Evolution of safety in industry 4.0: future opportunities adopting resilience and antifragility engineering and virtual and augmented reality

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The paper offers a reflection on the evolution of Occupational Safety approaches through the ages until the Industry 4.0. A brief overview on the constant increase of the system complexity is discussed to introduce the problem. Later, the study shows how Safety can be approached in different ways discussing pros and cons. Then, the paper proposes two applications of Virtual Reality and Augmented Reality as new tools for addressing safety issues in Industry 4.0. Finally, some reflections and suggestions are pinpointed.
Keywords: *Occupational Safety, Resilience Engineering, Antifragility Engineering, Industry 4.0, Virtual Reality, Augmented Reality.*

Evoluzione della sicurezza nell'industria 4.0: opportunità future tra ingegneria della resilienza e dell'antifragilità e realtà virtuale ed aumentata. *Il lavoro offre una riflessione sull'evoluzione degli approcci di Sicurezza Occupazionale adottati fino alla recente Industria 4.0. Un breve quadro d'insieme riguardo al costante aumento della complessità sistemica è offerto per introdurre il problema. Successivamente lo studio discute come tale complessità possa essere gestita attraverso nuovi approocci evidenziando benefici e svantaggi. Alcune applicazioni di Realtà Virtuale e Realtà Aumentata sono presentate come possibili strumenti per migliorare la sicurezza nell'Industria 4.0. Infine una riflessione e qualche suggerimento su come utilizzare gli strumenti citati sono proposti.*
Parole chiave: *sicurezza occupazionale, ingegneria della resilienza, ingegneria dell'antifragilità, industria 4.0, realtà virtuale, realtà aumentata.*

Evolution de la sécurité au travail dans l'industrie 4.0: opportunités futures en intégrant l'ingénierie de la résilience et de l'antifragilité et la réalité virtuelle et aughmentée. *Authors offrent une réflexion sur l'évolution des approches de la sécurité au travail adoptées jusqu'à la récente Industrie 4.0. Un bref aperçu de l'augmentation constante de la complexité systémique est proposé pour introduire le problème. Par la suite, l'étude examine comment cette complexité peut être gérée par de nouvelles approches, en mettant en évidence les avantages et les inconvénients. Certaines applications de réalité virtuelle et de réalité augmentée sont présentées comme des outils possibles pour améliorer la sécurité dans l'Industrie 4.0. Enfin, une réflexion et des suggestions sur l'utilisation des outils mentionnés sont proposées.*
Mots clé: *sécurité au travail, ingénierie de la résilience, ingénierie de l'antifragilité, industrie 4.0, réalité virtuelle, réalité aughmentée.*

1. Introduction

1.1. Industry Evolution

The constant technology development offers the opportunity to the Industry to progress through the ages. This progress undoubtedly brings positive consequences but also many challenges to face, especially in terms of safety and reliability.

Figure 1 resumes how the Industry evolved since the 18th century. According to some specific ground-breaking progresses, it is possible to identify four well-known steps in the industry evolution that generated societal revolutions:

- Mechanization and introduction of steam power (Industry 1.0);
- Mass production and assembly line (Industry 2.0);
- Digitalization and automation (Industry 3.0);
- Cyber Physical Systems and Internet of Things (Industry 4.0).

Nowadays, the industry is experiencing the very first effects of Industry 4.0 and Cyber-Physical Systems – CPS. As described by Lasi *et al.* (2014), Industry 4.0 is a general term to include a quite broad variety of concepts and new applications: from equipping machines with sensors to merging physical and digital levels for improving system performance, from decentralizing manufacturing to empowering human tasks adopting virtual and augmented reality solutions.

1.2. Increase of System Complexity

As result of the Industry evolution through the centuries, System Complexity is exponentially increased. As mentioned by Martinetti *et al.* (2017), this phenomenon can be observed at different levels (Fig. 2):

- at system of systems level. The infrastructures (i.e. urban metro lines) become larger and with more stations. It is no longer feasible to rely only on risk analysis based to identify what could go wrong.
- at system level. The number of components of a single machine

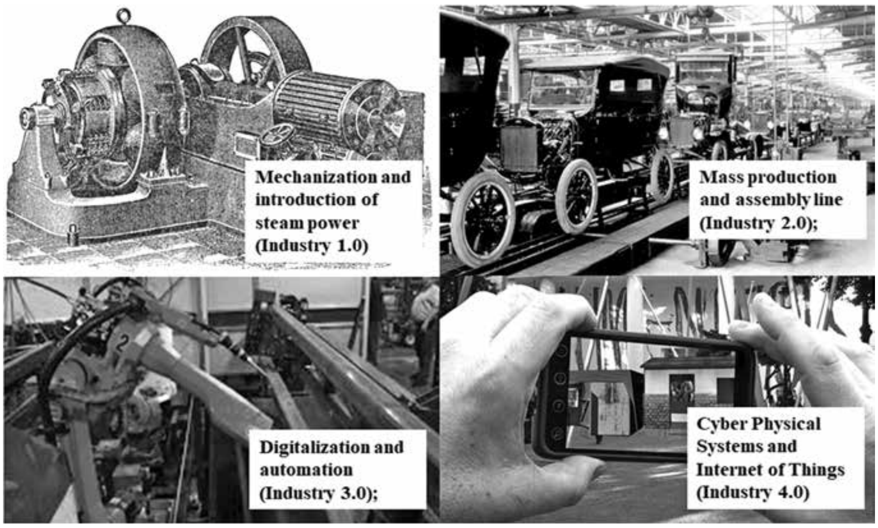

Fig. 1. Industrial Revolutions.
Rivoluzioni Industriali.

(i.e. tractor) moved from around 1800 components (1940) to more than 3500 nowadays. An increase of almost 100% in terms of components.

The mentioned complexity increase is partly related to a high interaction between mechanical, electronic and IT components. On one hand, this innovation brought several advantages (i.e. real time monitoring with sensors), but on the other hand it has also created concerns regarding the reliability of the all system. Coming back to the evolution of the "tractor", a study conducted by Kececioglu (2002) highlighted that, assuming an average component reliability of 99.99%, the tractor reliability (calculated on failures per year/1000 tractors) has been reduced of around 15% from 1940 to 1990. The relevant connection between need for simplicity, the number of components and reliability is also well pinpointed by the approach used for designing and building the aircraft Boeing 747 and the spacecraft Mariner/Mars 1964: 4.500.000 vs 138.000 components (Martinetti *et al.*, 2017). I highlightg how important is the reduction of parts in critical scenarios.

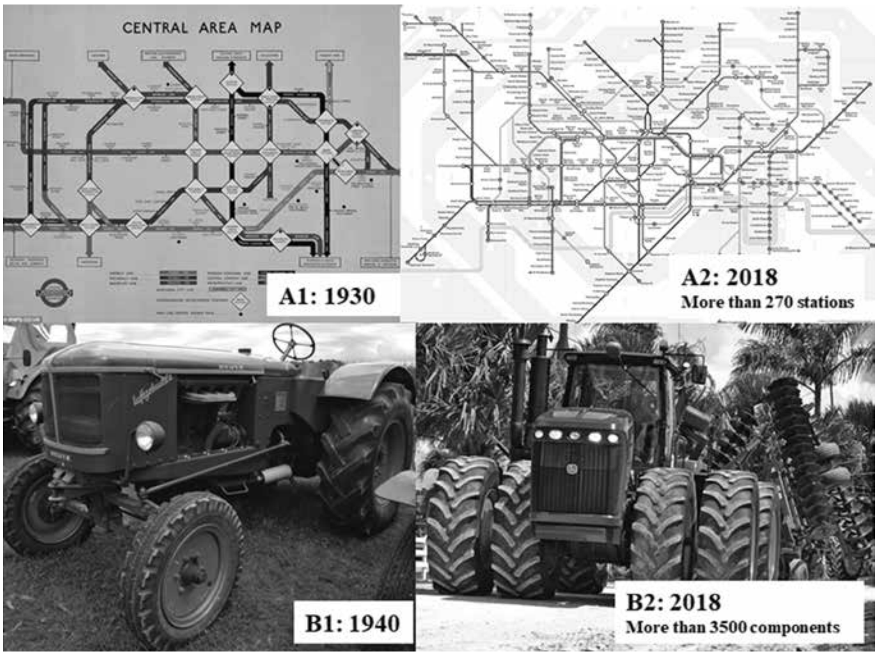

Fig. 2. Evolution of system complexity at different levels: A1 and A2 (Daily Mail, 2012) show the complexity increase in the London Metrolines System according to the number of stations. B1 and B2 show the complexity increase in tractors according to the number of components.
Evoluzione della complessità sistemica a differenti livelli: A1 e A2 (Daily Mail, 2012) mostrano l'aumento di complessità nella metropolitana di Londra in numero di stazioni. B1 e B2 mostrano l'aumento di complessità nelle macchine agricole in numero di componenti.

2. Safety Approach Evolution: towards a more strategic approach

As suggested by several researches (Leverson, 2012; Mannan *et al.*, 2016), the Industry evolution forces engineers and professionals to consider new solutions in terms of safety to face challenges brought by technological innovations. As mentioned in the introduction, approaches only based on risk analysis to investigate possible faults are not sufficient to guarantee a full prediction of the behaviour of the system. Looking at how complexity is evolving, probably, striving for reaching this goal it is not a feasible way.

Tracking the evolution of Safety approaches, as proposed by Pillay (2015) and modified by Martinetti *et al.* (2018a), interesting developments can be identified.

The history line of Safety can be roughly divided in three main Eras (1920-1960, 1960-2000, 2000-present) characterised by specific mind-sets and objectives regarding risk reduction.

In the first Era, risk analysts focused their attention to understand how the system could fail from both technology and human behaviour perspectives. It is called "Safety I" Era.

In the second Era, with the introduction of so-called "Advanced Approaches", the focus has been oriented to understand the socio-technical and cultural complexity of a system, trying to emphasize the successful parts in order to learn from them. It is called "Safety II" Era. Understanding and getting benefit from what goes right.

However, a big change in approaching Occupational Safety (and more in general risk analysis) has been done with the studies performed by Hollnagel *et al.* (2006) shaping the concept of Resilience Engineering in the context of risk analysis and safety and by Taleb (2012) proposing the concept of Antifragility. If Resilience Engineering aims to build systems able to face unexpected events (robustness), Antifragility proposes to create systems not only able to resist, but also to gain from disorders, learning from failures and hazards. These innovative approaches undoubtedly will change the way to think about Safety, initiating the third Era marked by "Sophisticated Approaches"; the complexity of the systems (or of the system of systems), emphasised by Industry 4.0 and machine learning solutions, is fuelling the rapid diffusion of Resilience and Antifragility Engineering.

3. Industry 4.0 solutions for improving Occupational Safety in training and operations

As pinpointed by Gorecky *et al.* (2014) and by Zhou *et al.* (2015) the Industry 4.0 brought several options for improving the human-machine interaction. Interfaces as Virtual Reality and Augmented Reality give the opportunity to workers to safely experience reaction of the CPS and to constantly be assisted and empowered by virtual objects.

The introduction of Virtual Reality, especially for training purposes and Augmented Reality, especially for operations, offer the opportunity to partially compensate for lack of specialised personnel and the distance between skilled personnel and product.

1.1. Virtual Reality in Rolling Stock Maintenance

The already mentioned complexity of the new systems, the increasing of asset variety and time constraints at the same time reduce the available time for a proper information, formation and training of the personnel and increase the number of information to remember. To tackle these issues some studies are already been carried on in different industrial sectors showing promising results.

Martinetti *et al.* (2018b) successfully created and tested a Virtual Reality environment for the training of rolling stock maintenance technicians (Fig. 3). The 29 task procedure has been used to train technicians for correctly maintaining new rolling stocks. As stated: *"when correctly designed, the technician can train and study components of trains without the need for the asset, classrooms, or practice instructors. A complete virtual learning system can instruct and evaluate the technicians".*

1.2 Augmented Reality for maintenance solutions

If Virtual Reality offers great benefits during the training of workers, the Augmented Reality offers several options when you need to increase the operator flexibility, to reduce operation time and to reduce errors in routine operations. Schiphorst (2018) has tested some valuable solutions (Fig. 4).

The development and testing of the prototypes verified that the system has high potential; however, it is questionable if the industries (and the employees) are ready for such a drastic change. There is a considerable difference between working from a paper manual and

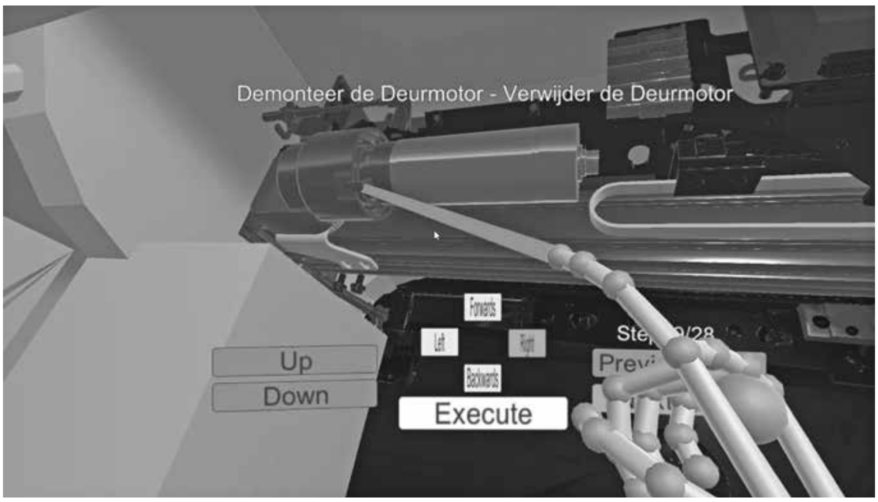

Fig. 3. Virtual Reality training environment (Martinetti *et al.*, 2018b).
Ambiente a Realtà Virtuale (Martinetti et al., 2018b).

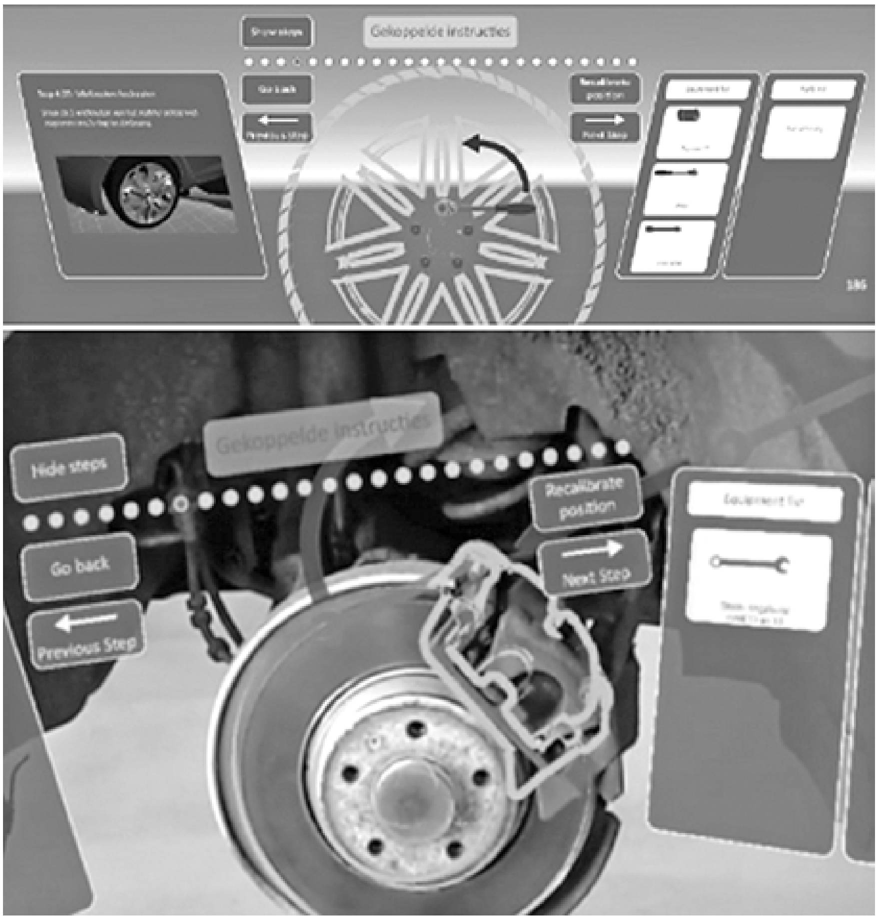

Fig. 4. Augmented Reality solutions for replacing brake pads (Schiphorst, 2018).
Realtà Aumentata come supporto per la sostituzione di pastiglie di freni a disco (Schiphorst, 2018).

working with holographic support from a cognitive perspective. It is interesting to mention that, according to the surveys provided during the research, the age of the workers is not always considered as a limitation. Otherwise, the trust that the workers need to place in the digital system can represent an obstacle to the deployment of this technology on the workplace; especially, when misunderstandings or mistakes can have drastic consequences.

4. Conclusions

Even if the novel approaches (Resilience and Antifragility Engineering) are very promising in terms of safety level improvements, they have still some limitations that have to be taken into account.

Firstly, they need to be applied at a strategic and organizational level (system of systems) before than component-machine level (system) to provide better results. The implementation at a strategic level can offer a more heterogeneous benefit over all the system. A working solution on a component-machine level can be really interesting nevertheless, according to the authors experiences, it tackles a limited number of possible problems and it should be taken into account only after implementations at strategic level.

Secondly, the application of Virtual and Augmented Reality is, as said, one of the key points for the migration to an Industry 4.0 scenario. However, those innovative technological tools need to be applied firstly to the most critical situations, correctly identified by a thorough risk analysis. An incorrect evaluation of the most urgent problems could lead to unsatisfactory results in terms of risk reduction and to useless investments.

Finally, companies (and engineers and professionals as well) need to be prepared with adequate infrastructures and departments to support the ongoing changes both in technology and safety sides.

References

Gorecky, D., Schmitt, M., Loskyll, M., Zuhlke, D., 2014. *Human-machine-interaction in the industry 4.0 era, in Industrial Informatics (INDIN)*, 12th IEEE International Conference on. IEEE, pp. 289-294. DOI: 10.1109/INDIN.2014.6945523

Hollnagel, E., Woods, D.D. & Leveson, N.C. (Eds.), 2006. *Resilience engineering: Concepts and precepts*. Aldershot, UK: Ashgate.

Kececioglu, D., 2002. *Reliability Engineering Handbook*, Volume 1, Pennsylvania. ISBN: 1-932078-00-2.

Lasi, H., Kemper, H-G., Fettke, P., Feld, T., Hoffmann, M., 2014. *Industry 4.0. Business & Information Systems Engineering*, Vol. 4. DOI: 10.1007/s12599-014-0334-4.

Leverson, N.G., 2012. *Engineering a safer world: systems thinking applied to safety*. Boston (MA): MIT Press.

Mannan, M.S., Reyes-Valdes, O., Jain, P., Tamim, N., Ahammad, M., 2016. *The Evolution of Process Safety: Current Status and Future Direction*, Annu. Rev. Chem. Biomol. Eng., Vol. 7, pp. 135-62. DOI:10.1146/annurev-chembioeng-080615-033640.

Martinetti, A., Braaksma, A.J.J., & van Dongen, L.A.M., 2017. *Beyond RAMS Design: Towards an Integral Asset and Process Approach*. In L. Redding, R. Roy, & A. Shaw (Eds.), Advances in Through-life Engineering Services (pp. 417-428). (Decision Engineering). Springer International Publishing. DOI: 10.1007/978-3-319-49938-3_25

Martinetti, A., Chatzimichailidou, M.M., Maida, L., van Dongen, L.A.M. (2018a). *Safety I–II, resilience and antifragility engineering: a debate explained through an accident occurring on a mobile elevating work platform*, International Journal of Occupational Safety and Ergonomics, DOI: 10.1080/10803548.2018.1444724.

Martinetti, A., 't Hart, K., Damgrave, R., van Dongen, L.A.M., Turkenburg, R., Nouwens, A. (2018b). *There is no spoon: applying virtual reality for maintenance training of rolling stock technicians*, International Journal of System of Systems Engineering, SI: Critical Success Factors for Public Transportation, In press.

Pillay, M., 2015. *Accident causation, prevention and safety management: a review of the state-of-the-art*. Procedia Manu., Vol. 3, pp. 1838-1845. doi:10.1016/j.promfg.2015.07.224

Schiphorst, J., 2018. *Development of a universally applicable framework designed for smart maintenance implementations*, MSc Thesis in Industrial Design Engineering, University of Twente.

Taleb, N.N., 2012. *Antifragile: Things that gain from disorder*.

Zhou, K., Liu, T., Zhou, L., 2015. *Industry 4.0: Towards Future Industrial Opportunities and Challenges*, 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), pp. 2147-2152. DOI 10.1109/FSKD.2015.7382284

Webography

Daily Mail, 2012. Growing Underground! Remarkable maps show how London's Tube network has expanded and changed over the past century. Accessed on 12/07/2018: http://www.dailymail.co.uk/news/article-2212174/Maps-Londons-Tube-network-expanded-changed-past-century.html

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