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Lessons Learned from Covid-19 towards Resilience of Complex Industrial Systems

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The emergency of the COVID-19 pandemic spreading in different waves marked an unprecedented world crisis considered as the most critical one since the Second World War. To contain the pandemic spread, governments implemented both prevention measures to limit the occurrence of undesired events and protective measures to reduce the severity of potential consequences, e.g. physical distancing, travel restrictions, working remotely, wearing face masks and prolonged closures of schools and non-essential businesses industries. Consequently, there were substantial economic setbacks and operational disruptions, reduced logistical and productivity performances, in addition to evident health and social impacts. To learn remarkable lessons from COVID-19 experience, this work analysed results of an *ad hoc* questionnaire to collect workers' perceptions and to evaluate systems vulnerability and response ability of ensuring business continuity. The data obtained from questionnaires and accident records were processed by a multi-step methodology, to attain descriptive and inferential statistical analyses and identify statistically significant relationships on accident dynamics. Outcome of the study can help improving organizational resilience of systems, referring to its ability to monitor, respond, anticipate and learn, to achieve improved safety levels and support operational continuity, under possible future unexpected events.

1. Introduction

The COVID-19 pandemic highlighted the lack of preparedness of systems to respond to unforeseen events, revealing the vulnerability of both the healthcare and industrial sectors (Marmo et al., 2022). To limit the spread of COVID-19 and prevent the collapse of the healthcare system, governments, including the Italian government (Vianello et al., 2021), implemented measures such as physical distancing, travel restrictions, and prolonged closures of schools and non-essential business (Prem et al., 2020). Both the healthcare and industrial sectors underwent drastic changes, leading to a sudden increase in demand for specific products and the imposed decrease in demand for other goods, and experienced a lack of resources and personnel in the workplace. The pandemic provided an opportunity to bring these two systems together and prompted researchers to investigate the theme of risk assessment to strengthen system resilience (Taarup-Esbensen, 2020) to ensure safety and prevent operational shutdowns (Fabiano et al., 2022). Resilience is defined as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events". The more resilient a system is, the more capable it is of continuing to function effectively in the presence of unexpected and unwanted disruptions. Resilience is based on four pillars: preventative control, mindful action, performance optimization, and adaptive innovation. This facet translates into the ability to monitor system performance, anticipate disruptions, be prepared to respond to threats, and learn from experience (Woods et al., 2006). Investigating the theme of resilience is crucial to highlight possible precursors of threats, to prevent them and prepare effective responses. In the industrial context, resilience allows anticipating the occurrence of potential damages, enabling rapid recovery, and ensuring business continuity. The reader is addressed to the combined scientometric and

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systematic review performed by Fabiano et al. (2023) to critically analyse tools and methodologies able to combine resilience analysis with more traditional assessment of risks posed by the COVID-19 crisis. In the present paper, Genoa Port was selected as case-study due to its highly significant reality, encompassing various commercial and industrial activities. This choice allowed to examine the impact of the COVID-19 pandemic on the occupational risk trends in port areas, while also briefly addressing the Major Accidents Hazard (MAH) and potential risk associated with the handling of dangerous substances. This project focus on the development and implementation of novel methodologies and strategies to enhance industrial safety and resilience of complex systems. In particular, this work aims at building a conceptual model based on indicators for assessing organizational resilience (OR) based on the experience gained during the pandemic through statistical elaboration of field data and questionnaire survey in Genoa Port (Italy).

2. Materials and methods

2.1 Reference industrial context

The port of Genoa (Figure 1) extends over a total area of 700 hectares, with a coastal length of approximately 22 kilometers. Its strategic geographical location makes it an important hub for international trade and logistics, and a crucial connection point between Europe and the rest of the world, including northern Africa, the Middle East and the Far East. Although not directly connected to more distant continents such as the Americas or Oceania, it plays a significant role in global connectivity. The accessibility to the port for heavy vehicles and workers is ensured through a series of checkpoints, controlled by the Guardia di Finanza (Financial Guard) and private security services, which allow for easy connection between the internal road network and the national network, particularly the highway system. Similarly, there is an internal rail transport network that connects to the national railways, with particular attention to connections with the inland areas where the Interporto di Rivalta Scrivia is located. This facility is strategically positioned for exchanges with major cities in Northern Italy, such as Milan and Turin. Thanks to its significant size and wide range of infrastructures, the Port of Genoa is capable of handling large volumes of maritime traffic. It has docks, modern container terminals, state-of-the-art cranes and equipment to facilitate loading, unloading and storage operations for both containerized and bulk goods ("rinfuse"). Furthermore, the port is also a cruise destination, so it manages automobile and passenger traffic as well. In recent years, the Port of Genoa has faced significant challenges. In 2018, there was a major disruption of port activities due to the tragic collapse of the Morandi Bridge, a crucial road infrastructure connecting the port to the highway, thus requiring new road stretches. More recently, energy transition efforts imply the appearance of risk "spots" due to the local increase of risk, due to distribution networks of new energy carriers like hydrogen and ammonia within the maritime context (Pasman et al., 2023).

Figure 1: Facilities and companies in the Port of Genoa from Cornigliano to Foce (area a) and from Prà to Cornigliano (area b). Adapted from AdSP Genova (2023).

Another major challenge arose with the outbreak of the COVID-19 pandemic, which imposed changes in the management of operations, in workers and sources availability, and safety measures for workers. Despite these difficulties, the Port of Genoa is constantly working to improve its infrastructure and operations to maintain its prominent position in the international maritime landscape. As a preliminary analysis, a comparison was made among the frequency of incidents occurring in the main port company and in other industrial sectors. Data were collected directly on-site or obtained from INAIL database (National Italian Institute for Workers' Compensation). As pointed out in scientific literature, the observed limitation is connected to possible grey labour situations and underreporting in the case of moonlighting. Additionally, it must be stressed that INAIL data include the claims of accidents due to COVID-19 contagion. Frequency index was calculated according to Eq. (1):

$$FI = \frac{Number\ of\ total\ accidents}{Number\ of\ worked\ hours} 10^6 \qquad (1)$$

From INAIL database, it was possible extracting raw data regarding the number of accidents per year, and, through INAIL tariff management, data related to the number of employees in the different contexts, as well worked hours. In this elaboration we considered accident that were actually compensated by INAIL. This allowed a first comparison and assessment of the impact of the COVID-19 pandemic as an additional risk factor.

2.2 Questionnaire development and evaluation

An "*ad hoc*" questionnaire was developed to gather information on a series of control variables related to workers' personal characteristics and to assess the pandemic impact on business continuity and safety levels of port work. Questionnaire data were evaluated by analysis of variance (ANOVA) to assess the significance of results. Outcome correlations were depicted by the response surface methodology (RSM), an effective approach to assess statistically significant factors and the overall level of risk perception of the respondents (Fabiano et al., 2022). The focus of the study is to estimate the degree of organizational resilience and consequently identify critical factors that have limited its full development, to make the system response to harmful events quicker and more effective in ensuring its operational continuity and performance quality.

3. Results and discussion

3.1 Injury trend

As shown in Table1, FI in the port of Genoa revealed a notable decrease in recent years. This trend indicates a general improvement in safety conditions, better preparedness of workers, but it may also be correlated with the overall economic situation of the Country. FI decrease was in fact very sharp until 2014 and subsequently slowed down in the following years. In addition to the data shown in Table 1, the spread of COVID-19 (affecting the last period) has halted the reduction of FI, which has stabilized over the last four years at an average value of 38.91. This highlights how the COVID-19 pandemic has been an additional risk factor due to the additional rules necessary for containing the spread: in fact, despite accidents decreasing in absolute value, this decrease has not been proportional to the reduction in working hours, which were significantly limited due to lockdowns and restrictions. By statistical elaboration of INAIL raw data, it was possible to ascertain that the decrease in the accident index was common to all industrial sectors. In this regard, the last report of INAIL (INAIL, 2023) observed a decreasing trend of COVID-19 related accident in Italy over time, since their incidence was of 1 in 4 in 2020, 1 in 12 in 2021 and 1 in 6 in 2022, all based on claim reporting. Observing the data shown in Table 1, it is possible to infer that Genoa port has a higher FI compared to higher-risk industrial sectors, even considering that the collected field data exclude COVID-19 accidents in the working environment.

Table 1: Frequency Index (FI) of accidents for industrial sectors (INAIL classification) over the period 2013-2021

Sector	Mean	2013-2015	2016-2018	2019-2021
Agricultural activities	14.74±1.09	15.69	14.58	13.95
Chemistry	10.19±1.08	10.81	10.75	9.00
Building	15.43±1.40	16.83	15.24	14.23
Electricity	10.16±1.49	9.41	11.59	9.48
Woodworking	15.86±1.31	17.07	15.85	14.65
Metallurgy	13.57±1.08	14.36	13.46	12.87
Mining	15.91±1.16	16.75	16.00	14.99
Textile and clothing	5.44±0.44	5.69	5.31	5.31
Transport	19.13±1.01	19.69	19.46	18.25
Various activities	9.11±1.74	9.22	8.20	9.92
Genoa Port	66.8±30.5	99.7	61.3	39.4

As for data from the local health agency ASL 3 PSAL, the total number of COVID-19 cases for 31 Companies in the port in the different waves resulted 158, 116 and 96 respectively in 2020, 2021 and 2022. This facet can be justified by the broad variety and hazards of port operations that are often carried out in crowded spaces and sometimes by outsourced personnel (such as workers occasionally called in to cope with the excess demands of terminal operators), which may be characterized by reduced specific formal and informal knowledge regarding a particular installation and inadequate training period (Fabiano et al., 2008).

3.2 Questionnaire statistics

To test the main effects of workers' age, job position, and on-site experience on the probability of injury, perceived cause of the incident, and the impact of the pandemic on safety and port work, a univariate analysis of variance (ANOVA) was conducted. The age, job position, and experience of the sample workers are shown in Tables 2, 3, and 4, respectively. To perform these preliminary analyses, five categories were used for demographics (less than 25, 25-35, 35-45, 45-55, over 55 years old), job position (shift workers, daily, on-call, office clerk, others), and on-site experience (less than 1 years, 1-2 years, 2-5 years, 5-10 years, over 10 years). It can be observed that the sample in this research does not include workers under 25 years old, while 95% are over 35 years old; half of the sample consists of daily workers, and 35% are shift workers; finally, almost the entire sample (92%) has declared having more than 10 years of experience in the port sector. The statistically significant interactions ($p < 0.05\%$) are reported in Table 5, namely the probability of injury ($p < 0.05\%$), perception related to the return to pre-COVID-19 shipment volume levels ($p < 0.01\%$), and perception related to safety and updates on new medical provisions ($p < 0.01\%$). Figure 2 shows the three-dimensional graph representing the response surface for variations in work modes and timings caused by remote work in the port sector as a function of age and job position. Results scored on a 5 points Linkert scale ranging from 1 (completely disagree) to 5 (completely agree), related to the item in the y-axis of Figure 2 allowed revealing two statistically significant relations, i.e. worker age ($p < 0.01\%$) and job position ($p < 0.05\%$).

Table 2: Age of respondent workers.

Age	Number	%
<25 years old	0	0
25-35 years old	11	5
35-45 years old	58	25
45-55 years old	126	56
>55 years old	31	14

Table 3: Job position of respondent workers.

Job position	Number	%
Shift worker	80	35
Daily	6	3
On call	113	50
Office clerk	23	10
Others	4	2

Table 4: Experience of respondent workers.

Years of experience	Number	%
<1 year	0	0
1-2 years	2	1
2-5 years	6	3
5-10 years	9	4
>10 years	209	92

Table 5: P-values resulting from univariate tests of significance.

	Age	Job position	Years of experience
Injury			0.0137
Shipments volume	0.0038		
Medical provisions		0.0035	
Remote working	0.0056	0.0278	

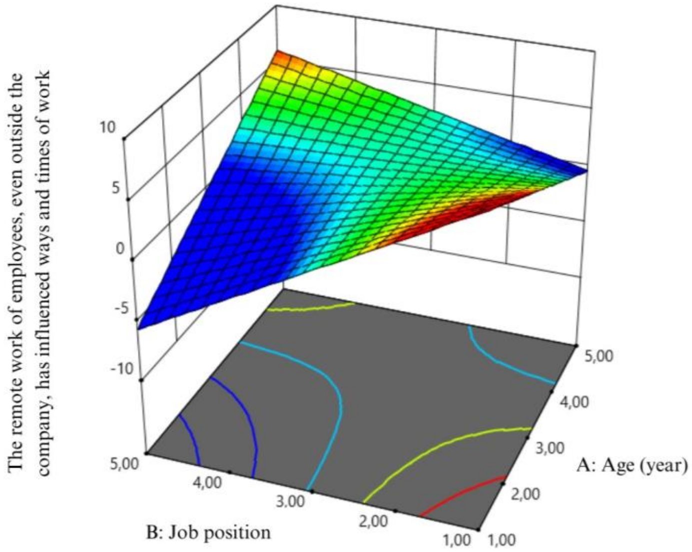

Figure 2: Response surface for influence of remote working, as a function of workers age and job position.

In this case, it is evident how the responses are significantly dependent on the worker's role: in the case of an administrative role, the worker may have been more easily influenced by remote work, as it is more readily applicable to the position held, unlike other more "physical" tasks (for example, those related to cargo loading/unloading). Regarding the probability of injury, 62 workers (27%) reported having experienced an injury in the last three years (pandemic period), while the remaining 73% did not. In this case, the "experience" factor was found to be significant, and from the Pearson correlation coefficient value, it could be inferred that as experience increases, the probability of injury decreases. As a remark, accidents can be categorized into two groups, those related to individual failings and those arising from organizational shortcomings. As a common result, it follows that investing in the training and preparation of workers is an effective way to prevent accidents and near-misses. According to literature (Kosmowski and Kwiesielewicz, 2000), approximately 80% of the perceived causes of accidents are connected to human failures: the most common items are the need to operate quickly and the difficulty of conducting the operation under the pandemic constraint.

3.3 Organizational Resilience (OR) critical factors

Starting from the perspectives of the respondents, highlighting the main aspects to be faced, a list of interrelated factors critical in OR development has been created. These factors enable the identification of precursors to unwanted events and are connected to the four pillars of resilience, as summarized in the following.

· Anticipate: higher-level strategies, including health plan; financial studies on organizational impacts of health emergency; identification of key sources of information on the epidemic, including trade associations, research institutes and experts; assigning responsibility for planning in the event of an epidemic.

· Monitor: identification of critical activities that cannot be suspended; identification of circumstances in which it may be necessary to suspend operations; the possibility of remote process control (e.g., SCADA); assessment of the effects on the safety of the procedural changes introduced to meet the needs of the health plan; assessment of the safety impact of organizational changes, including selected staff and supply outage; assessment of collective and personal protective equipment; specific attention to work permits, with the extension of measures also to third parties; identification of the necessary resources to support critical activities (people, processes, equipment).

· Learn: timely documentation of the activities carried out for health emergencies; staff behaviour observation system; specific measures for a safe shut down for a longer or indeterminate period, considering the degradation of hazardous materials; measures for a safe restart after prolonged shutdown, including warehouses; analysis of the system's reactions to the pressures of the external context (evaluation of strengths and weaknesses) and sharing with all staff.

·React: business continuity plan (activities essential for safety, recovery time, etc.) in the event of emergencies outside the plant; review of the response of the safety management system to the health emergency and changing demands due to environmental stressors (Bragatto et al., 2021); define face-to-face and remote meetings; policies for employees infected or suspected of being infected; agile/flexible work policies and flexibility of working time, including permits, temporary leaves and travel restrictions; communications to personnel and other interested parties on the progress of the emergency and the repercussions on the

management system; availability of individual and collective protection equipment; sanitation of work environment.
To optimize the resilience of a system, it is necessary to consider additional principles, including redundancy, efficiency, adaptability, collaboration, diversity, strength, autonomy, and mutual support (Woods et al., 2006).

4. Conclusions

In this study, the risk assessment methodology has been applied to analyse and promote the resilience of complex systems in pandemic conditions. The aim is to provide insights and outline as broad directions as possible to ensure organizational and operational resilience, not only in the explored context but also in all industrial settings. Despite the study being limited to Genoa Port and occupational risk, findings are fully applicable to companies subject to high process risk, to assess whether the structure of the SMS-MAH is more or less oriented towards resilience. In recent years, the substantial decline in the number of accidents, especially for those of short duration, demonstrates the effectiveness of endeavours to promote adequate safety culture and improve worker training. However, further remedial efforts are needed to anticipate threats to system safety and operational continuity focusing on workplace and organizational factors. The pandemic has proven to be an additional risk factor due to the additional stress and the numerous rules to be followed to limit contagion; indeed, during those years the number of accidents decreased not consistently with worked hours which were drastically limited due to repeated lockdowns and restrictions, contributing to a significant reduction in traffic volumes. Starting from the four pillars of organizational resilience, it is possible to identify the resilience factors that may be critical for complex systems and incorporate them into a comprehensive framework for risk analysis of industrial systems. Observing that resilience organizations are anticipatory responders to both innovations and disruptions, an interesting future research direction lies in the implementation of dynamic early warning systems based on AI and ML to detect negative events in advance and ensure a resilient response.

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