unlike S1 and S2, short-term reduction of onsite workers may be necessary. The rationale is to temporarily *reduce the workforce capacity* due to orders plummet or unsafe working conditions on the shop floor. Given to the nature of human work, shop-floor operators are forced to stay home on a (usually paid) leave and cannot "bring their work home". As a consequence, the company records losses due to production stoppages and inactive workers.

The next two strategies are referred to *shift flexibility*, that in some cases might allow the entire (or almost) workforce to work onsite safely:

4. *Occasional overtime (S4)*

In critical situations where the workforce is stretched thin and it is hard to find other skilled workers, employers may ask selected workers about their availability to do occasional overtime and *increase their shifts* (or working hours). In this case, although proper overtime compensation and incentives are paid, this strategy stands against the principles of harmonic (or human-centered) innovation, as it would have serious impacts on the employee's well-being (and indirectly on their productivity).

5. *Flexible and rotating shifts (S5)*

The alternative to S4 is to refine production schedules and *rotate work shifts flexibly* on a, e.g. daily, basis depending on the status of work, the inventory available, changing demand, available workforce and what they are capable to build. That would allow firms to reduce the crowd in the shop floor in case of pandemics and leverage on a workforce that is willing to have rotating shifts or even work overnight when needed (Zucchi et al., 2020). This approach would require not only advanced planning and scheduling processes, but also would impact seriously on the employee's well-being.

The strategy related to the *decrease of number of working hours* (or shifts) is here treated as S3, therefore it is not considered separately in this list.

6. *Physical distancing (S6)*

Physical distancing (PD) measures are proved to reduce substantially the spread of SARS-CoV-2. To ensure proper PD at the workplace, layout changes or designated one-way pathways may be successful strategies to ensure a resilient workforce in case of pandemic. When this is not possible, some workplaces may adopt 'cohorting' to reduce the number of people each worker has contact with (Shaw et al., 2020). Depending upon the constraints of a given production or logistic process, such work bubbles might be created in a variety of ways, either through physical separation within a workspace or temporal separation via a rotating work schedule (see S5), thus eliminating the overlap between different cohorts. However, high risks of infection still exist: not only PD protocols may not be respected by the workers, but in some cases PD is not even possible (e.g. collaborative assembly work).

7. *Hygiene & health monitoring practices (S7)*

Employers need to promote cleaning and sanitation practices, the correct use of Personal Protective Equipment (PPEs) and accelerate the adoption of staff health monitoring and screening procedures (e.g. temperature monitoring, mandatory or recommended ad-hoc testing carried out at periodic intervals). However, such solutions may be expensive and difficult to roll-out at scale (e.g. swab testing).

5.2. A digital toolbox for a resilient workforce

Every form of technology-enhanced cooperation (human–human and human–machine) will be integral part of post-pandemic production systems.

New digital approaches can accelerate the capability-building process and allow employees to develop new skills remotely. Such techniques include the remote delivery of training using e-learning systems or the use of virtual-reality technologies to familiarize operators with new tasks or plant layouts. Augmented-reality systems help shop-floor staff to receive training, advice, and support from remote colleagues. Specialist contractors can use such systems to guide shop-floor staff through machine maintenance or troubleshooting.

The application of digital twins, together with advanced human–machine interaction, automation technology and prescriptive engineering can lead to anticipatory rather than reactive systems capable to stand up to the disruptive impact of black swan events on the workforce. This section of the paper shows how a digital toolbox, defined by the authors and intended as a set of technological principles, tools and solutions inspired by the latest CPS-enabled manufacturing and Operator 4.0 paradigms, allows to overcome the challenges and limitations of the workforce resilient strategies presented in Section 5.1. The digital toolbox recommends three work design approaches for manufacturing and industrial companies who are willing to turn the pandemic in an opportunity to build a resilient workforce, digitalize their processes and innovate in a human-centered perspective, namely:

i. the Plug-and-Play worker (Section 5.3) addressing in particular S1, S2 and S3;
ii. the Remote Operator 4.0 (Section 5.4), addressing S4 and S5;
iii. the Predictive Well-being of Operational Staff (Section 5.5), addressing S6 and S7.

5.3. The "plug-and-play" worker

The pandemic impact on the workforce compelled companies to find people that could replace their actual workforce on the short term. However, the time-horizon of hiring is pretty much linked to the time-horizon of learning. Smart assistance technologies, natural human–machine interfaces and augmented reality have proved to speed up significantly the learning process by allowing workers to fit in a process and be fully operational in no time (Longo et al., 2017). Fitting in and ramping up to desired performance in no time – hence the concept of Plug-and-Play worker – thanks to Industry 4.0 technologies are the requirements for an agile and resilient workforce. Developing skilled employees for an "on demand" age is an urgent priority. We answer here the three hows that people would likely ask (Fig. 4):

1. **How many plug-and-play workers are necessary?** To forecast and estimate the workforce capacity (as a combination of employees already onsite and plug-and-play workers), simulation-based digital twin models combined with epidemiological models, big data analytics, predictive models and AI-powered prescriptive engineering could support the identification of critical workforce needs. This also includes the estimation of the impact of absenteeism and various levels of workforce availability and productivity on production schedules. AI-powered prescriptive tools can recommend the right amount of plug-and-play workers to hire and how to allocate them based on the expected workload and workplace safety.
2. **How can plug-and-play workers fit in a new production environment and be ready to get onboard?** For plug-and-play workers to be able to confront with and fit in an increasingly complex cyber-physical production environment, upskilling and continuous professional development are required to prepare workers. The pandemic teached us the importance of operators with digital skills as a critical requirement for the long-term sustainability and survival of businesses. Virtual reality- (VR-) or augmented reality (AR-) based training or serious game-based simulation can help to keep a "ready-to-go" plug-and-play workforce, that will be able to experience multiple manufacturing and industrial scenarios, experiment with tools and processes, and speed up the learning process even if they are not directly onsite.
3. **How can plug-and-play workers ramp up their operational performance rapidly?** In order to be fully operational and work

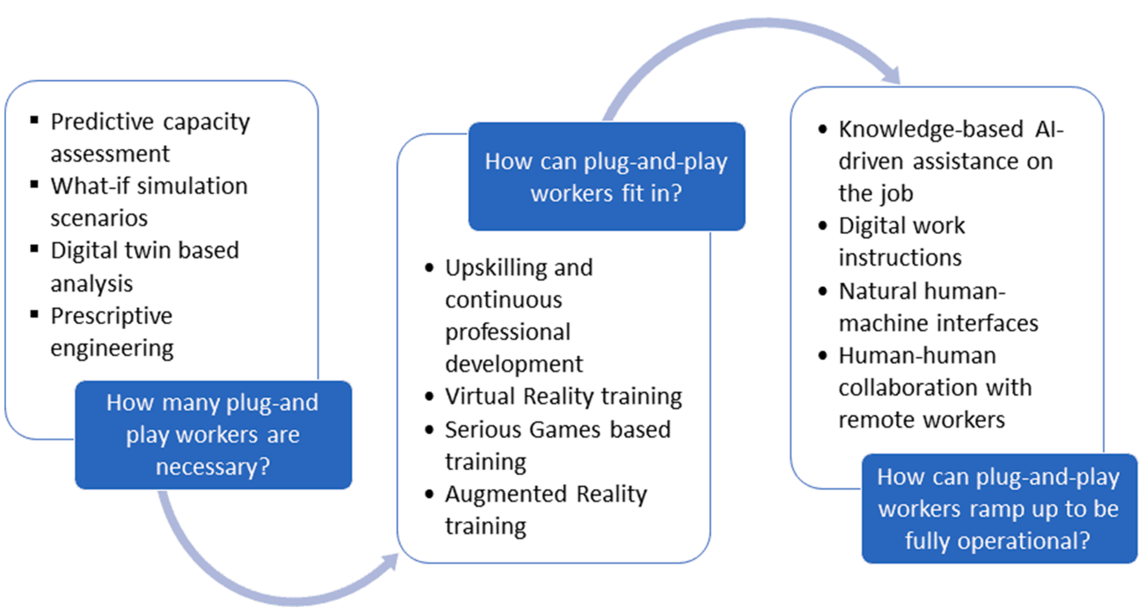

Fig. 4. The three "how" for the plug-and-play workers.

safely in a short time, knowledge-based AI-powered assistance on-the-job, digital work instructions and natural human–machine interfaces are today powerful approaches supporting low-skilled opertors on the job in the perspective of a learning-by-doing principle. Augmented Reality based assistance or intelligent voice-based information retrieval supported by machine vision and ambient intelligence can considerably support task execution, reduce the errors, avoid waste and speed up the decision-making process (thanks to the semantic analysis of how-to manuals or other data sources – including the digital twin of the manufacturing plant – that would compress a large amount of information in an easy-to-understand format). Next to digital support, plug-and-play" also have the possibility to harness an advanced human–human collaboration with remote workers via handheld or wearable technologies, i.e. direct feedback and advice from remote experts (e.g. workers in quarantine) through teleconferencing or hologram based augmented reality.

5.4. The remote operator 4.0

Current circumstances have prompted firms world-wide to quickly adopt remote working or work-from-home structures. However, this is not a viable option in the manufacturing industry (Okorie et al., 2020). Unlike office workers, shop-floor workers (e.g. machine operators, maintenance technicians, quality control experts) cannot "bring their work home". Despite some avantgarde manufacturing companies started to experiment 24-hour production with fully automated processes and unmanned night shifts (Rico, 2020), human presence is still necessary at the factory floor (cf. Section 3). This real example demonstrated that remote working for shop floor operators is possible though. In particular, shop-floor workers are expected to assume more and more the role of problem-solvers, decision-makers and managers of a robotic and digital workforce. The Remote Operator 4.0 is therefore a new type of worker that carries out work in a symbiotic interaction with technology at any time and at any place. We are living the digital era where technology allows us to "make every place our workplace" and consider our home like an extension of the factory floor (see Fig. 5) thanks to immersion technology and the possibility to interact with digital objects in a natural and intuitive manner.

Indeed, there are multiple examples of manufacturing environments where the remote working for shop floor operators is possible (Remote Operators 4.0). First of all, it is worth mentioning that the shop floor operator is a person that is required to work within the shop floor (e.g. at specific workstations) and/or to move around the shop floor. In each manufacturing environment, no matter which is the production type (custom manufacturing, intermittent manufacturing, continuous manufacturing and flexible manufacturing) or the industry categories (e.g. oil & gas, chemical, electronic and electrical equipment, metal industry, aerospace, furniture, etc.), the following are some example of operators take an active role on the shop floor:

- The Production Manager;
- The Manufacturing Cell Manager;
- The Squad Responsible;
- The Maintenance Manager;
- The Quality Manager.

There is no need to elaborate a different approach for these workforce groups. Thanks to 4.0 technologies and CPPS these operators can act remotely for:

1. Supervise

Supervise can be intended as remote monitoring and situation awareness that is enabled by:

- o Industrial Internet of Things (I-IoT, to receive data from shop floor machines and equipment);
- o Cloud service (to provide remote access to collected data);
- o Ad-hoc network connection (including local WI-FI coverage within the shop floor and high speed internet connection to provide data without latency and delays outside the shop floor);
- o machine vision and intelligent cameras (to see machines working productively and onsite operators at their own places);
- o web applications and dashboards (to summarize data and get desired information even faster comparing to walking around in the shop floor);
- o virtual reality to be physically immersed in 3D Digital Twin of the shop floor (in this case even a virtual "walking around mode" is allowed to provide the operator with the feeling to be in the real shop floor);
- o augmented and mixed reality. The Remote Operator 4.0 may define and send information and data to on site operators and support them to solve problems within the shop floor (remote assistance and remote troubleshooting). Onsite operators visualize data thanks to Augmented and/or Mixed Reality Applications This approach is currently revolutionizing the manufacturing as well as the service industry, as external employees (e.g. maintenance responsible) will no longer need to access the facilities. The authors are currently working to a completely new and innovative approach including both on-site and remote operators (this will be proposed as part of a new article).

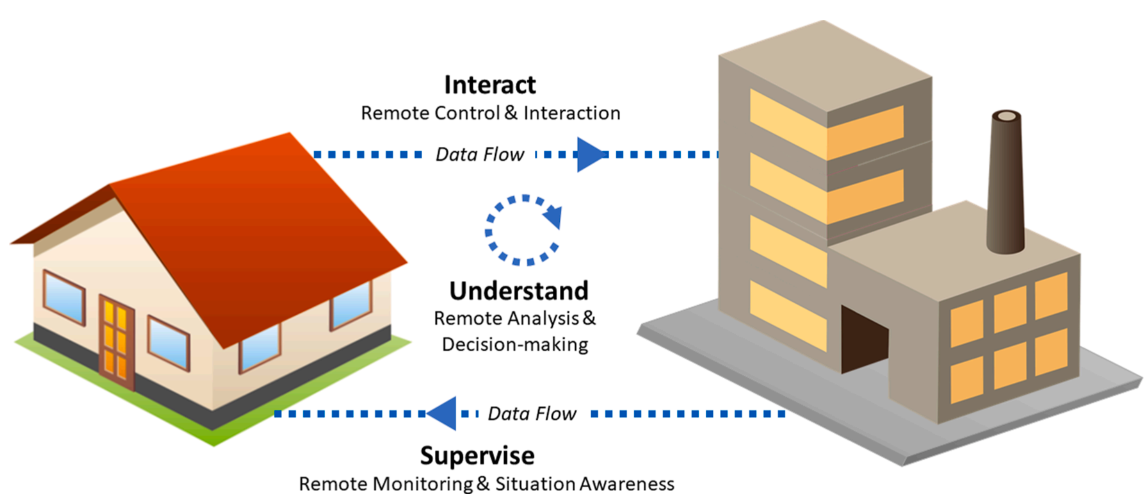

Fig. 5. Extending the factory boundaries: home-factory environment.

2. Understand

Understand can be regarded as remote analysis & Decision making. The data-driven manufacturing paradigm is the key enabling factor of a remote workforce. The combination of big data analytics, artificial intelligence, simulation, predictive and prescriptive analytics, and optimization algorithms opened a whole new paradigm characterized by the possibility to forecast future events, process large amounts of data and receive facts-based recommendations to enhance and speed up the human decision-making process. In this framework, Explainable AI (XAI) for example is the new trend that allows humans to understand what AI is recommending and why. Thanks to computer-based information processing and remote human–human collaboration enabled by teleconferencing tools, the Remote Operator 4.0 will be able to fully understand what is happening in a manufacturing plant kilometers away from his/her location.

3. Interact

Working in the factory floor means operating a closed loop system, where process data help the human worker to interact with physical manufacturing objects to regulate and control manually the process. In the future, the Remote Operator 4.0 will be able to use advanced HMIs on their personal devices (e.g. handheld devices or computers) to run the manufacturing process. Not only new interaction paradigms – such as gesture-based or vocal interaction or even tactile feedbacks to simulate the feeling to hold something in the hands – but also Virtual and Augmented Reality, intelligent digital dashboards, high-speed and secure communication enabled by high speed internet connection, will allow the workers to manage a robotic, automated and digital workforce remotely in an efficient and safe manner.

The Fig. 6 show an example of Virtual Reality Environments jointly developed by MSC-LES lab and CAL-TEK (that respectively are the University lab of the lab spin-off company where some of the authors work at). This virtual environment shows a part of the shop floor environment (a warehouse) and the operator (remotely connected) that is carrying out remote monitoring and situation awareness. In this case the Virtual Environment is fed with data representing the entities in the real environment (e.g. the forklifts, the parts being moved, etc.).

The Fig. 7 shows the remote operator (left side) defining information and data to be sent to the onsite operator (right side); the latter is using a Mixed Reality application through Microsoft Hololens©. In this case, the remote operators can send specific information to the onsite operator with the aim of carrying out remote assistance and remote troubleshooting. The Mixed Reality application (see right side of Fig. 7) can be also used in a stand-alone mode by an onsite operator (receiving data locally from the company informative system) or by an remote operator (as explained later on in section 5.6).

5.4.1. Setting-up a practical implementation of the remote operator 4.0

Regarding the implementation of the Remote Operator 4.0 (through the use of the methodologies and technologies mentioned above), the following additional information can be very useful to setting up the environment to carry-out a practical experimentation with Remote Operators 4.0:

- It is worth mentioning that while R&D activities continuously move forward the frontier of the state of the art, in some cases legislations may require more time to cope with the new possibilities offered by the new enabling methodologies and technologies. This is surely the case of manufacturing machines remote control. While the remote operator may have different types of control on the real machine, such control may be not allowed by current legislations (e.g. for safety and security reasons). Therefore, if the Remote Operator 4.0 has to control directly a machine, then national legislations related to safety and security at work must be checked before going ahead.
- The proposed approach, that sees a joint use and integration of data sensing, IIOT, Cloud, web application and Extended reality (the latter including Virtual/Augmented and Mixed Reality), is independent from the level of machines automation or robotization. What is currently needed is:
  - o machines equipped with systems to get data that are relevant for the remote operators, e.g. PLCs providing the status of the machines or other specific indicators. Data provided by PLCs must be available both locally in the plant and outside the plant over the cloud.
  - o Capability for the ERP systems (currently used in the manufacturing system) to provide data and information (over the cloud) needed by the remote operator. Obviously, data and information to be sent over the cloud depends on the type of remote operator. The Production Manager usually needs information about orders currently worked on each specific machine, overall

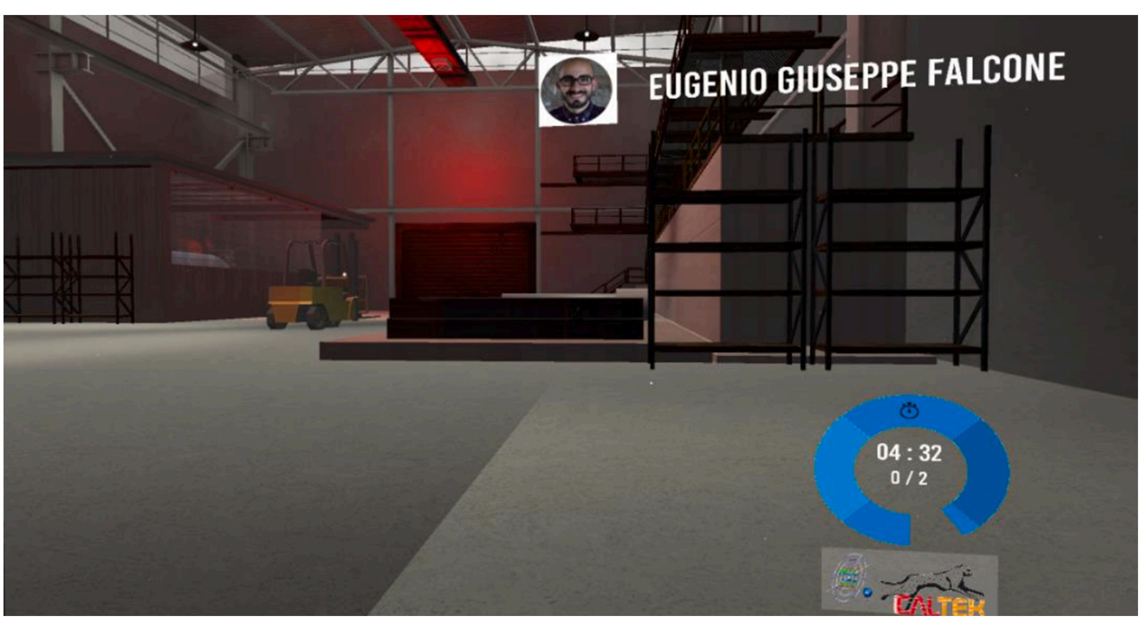

Fig. 6. Remote Operator 4.0: Example of Virtual Relity for remote monitoring and situation awareness.

Fig. 7. Remote Operator 4.0: example of Mixed Reality application to support onsite operators.

equipment efficiency, productivity, pieces produced per day, etc. The Quality Manager needs information and data about defectives products or part, ratio between defective products and total production, number and types of quality controls being executed, etc. The Maintenance Manager needs information and data about machines that are currently under maintenance, anomalies, failures, mean time to repair, etc. Similar considerations must be done for each remote operator type.

- The network infrastructure must include local WIFI service over the entire shop floor as well as high speed internet connection (100 Mbps or higher).
- The computational capabilities are mostly related to AI functionalities for big data analysis. These must be set-up according to each single case. Nevertheless, there are companies providing both space over the cloud and computational capabilities. To cite an example, Microsoft provides the Azure Cloud jointly with the Azure AI algorithms for building machine learning applications, knowledge mining applications, conversational applications, document process automation, machines translations and speech transcription. The service offered by Microsoft provides computational capabilities for all manufacturing systems' needs (it is possible to manage and scale up to thousands of Linux and Windows virtual machines). To provide evidence on the maturity level of the solutions already available on the market, it is worth mentioning that, at the time of writing this article, Microsoft provides a 12 months' free account with 750 h of computational time already included, 128 GB of cloud space, up to 10,000 transactions and a number of additional features and functionalities (https://azure.microsoft.com).
- There is no need for specific (and new) Human Machine Interactions. The idea proposed for the Remote Operator 4.0 is to make use, where needed, of the interfaces provided by the Virtual, Augmented and Mixed Reality equipment (e.g. Head Mounted Display like Microsoft Hololens, HTC Vive, Oculus, etc.) without the need of creating new Human Machines interfaces.
- The solution proposed for the Remote Operators 4.0 does not require to invent new technologies but mostly to integrate (in a way that is useful to the Remote Operator 4.0) technologies and methodologies already available on the market. Indeed, the integration of data sensing, IIOT, Cloud, web application and Extended reality (the latter including Virtual/Augmented and Mixed Reality) can be considered as the only technological gap to be covered. According to authors' experience, there is not a homogenous situation; each manufacturing system is covering this technological gap according to its own needs and possibilities. Some manufacturing system are running ahead in the digitalization process, some other are still in an early phase.
- Cybersecurity threats must be taken into account when considering the possibility to start an experimentation with remote operators. Threats are mainly the same that affect any other software and client–server architecture (including typical attacks like buffer overflow, denial of service, spoofing, etc.). Countermeasures include the use of updated operating systems as well as the use of the most recent advances in terms of software cryptography, authorization and authentication.

5.5. Predictive well-being of operational staff

Smart working (or working from home) surely represents the best pandemic mitigation measure, but is not always applicable: in this case, technology can help ensuring the highest safety level at the workplace. The COVID-19 pandemic represents an incredible opportunity to rethink the HO4.0. With the right hardware, analytics infrastructure and software, organizations can sustain a healthy, safe and competitive workforce.

In the first place, measures to prevent the transmission probability do not only include PD but also the *minimization of unnecessary touching of potentially contaminated surfaces and sharing of physical spaces.* Increasing digitization and use of personal mobile devices connected to the enterprise local network would allow workers onsite to access a wealth of knowledge without moving around the factory. As spaces as well equipment, machinery and tools are shared among multiple people, sensors and new human–machine interaction paradigms – such as touch-free, voice- or gesture-based interaction (for example using MYO armbands), biometric access (e.g. Face ID) – would considerably reduce the spread of infectious diseases at the workplace. PPEs could also be equipped with intelligence (e.g. connected face shields, smart helmets, etc.) and provide real-time feedback (or even AR content) to the workers.

But what matters the most is that, as personal technology becomes mainstream, employers can gather biometric data and *unleash the power of predictive analytics* to detect early signs of the disease or of potential ergonomic injuries, reduce health risks, and better manage possible future problems. A solution architecture of a software-as-a-service (SaaS) platform for secure collection, storage, processing, and health data analysis is proposed. As illustrated in Fig. 6, different implementations are possible depending on the requirements (e.g. data volumes, security levels, type of devices, real-time or near-real-time analytics etc.). Data may come from a variety of sources, ranging from biometric data (heart rate, sleep patterns, activity, skin temperature, etc.) collected continuously by wearables and other sources to personal medical records, social media, self-reported health information, and more – all stored and analyzed in an encrypted standards-compliant cloud solution or on-premises data lake. For example, glucose levels and oxygen saturation have been biometric indicators largely used used in clinical analysis to diagnose the COVID-19 disease. In a workplace, a biosensor patch might be employed for early detection of such symptoms (Javaid et al, 2020).

After the data is collected, extracted, transformed, and loaded into the database, an analytics engine can transform data into actionable information. With a combination of historical and real-time analysis, benchmarking, and predictive analytics, and with a link to the digital twin of the manufacturing system, this engine helps managers and operators to detect patterns, track and trace, model risks, visualize which cohorts are at risk and gain valuable real-time insights on workers' health. Additionally, the platform can launch personalized, event-triggered automated alerts that can encourage operators to respect health practices in the case of pandemic and reduce their risk profiles (e.g. wash their hands or check their PPE). For example, a buzz or a color-coded warning on a smartwatch could let two workers know when they are within 2 m of each other. Analysts and health managers can also access synthesized data in real-time via web-based applications to enhance existing policies and optimize processes and layouts in the factory. This solution would also allow to better plan and forecast workforce capacity needs and immediately deploy a contingent strategy to face the disruption (cf. S1, S2, S3, S4, S5). Finally, we envisage a *HO4.0 digital twin platform* that will also make it possible to simulate future production scenarios (including exceptional situations, like a pandemic), the impact of certain mitigation measures (cf. Section 5.1) and the corresponding consequence on the well-being of operators. We argue that if a culture of predictive well-being of the operational staff is established, employers will benefit because healthy and serene employees are more productive.

5.6. Use cases

This use case presents some mockups and prototype applications designed and developed at the Modeling & Simulation Center – Laboratory of Enterprise Solutions (MSC-LES) of the University of Calabria, and later industrialized and commercialized by CAL-TEK S.r.l., a Spinoff company of the University of Calabria. They show how the plug-and-play worker, the remote operator 4.0 and the healthy operator 4.0 are being implemented in a collaborative effort with companies toward envisioning the future of work. Independently from the shop-floor level (where a variety of factory automation and network technologies are deployed) and from the location of data (i.e. external cloud or on-premise data lakes), the three types of workers here discussed can use a multi-device system front-end to interact with the factory. The application and device layers of the architecture depicted in Fig. 7 shows the different possibilities in terms of hardware and technological solutions that could be used to allow the three types of workers to connect and interact with the factory "at any place and at any time".

An example of industrial machine's innovative interface (that is over-imposed on the real machine) is proposed in Fig. 8 for plug-and-play workers and remote operators 4.0. Functionalities of the interface include:

i. fast and intuitive access real-time data regarding the machine status (e.g. a crown wheel can be used to track the operation progess percentage);
ii. easy access to a wealth of knowledge about the machine itself (e.g. images, videos, audio), both recorded in real-time through a camera-microphone-sensor system (e.g. machine prognostics and health management, PHM, data) onsite and from past manufacturing activities usually not directly available at the workplace onsite or in a remote location;
iii. intelligent consultation of general information and how-to manuals of the machine;
iv. run and control the machine remotely (e.g. start a new program, set up the machine, etc.);
v. access a set of VR, AR, and MR-based training tools, that enable the users to learn how to interact with the machine using its digital twin.

Three scenarios can be then envisioned for a pandemic workforce or for the workforce of the future (Fig. 9):

i. onsite plug-and-play workers can use advanced gesture-based interface to interact in an intelligent manner with the machine (Fig. 9.a). Legacy HMIs will be replaced in the future with AI-powered "personal" assistants that will allow plug-and-play workers to "establish a dialogue" with factory machines and be assisted throughout their activities onsite with the support of Augmented and Mixed Reality.
ii. shop-floor operators can shift to remote working (or "smart working") thanks to the possibility to access the same HMI even from home through secure networks (Fig. 9.b). The next generation of a pandemic workforce or the workforce of the future will be able to monitor and control the machine sitting at their home desk thanks to the use of handheld mobile devices (e.g. smartphone, or tablets) but especially head-mounted displays for virtual and mixed reality (e.g. Hololens, Oculus Rift or HTC Vive) that would provide the operators a higher level of immersion.
iii. digital twin technology can even further empower the remote workers, who will be able not only to access the interface, but also visualize in a VR- or MR-powered environment the cyber-twin (i.e. the exact digital copy) of the physical machine. To do so, ambient intelligence, advanced sensors, machine vision

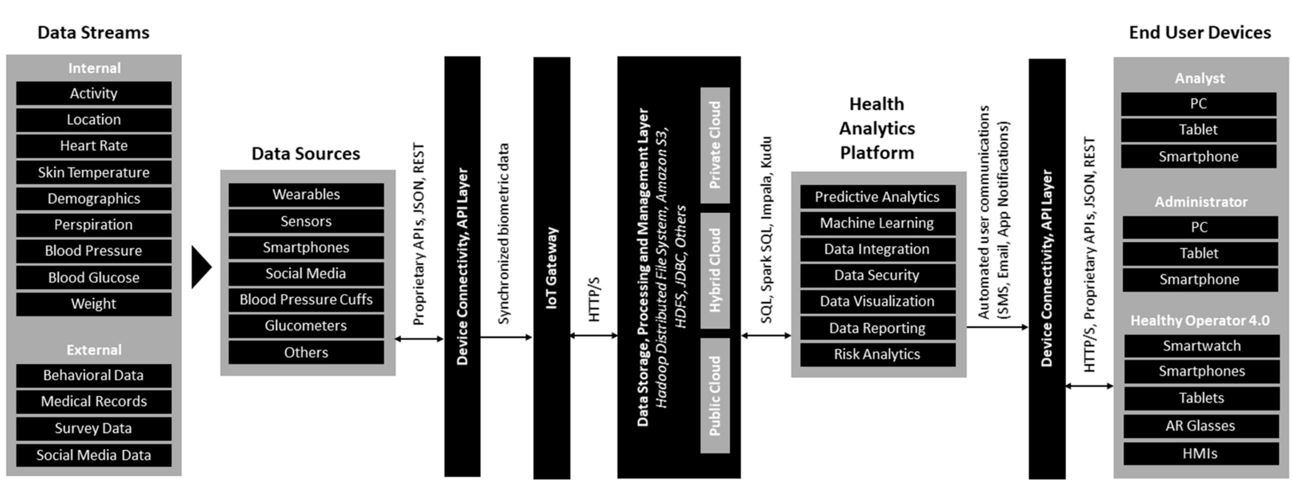

Fig. 8. A solution architecture for the Predictive Well-being of the Operational Staff.

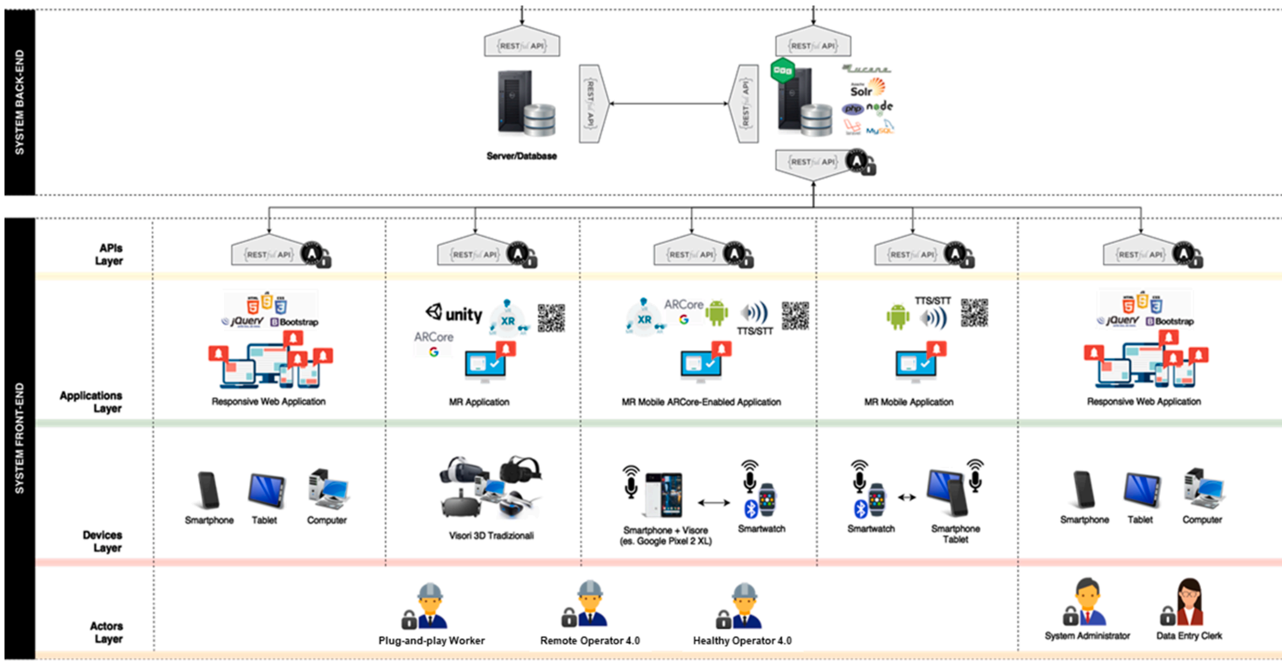

Fig. 9. Technological architecture and solutions for the three types of workers.

technology, audio systems and machine health data will allow to reproduce exactly in the cyber environment the machine.

We are living the digital era where technology allows us to "make every place our workplace": for example, a Mixed Reality application powered with ambient intelligence, motion tracking, environmental understanding capabilities provided by the Google's ARCore enable a natural and intuitive interaction with digital objects in any environment, from your home (Fig. 9.c) to even a parking lot (Fig. 10). The shop floor workers of the future can place the digital twin of a machine wherever they want, make annotations or add information in a way that integrates seamlessly with the real world. They can move around and view the digital twin from any angle and interact with it like they would do in the real shop floor (see Figs. 11 and 12).

It is worth mentioning that demonstrators and prototypes presented in this section are just some of the solutions developed by the authors and they have not to be regarded as a one-time effort for this specific article. They have been developed over the years and systematically

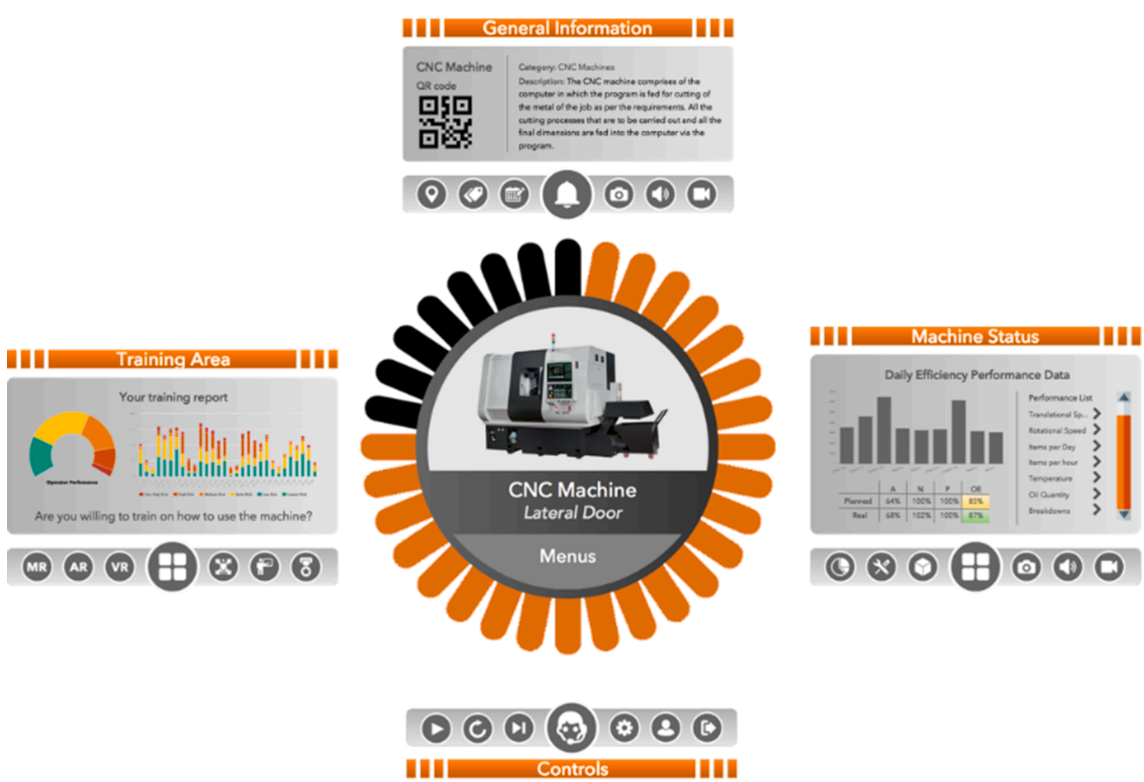

Fig. 10. A possible human–machine interface for plug-and-play workers and remote operators 4.0.

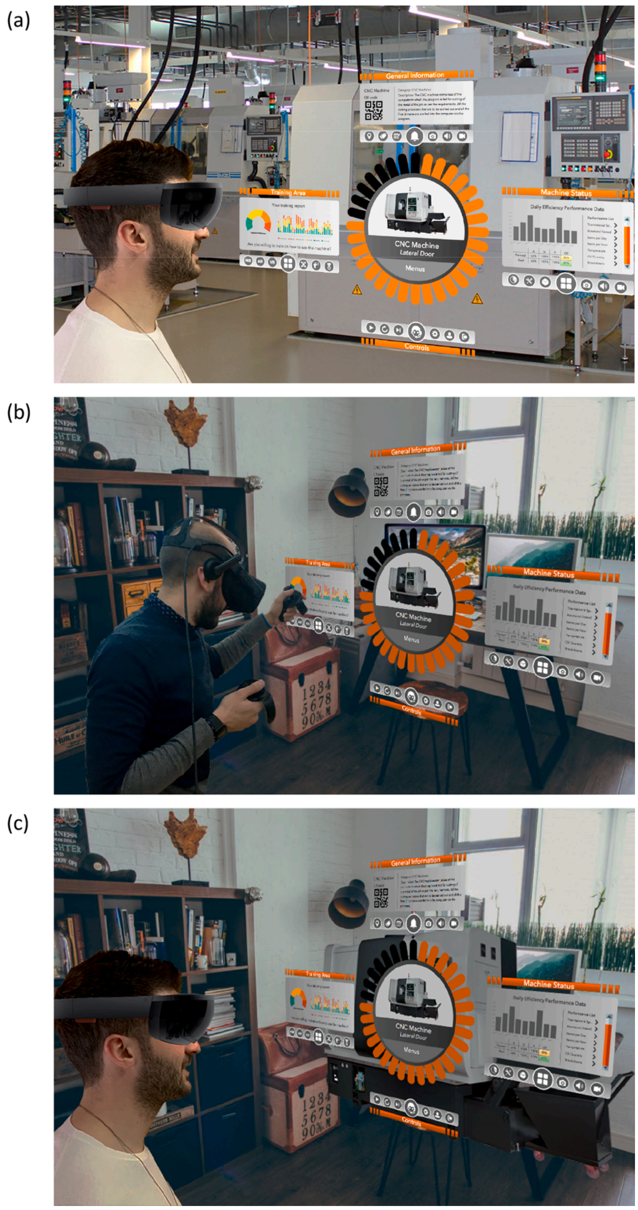

Fig. 11. New interaction paradigms for a pandemic workforce: (a) onsite plug-and-play workers using gesture-based interaction with the machine through Mixed Reality, (b) remote operator 4.0 monitoring/controlling the machine tool with Virtual Reality, (c) remote operator 4.0 positioning the digital twin of the machine and interacting with it via vocal-based instructions.

updated to include new features and functionalities (according to new results obtained by authors in different research projects and to the technological evolutions that have characterized some of the Industry 4.0 pillars, e.g. Extended Reality, Cloud, web and mobile applications, etc.). These continuous research activities have finally led to the identification of the three types of workers presented in this article (the plug-and-play worker, the remote operator 4.0 and the healthy operator 4.0).

Additional information about the research projects in which demonstrators and prototypes presented above have been developed, industries involved, their operating sectors, the as-is situation before the implementation and the target situations can be found in the following research works published by the authors (such information are not reported in details in this article because they are already available in the literature and for a matter of space). However, for the sake of completeness, a summary is reported below:

- Longo et al. (2017): solutions based on the use of AI powered Personal Assistant and Augmented Reality are presented. The solutions have been developed under two different funded R&D projects: the SISOM project and the SG-ICT project. Operating Sector: manufacturing companies working in the area of sliding bearings production. Situation as is before implementation: no use of AI personal assistant and Augmented Reality. Targeted situation after implementation: enabling a smart operator concept and improving training capabilities. Benefits as well as hurdles are described in the reference.
- Longo et al. (2019a): solution based on the use of VR for improving operators' preparedness in case of emergency in industrial plants and for monitoring and control through Remote Operators. The solution has been developed under the DIEM-SSP funded project. Operating Sector: Oils and Refineries (specific case study on re-refining of waste lube oil). Situation as is before implementation: no use of VR solutions. Targeted situation after implementation: proved capabilities of VR solutions for operators' training, possibility to fed a Digital Twin for remote monitoring and control. Benefits as well as hurdles are described in the reference.
- Longo et al. (2019b): a solution for implementing the ubiquitous knowledge concepts in manufacturing systems (knowledge available everywhere, no matter where you are) as part of a Digital Twin. This solution has been internally developed by MSC-LES and CAL-TEK and the case study has been funded through a specific research contract. Operating Sector: manufacturing of turbines and pumps for the Oil & Gas Sector (Baker Hughes General Electric plant, located in Italy). Situation as is before implementation: no use of Digital Twin solutions, limited use of the ubiquitous knowledge concept. Targeted situation after implementation: statistically significant improvement of multiple production and business performances have been achieved. Benefits as well as hurdles are described in the reference.
- Bottani et al. (2021): a solution based on Mixed Reality (through Microsoft Hololens©) and Mobile technologies providing new enabling interfaces for shop floor operators. This solution has been developed as part of the W-ARTEMYS funded project. Situation as is before implementation: no use of Mixed Reality and mobile app solutions. Targeted situation after implementation: positive impact on operator's productivity, downtimes reductions and employees' safety enhancement. Benefits as well as hurdles are described in the reference.

5.6.1. Lessons learned and future work

Lessons learned are gained from the analysis of the above use cases.

Lesson #1: Digital manufacturing is not reducing, rather asking for more workers in a pandemic.

Kumar et al. (2020) asserted that manufacturing plants should shift their manufacturing capabilities to digital manufacturing to reduce the number of onsite workers and consonantly reduce the chances of the pandemic situation. Instead, we argue that the digital toolbox for a pandemic workforce fosters a renewed focus on the future of industrial work and on the safety levels at workplaces. Plug-and-play workers, remote operators 4.0 and the healthy operator 4.0 will transform how workers relate with the work environment and will enable new flexibility to meet production requirements.

Lesson #2: Workplace design and space architecture will evolve towards a harmonic innovation paradigm.

All the spaces where the operators live require a new design, coherent to this new view. Beside the adoption of hygiene and social distancing practices, workplace design is about how people interact in the factory of the future. Since we know that a direct correlation exists

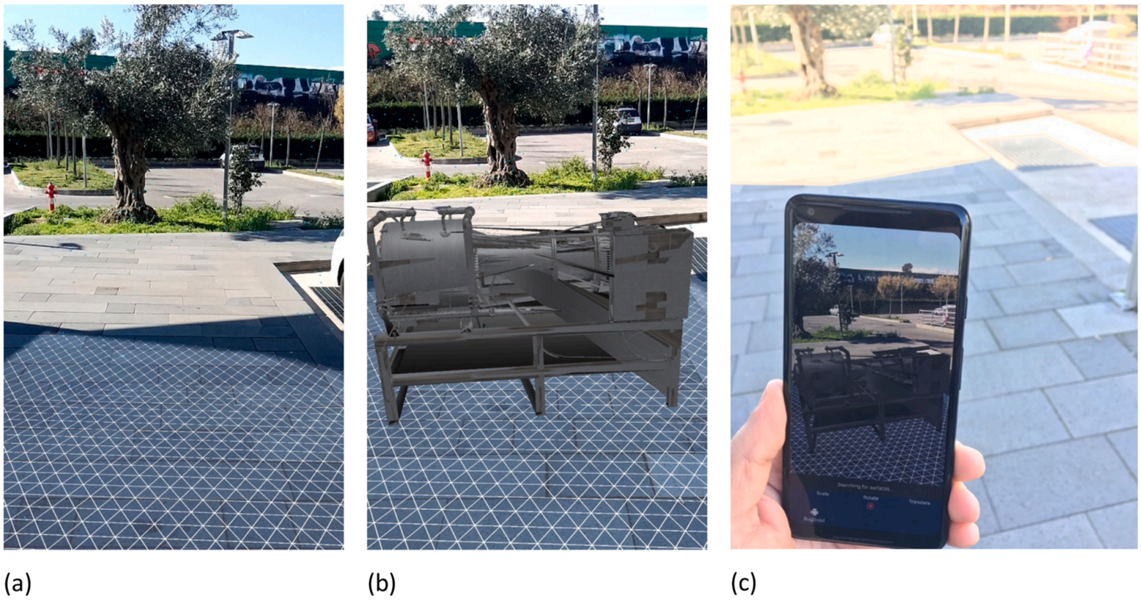

Fig. 12. Make every place your workplace: visualize remotely the digital twin of machines thanks to "environmental understanding capabilities" of a MR Mobile ARCore Enabled Application: (a) scanning the environment, (b) placing the machine digital twin to interact with, (c) using a handheld device to more around the digital twin.

between the work environment and human behavior, we must take this into account and carry out the spaces design accordingly.

In such a scenario, where every place is my workplace, Roj (in press) explains that the "Organizational evolution has led to imbuing space with different meaning, highlighting the sense of belonging, with attention to social aspects, creativity, dialogue, entertainment and autonomy".

What this means in terms of office space and work areas, is the provision of dynamic, flexible, healthy, efficient and pleasant contexts. While integrating architectural solutions, such as biophilic design, into the workspace has pushed companies (such as Ferrari in its Maranello headquarter) to create healthier and pleasant contexts, a harmonic space planning and design in work environments is recently germinating as a new school of planning culture that will merit further scientific, methodological and operational investigation. In this sense, the pandemic has strongly suggested that the watchwords for workplace layout design are flexibility, collaboration and sharing. This must be true for both offices spaces and for the shopfloor spaces.

There will be a rise in multifunctional work areas that make efficient use of floor plans to ensure more flexibility on where and how staff can work and encourage a more efficient flow of employees. While a "clubhouse" or "hoteling" model – with employees visiting the office when they need to collaborate and returning home to do their focused work – may be a viable solution for office workers, an activity-based working model (with operators moving between a variety of workspaces) sound more logical for shop floors and manufacturing environments. To this end, the authors believe that the setting-up of the shop floor for the smart operators should be characterized by a "well designed presence" of portable and wearable devices (always connected to the internet) equipped with enabling technologies (AI based Personal Assistants, VR, AR, MR) and with their own charging stations. Thanks to this approach, remote operators may be always connected with onsite operators working in the shop floor, while plug and play operators may easy switch between machines and workstations (above all when required by critical situations, e.g. scarcity of manpower due to a black swan event). Thanks to these devices (and their own software applications), plug and play operators will be supported by a continuous training and better capabilities in terms of activities planning and executions (also thanks to their continuous connection with remote operators).

Furthermore, some companies are also using digital twins of their facilities to simulate (with real time data) operations under different staffing levels and production scenarios and evaluate the impacts of changes on traffic flows (e.g. workers' movements, material movements). This approach can support many aspects of operational planning, including determining the mix of skills that on-site teams will require based on skills matrix to identify potential shortages of critical capabilities on a day-to-day tactical basis and, together with scenario modeling, guide decisions about staff training, reskilling or upskilling to improve workforce resilience or recruitment requirements. These analyses can be very helpful to design the correct positions of the portable and wearable devices throughout the shop floor as well as to understand functionalities that must be provided in each software applications and how to distribute training capabilities within the shop floor.

Lesson #3: The digital toolbox is a promising set of solutions and strategies for a robust and resilient workforce.

The proposed concepts of plug-and-play worker, remote operator 4.0 and healthy operator 4.0 are promising solutions that can considerably increase the robustness and resilient of the industrial workforce and give manufacturing firms the capability to resist the impact of black swan events and even improve their pre-pandemic performance (cf. Section 2).

Industrial automation paves new ways for machines and humans to collaborate thereby increasing efficiency and simultaneously driving down complexity and overhead costs. A new generation of robots that are more flexible, versatile and affordable can be adopted and trained by the frontline staff to perform more complex tasks consistently.

Lesson #4: The benefits of the adoption of the digital toolbox will counterbalance (or overcome) the implementation costs.

Industry 4.0 comes with the promise to provide incredible benefits but at significant costs. The pandemic, however, teached us that the costs of production stoppages or rigid manufacturing systems are even higher. Digitalization and resilience roadmaps are required to drive investments and actions and gain benefits in the future. Making onsite labor a variable cost, greater digitization and automation, more demand for independent contractors, increased reliance on remote work, increased health and reduced workplace-related risks have the potential to deliver better productivity, lower costs, and enhance resilience after the pandemic subsides. This is even more interesting if we think that the average expense per single worker for complying with health protocols at the shop floor (hand sanitizer, masks, facility cleaning and sanitation) was estimated to be 125€ (Confindustria, 2020). Future studies may provide economic insights on the impact of such solutions.

Lesson#5: What is disruption today (e.g. pandemic) can be an opportunity to create a sustainable and healthy workforce inspired by the principles of harmonic innovation and digital humanism.

If the digital toolbox is implemented with a forward-looking perspective, what today is prevention and risk mitigation measures, tomorrow can become the opportunity to succeed in a more and more competitive scenario and increase the safety, well-being and sustainability of the workforce. In the next future, every place will become their workplace thanks to the digital twin and data-driven manufacturing paradigms. Even shop-floor workers will be able to run the machines remotely, thus reducing their mobility and commuting to the factory (and, reducing the environmental impact). A new digital humanism will foster the centrality of man and the importance of a sustainable future of work.

Lesson#6: Industrial systems and work designers have to examine human values and ethical aspects a priori, so that they are not construed as costs, but instead as design requirements.

Since an increasing human–machine symbiosis is predicted for the next future of work, more and more ethical questions and concerns arise. Institutions, such as the European Union, are already fostering the attention towards "ethical and responsible innovation" in the Factories of the Future. Since converging technologies blur the line between human and technological capabilities, future work design studies need to investigate how to design H-CPPS for human values (e.g. privacy, trustworthiness, explainability, accountability, self-actualization, welfare, security, etc.).

Lesson#7: Making every place your own workplace may have social and psychological impacts.

The flexibility and greater autonomy associated to remote work can also result in some adverse effects for the mental and physical well-being of workers, related to the so-called autonomy paradox (already studied for emails management through mobile devices that allow total professional flexibility from everywhere, Mazmanian et al. 2013). This concept – the autonomy paradox – means that although higher levels of autonomy and flexibility for workers (which are, for example, a result of remote work) have positive effects on workers, such as making work more rewarding, enhancing job satisfaction and other aspects mentioned above, they can also have negative effects, such as increased work intensification, longer and more irregular working hours, higher stress levels and a disrupted work-life balance.

Organizations have been struggling to create guidelines around their work environment: in many cases, employees are left in a flux state, unable to switch off and rest/recover from work with blurred lines separating work and personal lives that are no longer compartmentalized. Nevertheless, a recent study on subjective cognitive failures and their psychological correlates in a large Italian sample during quarantine/self-isolation for COVID-19 (Santangelo et al. 2021) has shown that there is no difference, in terms of cognitive failure, between smart-workers, non-smart-workers, and those currently not at work. Vice-versa, people not having a job experienced more frequent cognitive failures. This helps in understanding that, while "making every place our own workplace" may bring to work intensifications, the remote working does not seem creating cognitive failures or disturbances. The problem is instead amplified for vulnerable people (e.g. people without a job) for which psychological support interventions to reduce anxiety, depression, and anger are needed.

The value added of the remote working is finally confirmed by the "State of Remote Work" (2021) where the following results are indicated by 2300 participants: 97.6% would like to work remotely at least some of the time during the entire career, 97% recommended the remote working (while only 27% stated that they are not able to unplug and only 16% cited loneliness as negative outcome of smart working).

6. Supply resilience

Normally process design in manufacturing field require an intense work in order to ensure the right times and methods to acquire materials, move them aloing the logistic chain, transform the materials within the plants. Recently, suppliers are sometimes part of the development team, in order to add value to the value chain according to their specific experience.

This integration and research of the maximum efficiency may results in points of weakness when a black swan event occurs: if supply chain breaks, it becomes really difficult and challenging to ensure the normal production rate. What normally happens is that production rate decreases and a spasmodic search of new suppliers begins in order to rebuild the same supply chain configuration: this faults when the black swan event occurs at a global dimension and generates a shock all over the World.

6.1. Strategies for a resilient supply in times of pandemic

Production resilience means capacity of the production system to overcome a shock due to unpredictable events. We learned by COVID-19 experience how it is possible, although unexpected, that a production system can be affected by a limitation of the available workforce in the plant and, contemporarily, a break of the supply chain due to some suppliers' lock-down.

As above described (cf. Section 5), technology would help to redesign the process control allowing some distance-workstations outside the plant, ensuring the same process efficiency and effectiveness.

Supply chain breaks naturally enlarges the supplier research domain according to the Liquid Supply Chain paradigm recently postulated by some of the authors (Passarelli et al., 2021). But the latter is an external answer to the industry need. At the same time, technology allows also an internal answer.

Industry can move toward two different directions, at least for some production processes:

i. Allow the vertical integration of some processes in order to face an eventual supply chain break.
ii. Invest in alternative technologies which can substitute the traditional ones in case of supply chain breaks.

Both of them increases industry resilience since the organization has more chances to overcome temporary reduction of the supplier production. Actually, vertical integration which means internalization of some manufacturing processes is really costly because requires at least three elements:

1. Skilled workforce able to execute some specific processes;
2. Proper equipment;
3. Enough space inside the plant.

For the above reasons, internalization is usually reserved to very critical processes for which the risk coming from market is really strong.

On the contrary, the acquisition of technologies able to substitute other conventional processes, even if slower and more expensive, can be a suitable strategy.

In our common experience we understand how it is possible to obtain different products using diferent processes: a dress can be manufactured by hands instead of machines, a screw car be produced using a forming machine or a lathe, a dish can by produced by a moulding machine but also using a Fused Deposition Method (FDM) additive manufacturing machine. Thus, if vertical integration (i) may upset the industry organization because it may require a huge investment in terms of resources, the use of substitutive technologies (ii) seems to be a suitable solution to increase process robustness in case of supply chian troubles. According to I4.0 paradigm, a massive research on the use of additive manufacturing technology, intended as a *digital & unconventional sourcing*, instead of the traditional ones is carried out all over the World (Achillas et al., 2017).

On the other hand, what is really disruptive is the use of:

i. COVID-19 pandemic as an extraordinary opportunity of innovation.

In such cases, indeed, supply chain interruption was not easily supported by an internal or external substitution of the previous suppliers. The pandemic acts as an innovation booster, allowing a quick product development to overcome the supply chain weakness. Thus, a dress can be manufactured using the local natural fibres; screws can be substituted by new fastening methodologies; dishes can be replaced by new trays made of a special cardboard.

6.2. Use cases

During pandemic time several published papers described how resilient companies changed their production to manufacture products useful to cope with the disease. Masks for breath protection, components for pulmonary fans, medical dress and devices, spacer fences are just few examples (Fairgrieve et al., 2020). However, here we present and discuss some business use cases showing how companies decided to preserve their production looking at their products after pandemic.

6.2.1. A textile company

The first example concerns a textile company. They produce human clothes and the raw material was historically imported from China for sake of cheapness. During the first lockdown the cost of raw material increased by a factor ten due to the strong demand for mask manufacturing all over the World. This problem is known in scientific literature. For instance, in McMaster et al. (2020), the authors claim that "given the potential for outbreaks to disrupt input-sourcing, managers should consider adjusting the sourcing mix to better diversify risk (…)". To overcome the problem, they recommend "include reallocating inventory across regions or reducing dependence on products at risk of disruption".

Thus, the company we are discussing about, decided to procure the textile yarns locally, even if the cost is from 3 to 5 times the one paid to Chinese supplier before crisis. Of course the price of the final product has been increased by 20–25%, but the company was very clever to arrange a new storytelling about the products, focusing the attention on the quality of materials and the very short production chain.

The market response was very enthusiastic so that the company decided to increase the cooperation with the local producers, positioning the product in a higher quality segment but at a sustainable cost for the customers. The company set a "new normal" according to Ralf Seifert and Richard Markoff definition in their work "Digesting the shocks: how supply chains are adapting to the Covid-19 lockdowns" (Seifert & Markoff, 2020).

6.2.2. An aluminium window frames manufacturer

The second example we discuss here concerns a company which produces aluminium window frames. They used some polymeric small parts produced by a big company which was overwhelmed during the first pandemic wave and the subsequent lockdown. In order to avoid the manufacturing stopping after the end of stock, they decided to redesign the components using an additive manufacturing (AM) machine to produce the new particulars. Actually, the cost of AM can be also 5 times the one of injection moulding process according to Atzeni & Salmi (2012).

However, the company had a very good idea because the small parts were designed according to the new manufacturing process, which allows a sudden change of section that is not recommended in injection moulding. Thus, the number of parts was reduced and the number of the operator manual operations reduced by 30%. In this way, taking into account the extra production cost and the time saving, the change did not impact the final cost of the window and, at the same time, the orders have been dispatched in the right time.

What is more, the company is further modifying the parts and began the procedure to patent a new window internal device, confirming how changing technology from injection moulding to additive manufacturing could generate different advantages for the company (Vasco et al., 2019).

6.2.3. The decision process used by the two companies

The two companies mentioned in the previous sections (the textile company and the aluminum windows frame manufacturer) experienced the stock breaking since it was not possible to guarantee the procurement (supply chain integrity). Thus, in this case, the company management can, potentially, use three different approaches:

1. Wait for the situation improvement, even if this could cause a long production stop (stand-by manpower, plant maintenance, government benefits, etc.).
2. Design new products attacking new markets, but this decision is risky, because the lack of experience and the volatility of some new markets (e.g. the one of the sanitary devices);
3. Remain in the same market but modifying the supply chain, according to new opportunities deriving from local market and technology. The long experience of the company in the field may, at least, reduce product quality problems; in some cases, quality can also be improved by the use of new technologies and the increase of manufacturing costs.

Nevertheless, it is important to mention that, according to many research studies on supply chain resilience (even in outdated studies like Craighead et al. (2007) that has been cited by hundreds of other papers), resilience must be created before the supply chain disruption happens, to avoid critical situation where companies are not able to maintain their "equilibrium position" on the market or to return back to a normalcy post-disruption. This helps in understanding three important points:

1) Supply chain resilience is not something new; it was deeply investigated and studied above all in the aftermath of 9/11 terrorists' attacks (Christopher and Peck (2005); Sheffi (2005-b); Sheffi (2006)).
2) Resilience must be mostly built before catastrophic events. When a black swan event occurs (e.g. Covid-19, 9/11 terrorist attacks, the mad cow disease, just to cite a few in different sectors) then the company is not in the case of "building resilience", it is in the case of "restoring resilience". As a matter of fact, restoring resilience after a supply chain disruption means resolving a contingency that, in turn, force companies to neglect, at least at the beginning of the recovering process, other aspects such as quality, revenues, profits, etc.
3) The most important aspects affecting supply chain resilience are: flexibility, agility, velocity, visibility and redundancy. Christopher and Rutherford (2004), the report "Creating a Resilient Supply

Table 1
Resilient Workforce and Resilient Supply Chain versus different types of Black Swan Event.

	Resilient Workforce			Resilient Supply Chain				
	Plug-Play Operator	*Remote Operator 4.0*	*Well Being of Operator Staff*	*Flexibility*	*Agility*	*Velocity*	*Redundancy*	*Visibility*
Pandemics	XXX	XXX	XXX	X	XXX	X	XXX	X
Terroristic Attack	X	XX	–	X	XXX	X	XXX	X
Supply Chain Contamination	–	X	XXX	XXX	XXX	X	X	XXX
Industry and Supply Chain Failure	X	XXX	–	XX	XX	XXX	XXX	XX
Natural or Human Made Disaster	XXX	XXX	X	XX	XX	XXX	XXX	XX

Chains: A Practical Guide" (2006) propose an accurate definition and description of the supply chain agility, velocity, visibility and redundancy. Agility is defined as the company capability to quickly respond to unforeseen and unpredictable demand/supply markets changes. Note that the agility of a company also depends on the agility of all the actors involved in the supply chain. The velocity must be interpreted as time required for moving goods along the supply chain. The velocity is usually measured in terms of lead times. The visibility is the capability of the company to see all the information regarding the flow of products, information and finances both downstream and upstream along the supply chain. The redundancy is the augmentation of capacity and inventory in each node of the supply chain for facing supply chain disruption events

6.2.4. Lessons learned and future work

The real world business use cases here discussed come with three relevant lessons learned for scientists and practitioners.

Lesson #1: The pandemic pushes companies to reallocate inventory sourcing mix across geographical regions to better diversify risk and to adapt their business model.

On one side, we argue that supply chain will be shortened and globalization will be reduced in favor of local suppliers and supply chains. Shorter delivery times and better responsiveness of local networks will allow companies to keep their production processes up and running even when global supply chains are interrupted and disrupted. On the other side, increased connection with diversified global suppliers (located in different geographical areas) will allow to reduce dependence on products at risk of disruption.

Lesson #2: The pandemic – or any other disruptive event – is an opportunity for product innovations and different business models.

The need to find substitute suppliers or material could be reimagined as a moment to innovate the product. It goes without saying that different business models are required depending on the source. For an Italian company, for example, leveraging on local suppliers generally means exploiting the "Made in Italy" and selling higher quality products at a higher price. Using diversified international suppliers, instead, would allow lower costs.

Lesson #3: The pandemic – or any other disruptive event – is an opportunity to substitute conventional manufacturing technologies with new flexible ones, such as the additive manufacturing.

Industry 4.0 key enabling technologies, such as additive manufacturing (AM), may be critical to guarantee the production and business continuity. Despite AM is generally associated to higher costs than traditional manufacturing processes, such drawbacks may be offset by (or even less than) stopping the production process (or slowing down its throughput). AM is not only a promising open source solution, especially during emergency situations, but will allow rapid inventory replenishments. In a pandemic scenario, this process could be even potentially fully automated (from material loading to machine setup).

7. Insights for future black swan events

Needless to say, there are a number of black swan events types and, of course, pandemic is a particular kind of "black swan event" because it involves any area of the world. Additional relevant events (the list below is not exhaustive but gives an idea of black swan event types that have been experienced over the last 30 years) include:

- terroristic attacks: the 9/11 attacks, USA (2001), Madrid train bombings, Spain (2004), 7/7 bombings, London, UK (2005).
- Contamination in the food and non-food supply chains: the Mad Cow Disease, UK (1996); the high levels of Dioxin in Coca-cola drinks, Belgium (1997); the high levels of Dioxin in Belgium Poultry (1999); the diethylene glycol in the Colgate toothpaste (2007); the Mattel Lead Contaminated toys (2007).
- Major industries and supply chain failures: the Nokia-Ericson case (2000) and the Land Rover case (2001), Suez Channel obstruction (March 2021).
- Natural Disasters: ash cloud over Iceland (2010), Japan Earthquake and Tsunami (2011).

Table 1 provides a matrix that shows how the different operators types and supply chain resilience concepts can be applied to different types of Black Swan Events. This matrix is an attempt by authors to discuss which solutions, among the ones provided in Section 5 and 6, are appropriate for each type of disruptions. The importance of the resilient workforce and of the resilient supply chain is expressed by using: X (low importance), XX (medium importance), XXX (high importance).

The importance of the resilient workforce and resilient supply chain during a pandemic has been already discussed in previous sections (and it is also within the aim of this article). By taking in mind all the considerations done for the pandemic case, an extension to other black swan event types is possible.

- *Terroristic Attack*: evn considering big terroristic attacks (e.g. 9/11), these are usually focused on one or more specific targets. Most of the countries can face a terroristic attack with their own workforce (including military, police, firefighters etc.). In addition, terroristic attacks that are intended to create large damages, need time to be prepared and, many times, they are blocked before execution thanks to the work done by the Intelligence. To this end, it is simple to understand that the importance of a plug-play operator is low, while the Remote Operator 4.0 may assume a medium importance considering that a terroristic attack may also involve destruction of workplaces. The well-being of operational staff is not applicable to the case of terroristic attacks. Regarding the supply chain resilience, a major role during a terroristic attack is played by agility and redundancy (respectively the capability of the entire supply chain to react quickly and the augmentation of capacity and inventory in each node of the supply chain to face the disruption).
- *Supply Chain Contamination:* regarding the resilient workforce, the well-being of operational staff may be critical in this case as the

contamination may affect not only final customers but also plants and supply chain operators. The supply chain resilience is increased by flexibility (capability to of quickly readapting other or new products to replace contaminated ones), agility as well as visibility. The latter is strategic because it allows tracking contaminated products (or parts) downstream and upstream the supply chain.

- *Industry and Supply Chain Failure*: among the cases of industry and supply chain failures already cited at the beginning of this section, it is clear that the lacking of information can be the critical point. A resilient workforce with the use of remote operators may improve the situation: in this case, the remote operator helps in increasing the interoperability between the industry and supply chain actors involved in the failure providing better information sharing and management. Regarding the supply chain resilience, velocity and redundancy have to be considered as the critical points: the Suez Channel obstruction has clearly shown a need to reduce the time for moving goods (velocity) and the need to have additional capacity and inventory to replace blocked or destroyed items and products (redundancy).
- *Natural and Human Made Disaster*: like pandemics, natural and human made disaster may affect large areas and entire populations. In this case, a resilient workforce should include plug and play operators as well as remote operators 4.0. Supply chain flexibility, agility and visibility are important, but restoring a quick movement of products along the supply chain and having enough redundancy can make the difference the reestablish the normalcy after disruption.

8. Conclusions

The pandemic will have profound implications on the manufacturing environment as we are used to imagine it. The post COVID era opens an opportunity window for the sustainable business transition, and need to make supply and production systems more resilient.

The presented research contributes to a growing body of literature on sociotechnical industrial environments and human cyber physical production systems. The ultimate goal is to identify and discuss strategies that allow companies to cope with a disruptive scenario like a pandemic. Further research in a number of directions to unlock more intelligent and flexible capabilities, as well as to increase adoption of new digital and technological innovations in industrial sociotechnical environments is needed.

CRediT authorship contribution statement

Giuseppina Ambrogio: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Luigino Filice:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Francesco Longo:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Antonio Padovano:** Conceptualization, Methodology, Software, Validation, Visualization, Investigation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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