Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)
Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-5183-4_S10-08-412-cd

Digital twins and collaborative robotics: a SWOT-AHP analysis to assess sustainable applications

Giulio Paolo Agnusdei

Department of Innovation Engineering, University of Salento, Italy. E-mail: giulio.agnusdei@unisalento.it

Valerio Elia

Department of Innovation Engineering, University of Salento, Italy. E-mail: valerio.elia@unisalento.it

Maria Grazia Gnoni

Department of Innovation Engineering, University of Salento, Italy. E-mail: mariagrazia.gnoni@unisalento.it

Fabio Fruggiero

School of Engineering, University of Basilicata, Italy. E-mail: fabio.fruggiero@unibas.it

Digital twins, complex infrastructures able to connect physical systems with virtual ones in a bi-directional way, seem to be promising enablers of production system replication in real time. In the manufacturing field, cooperation and collaboration between humans and robots (properly cobots) in a shared environment is spreading. Digital twins and cobots are becoming fundamental tools to support humans in the workplace. This study aims at evaluating the benefits as well as criticalities of applying digital twin technology for cobot implementation within manufacturing operations. The adopted hybrid methodology combines SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis and AHP (Analytical Hierarchical Process) to assess the sustainability of digital twins and cobot implementation in a specific workplace by analyzing economic, as well as safety and environmental impacts.
The main findings reported that application of digital twins and cobots may improve safety in the workplace by reducing hazards. Furthermore, the potential integration of digital twins and cobots represents an effective solution to overcome the weaknesses and threats of correlated systems, that have been envisaged separately. The potential contribution of using digital twins in designing and managing these applications could help researchers and technicians. Results have practical implications as they allow for the application of optimal innovative solutions in the manufacturing and re-manufacturing sector with an extending domain for further research.

Keywords: digital twin; cobot; safety; reliability; sustainability; SWOT; Analytical Hierarchical Process.

1. Introduction

In recent years, design and manufacturing patterns have changed due to an exceptionally rapid expansion of computerization, automation and robotization. Innovative information technologies, such as virtual reality, artificial intelligence-based solutions and robots are spreading in the manufacturing systems to an increasingly great extent.
Since digital twins are a complex infrastructure able to connect physical systems with virtual ones in a bi-directional way, they seem to be a promising enabler of production system replication and analysis in real time (Agnusdei et al., 2021a). In the near future, collaborative robots, also named cobots, cable of smart collaboration with humans, will constitute relevant elements of industrial plants (Rodríguez-Guerra et al., 2021). In the light of a sustainability perspective, the study assesses the strengths, weaknesses, opportunities, and threats (SWOT) in adopting digital twins aimed at cobot implementation, by considering economic, as well as safety and environmental impacts.
SWOT analysis is a methodology generally applied to both internal and external business environments to develop a systematic approach and support to decision-making. However, it does not analytically determine the importance ranking of SWOT factors, nor assess the decision alternatives based on these factors (Kangas et al., 2003).

For this reason, a multicriteria decision making technique was proposed to enhance the SWOT analysis and to determine priorities among SWOT factors systematically. Firstly, pairwise comparisons between the identified SWOT factors (Shinno et al., 2006) were performed and then the comparison matrices were analyzed through the eigenvalue method applied within the Analytic Hierarchy Process (AHP) to calculate priorities and assign the relative importance of each SWOT factor (Ho, 2008).

2. Background

Industrial robot systems are usually separated from humans in the workplace, in order to protect people from potential injuries. With the increasing spread of Industry 4.0 technologies in various fields (Krstić et al., 2022), there is a growing potential to integrate the great capability of robots with that of humans aiming to improve productivity. Combining the creativity and decision-making of humans along with the repeatability and strength of robots may result in a collaborative environment where robots cooperate and collaborate with humans within a defined workspace, thus being definable cobots (Bragança et al., 2019; Terziyan et al., 2018). On the one hand, allocating repetitive and fatiguing tasks to collaborative robots could contribute to improving the occupational safety of workers, e.g., reducing and/or deleting potential physical injuries due to repetitive motion injuries (Sherwani et al., 2020; Soto-Leon et al., 2020); and on the other, new emerging risks due to ergonomics as well safety issues must be considered. In fact, safety and ergonomics constraints need to go at the same pace as productivity requirements in order to allow for a safe and efficient collaboration (Gualteri et al., 2021). The ISO/TS 15066 - *Robots and robotic devices - collaborative robots* is the main standard on how to design safe collaboration between humans and cobots. The standard points out safety requirements for collaborative industrial robot systems as well as for the specific work environment. In December 2021, an update procedure was carried out to adopt two other standards (ISO 10218-1 and 2) adequate for cobotics. Recently, Vicentini (2021; 2020) performed a strong research effort as a first attempt to propose the standardization of safety issues in collaborative robotics. Besides these standardization efforts in the field of collaborative robots, few other recent studies have faced the safety topic from broader points of view, integrating established concerns with new ones. In particular, Martinetti et al. (2021) proposed a redefinition of safety in the light of human-robot interaction, critically reviewing standards and regulations. Gualtieri et al. (2022) proposed some guidelines to reduce mechanical risks in collaborative robotics-based assembly systems; while Rubagotti et al. (2022) focused on how to measure the perceived safety level of humans in such a collaborative environment where humans interact with different types of collaborative robots. The opportunities of using a digital twin to address the complexity of collaborative production systems (Malik and Brem, 2021) and to support the design, build and control of human-machine cooperation (Malik and Bilberg, 2018) have already been explored, but the evaluation of the benefits as well as criticalities of applying digital twins and cobots for sustainable applications within manufacturing is still lacking and requires an in-depth quantitative analysis.

3. Methods

In this study a quantitative Analytic Hierarchical Process (AHP) based on SWOT analysis was proposed to achieve the established aim. This hybrid methodology was adapted from Görener et al. (2012) and it is represented in Figure 1.

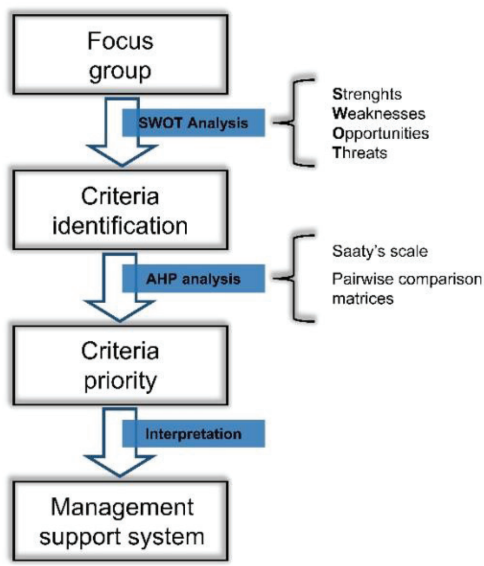

Fig. 1. Hybrid methodological scheme

The SWOT analysis was modelled to evaluate the sustainability of applying digital twins for cobot implementation.
The criteria identification phase was developed by forming focus groups, where experts from the manufacturing sectors and universities interacted directly. After two rounds, the criteria were identified and subsequently classified into four dimensions depending on their external and internal origin and positive or negative impacts. As shown in Table 1, each element in the SWOT matrix represents the specific criteria, included alternatively into the group Strengths, Weaknesses, Opportunities or Threats, based on the focus group results.

Table 1. SWOT matrix

INTERNAL FACTORS			
STRENGTHS		**WEAKNESSES**	
S1	Elimination of activities carried out in hazardous work environments	W1	Higher security risks
S2	Elimination or simplification of recurring and monotonous operations	W2	Lack of experienced workers for new profiles
S3	Real-time operational data availability	W3	Unexamined possible psychosocial implications
S4	Sharing information for operation planning		
S5	Increasing economic, environmental, and social sustainability	W4	High costs for system implementation
EXTERNAL FACTORS			
OPPORTUNITIES		**THREATS**	
O1	Employees' training through simulation tools	T1	Potential reduction of job candidates
O2	Modelling forecasting and predictive scenarios	T2	Non-compliant legislation and regulation
O3	Facing the challenges of SDGs		
O4	Creation of new job profiles	T3	Lack of qualified employees
O5	Increasing competitiveness		

Subsequently, after the criteria identification, each criterion was transformed into a measurable value. The Saaty's 9-point scale of relative importance was used to evaluate each criterion (Saaty, 2004), as reported in Table 2.

Table 2. Saaty's 9-point scale of relative importance

Importance	Explanation
1	Two criteria contribute equally to the objective
3	One criterion slightly favored over another
5	One criterion strongly favored over another
7	One criterion very strongly favored over another
9	One criterion absolutely favored over another
2, 4, 6, 8	From slight (2) to relevant (8) differences

A pairwise comparison matrix was created, and each component of the focus group judged each criterion identified within the SWOT analysis.
The AHP method is a robust Multi-Criteria Decision Making (MCDM) process for analyzing complex problems in different decision-making scenarios. In this study it was adopted to prioritize the SWOT criteria. A pairwise comparison matrix was derived using Eq. (1):

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{C_{11}} & \cdots & \boldsymbol{C_{1n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{C_{n1}} & \cdots & \boldsymbol{C_{nn}} \end{bmatrix} \tag{1}$$

where $\mathbf{M} = [\mathbf{c_{ij}}]\ \forall\ \mathbf{i}, \mathbf{j} = \mathbf{1}, \mathbf{2}, \mathbf{3} \ldots, \mathbf{n}$ is for $\mathbf{n}$ criteria identified, and $\mathbf{C_{ij}}$ indicates the importance attributed by the focus group. The weights for the criteria were calculated by normalizing each eigenvector to the principal eigenvector of the reciprocal ratio matrix. Then the ranking values for the different criteria were normalized to 1. The consistency in the decision from the focus group is controlled by the consistency ratio ($\mathbf{CR}$).

The ratio between the consistency index (**CI**) and the random index (**RI**) (Table 3) of the stochastic matrix for the matching vector is taken as the criterion to evaluate the decision's inconsistency. The **CR** is given by Eq. (2):

$$\mathbf{CR} = \frac{\mathbf{CI}}{\mathbf{RI}} \quad (2)$$

CI is calculated according to the following Eq. (3):

$$\mathbf{CI} = \frac{\boldsymbol{\lambda}_{\mathbf{max}} - \mathbf{n}}{\mathbf{n} - \mathbf{1}} \quad (3)$$

where $\mathbf{n}$ represents the matrix size and $\boldsymbol{\lambda}_{\mathbf{max}}$ denotes the principal eigenvalue.

Table 3. Random index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

A $CR \leq 0.10$ is considered suitable in terms of degree of consistency and results provided by the model can be efficiently used for the specific analysis. If $CR \geq 0.10$ there are serious inconsistencies and the AHP may not offer a meaningful result.

4. Results and discussions

The results of pairwise comparisons performed by focus group for SWOT matrix are reported in the following tables.

Table 4. Comparison Matrix of SWOT criteria

	S	**W**	**O**	**T**
Strengths	1.000	3.000	1.000	3.000
Weaknesses	0.333	1.000	0.250	2.000
Opportunities	1.000	4.000	1.000	2.000
Threats	0.333	0.500	0.500	1.000
CR = 0.06				

Table 5. Comparison Matrix of Strengths Group

	S1	**S2**	**S3**	**S4**	**S5**
S1	1.000	2.000	5.000	7.000	3.000
S2	0.500	1.000	4.000	6.000	2.000
S3	0.200	0.250	1.000	3.000	1.000
S4	0.143	0.167	0.333	1.000	0.333
S5	0.333	0.500	1.000	3.000	1.000
CR = 0.043					

Table 6. Comparison Matrix of Weaknesses Group

	W1	**W2**	**W3**	**W4**
W1	1.000	5.000	4.000	7.000
W2	0.200	1.000	0.500	3.000
W3	0.250	2.000	1.000	3.000
W4	0.143	0.333	0.333	1.000
CR = 0.052				

Table 7. Comparison Matrix of Opportunities Group

	O1	**O2**	**O3**	**O4**	**O5**
O1	1.000	3.000	4.000	6.000	4.000
O2	0.333	1.000	5.000	5.000	2.000
O3	0.250	0.200	1.000	3.000	1.000
O4	0.167	0.200	0.333	1.000	0.333
O5	0.250	0.500	1.000	3.000	1.000
CR = 0.100					

Table 8. Comparison Matrix of Threats Group

	T1	**T2**	**T3**
T1	1.000	2.000	3.000
T2	0.500	1.000	2.000
T3	0.333	0.500	1.000
CR = 0.012			

Finally, the overall priority scores of the SWOT criteria were calculated. Overall priorities are shown in Table 9.

Table 9. Overall priority scores of the SWOT criteria

SWOT group	Group priority	SWOT criteria	Criteria priority within the group	Overall Priority of criteria
S	0.367	**S1**	**0.434**	**0.159**
		S2	0.282	0.104
		S3	0.106	0.039
		S4	0.047	0.017
		S5	0.131	0.048
W	0.146	**W1**	**0.603**	**0.088**
		W2	0.136	0.020
		W3	0.196	0.029
		W4	0.065	0.009
O	0.365	**O1**	**0.456**	**0.166**
		O2	0.266	0.097
		O3	0.108	0.039
		O4	0.050	0.018
		O5	0.120	0.044
T	0.123	**T1**	**0.539**	**0.066**
		T2	0.297	0.037
		T3	0.164	0.020

The study findings, in line with previous literature (Pauliková et al., 2021), reported that, in terms of sustainability, the expansion of digital twins together with the potential cobot implementation has the greatest strength to replace people working in harmful or hazardous environments and the opportunity to assess predictive scenarios aimed at the reduction of economic, environmental, and social impacts of manufacturing activities.
Furthermore, the potential integration of digital twins and cobots represents an effective solution to overcome the weaknesses and threats of the correlated systems separately conceived. Disruptive changes in the implementation of work processes due to digital twins and cobots tend to cause some types of jobs to disappear, but, also, new ones to emerge. Skilled people who will be able to set up, maintain, and program digital twins and robotic equipment will be needed and the weakness related to the lack of qualified employees and high costs of implementation should be overcome.

5. Conclusions

The development of digital twins and collaborative industrial robots belongs to the technological and innovation priorities of Industry 4.0.
The current situation, characterized by the widespread transmission of contagious diseases on the scale of a pandemic, has also influenced employees' perception of their work with digital twins and cobots.
In the future, collaborative environments, where robots will be closer to humans, will increase. Safety and the reduction of accident risks will remain a priority (Agnusdei, et al., 2021b), but also the sustainable development goals could be progressively addressed through the digital twin and cobot applications.
The approach adopted in this study could be used as a management support system for critical decisions. The user can adapt the methodology to specific contexts of implementation, defining priorities based on the experience of the focus groups rather than the state of the art, in order collect different perspectives and points of view. Additionally, the results can represent a set of alternative strategies for organizations, with practical implications in terms of optimal innovative solutions in the manufacturing and re-manufacturing sector.
Further research directions can focus on which objective and subjective factors affect the degree of digital twins' and cobots' acceptance by employees and on examining the impact of the implementation of cobots or, in general, the introduction of Industry 4.0, on various jobs in the manufacturing sector.
Future research efforts could also be aimed at improving the methodology by using a combination of fuzzy logic and the AHP method to analyze cases with high degree of uncertainty more effectively.

Acknowledgements

The research is part of the activities carried out within the SO4SIMS project (Smart Operators 4.0 based on Simulation for Industry and Manufacturing Systems) funded by the Italian Ministry of Education, Universities and Research MIUR (Project PRIN – 2017FW8BB4).

References

Agnusdei, G.P., Elia, V., & Gnoni, M.G. (2021a). Is digital twin technology supporting safety management? A bibliometric and systematic review. *Applied Sciences*, *11*(6), 2767.

Agnusdei, G.P., Elia, V., & Gnoni, M.G. (2021b). A classification proposal of digital twin applications in the safety domain. *Computers & Industrial Engineering*, *154*, 107137.

Bragança, S., Costa, E., Castellucci, I., & Arezes, P. M. (2019). A brief overview of the use of collaborative robots in industry 4.0: human role and safety. In P.M. Arezes, J. S. Baptista, M.P. Barroso, P. Carneiro, P. Cordeiro, N. Costa, R.B. Melo, A.S. Miguel, G. Perestrelo (Eds.), *Occupational and Environmental Safety and Health. Studies in Systems, Decision and Control*, 641-650. Springer

Görener, A., Toker, K., & Ulucay, K. (2012). Application of combined SWOT and AHP: a case study for a manufacturing firm. *Procedia-social and behavioral sciences*, *58*, 1525-1534.

Gualtieri, L., Rauch, E., & Vidoni, R. (2022). Development and validation of guidelines for safety in human-robot collaborative assembly systems. *Computers & Industrial Engineering*, *163*, 107801.

Gualtieri, L., Rauch, E., & Vidoni, R. (2021). Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review. *Robotics and Computer-Integrated Manufacturing*, *67*, 101998.

Ho, W. (2008). Integrated analytic hierarchy process and its applications–A literature review. *European Journal of operational research*, *186*(1), 211-228.

Kangas, J., Kurttila, M., Kajanus, M., & Kangas, A. (2003). Evaluating the management strategies of a forestland estate—the SOS approach. *Journal of environmental management*, *69*(4), 349-358.

Krstić, M., Agnusdei, G. P., Miglietta, P. P., Tadić, S., & Roso, V. (2022). Applicability of Industry 4.0 Technologies in the Reverse Logistics: A Circular Economy Approach Based on COmprehensive Distance Based RAnking (COBRA) Method. *Sustainability*, *14*(9), 5632.

Malik, A. A., & Brem, A. (2021). Digital twins for collaborative robots: A case study in human-robot interaction. *Robotics and Computer-Integrated Manufacturing*, *68*, 102092.

Malik, A. A., & Bilberg, A. (2018). Digital twins of human robot collaboration in a production setting. *Procedia manufacturing*, *17*, 278-285.

Martinetti, A., Chemweno, P. K., Nizamis, K., & Fosch-Villaronga, E. (2021). Redefining safety in light of human-robot interaction: A critical review of current standards and regulations. *Frontiers in Chemical Engineering*, *3*, 666237.

Pauliková, A., Gyurák Babeľová, Z., & Ubárová, M. (2021). Analysis of the impact of human–cobot collaborative manufacturing implementation on the occupational health and safety and the quality requirements. *International Journal of Environmental Research and Public Health*, *18*(4), 1927.

Rodríguez-Guerra, D., Sorrosal, G., Cabanes, I., & Calleja, C. (2021). Human-robot interaction review: Challenges and solutions for modern industrial environments. *IEEE Access*, *9*, 108557-108578.

Rubagotti, M., Tusseyeva, I., Baltabayeva, S., Summers, D., & Sandygulova, A. (2022). Perceived safety in physical human–robot interaction—A survey. *Robotics and Autonomous Systems*, *151*, 104047.

Saaty, T. L. (2004). Decision making—the analytic hierarchy and network processes (AHP/ANP). *Journal of systems science and systems engineering*, *13*(1), 1-35.

Sherwani, F., Asad, M. M., & Ibrahim, B. S. K. K. (2020, March). Collaborative robots and industrial revolution 4.0 (IR 4.0). In 2020 International Conference on Emerging Trends in Smart Technologies (ICETST) (pp. 1-5). IEEE.

Shinno, H., Yoshioka, H., Marpaung, S., & Hachiga, S. (2006). Quantitative SWOT analysis on global competitiveness of machine tool industry. *Journal of engineering design*, *17*(03), 251-258.

Soto-Leon, V., Alonso-Bonilla, C., Peinado-Palomino, D., Torres-Pareja, M., Mendoza-Laiz, N., Mordillo-Mateos, L., Onate-Figuerez, A., Arias, P., Aguilar, J.., & Oliviero, A. (2020). Effects of fatigue induced by repetitive movements and isometric tasks on reaction time. *Human Movement Science*, *73*, 102679.

Terziyan, V., Gryshko, S., & Golovianko, M. (2018). Patented intelligence: Cloning human decision models for Industry 4.0. *Journal of Manufacturing Systems*, *48*, 204-217.

Vicentini, F. (2021). Collaborative robotics: a survey. *Journal of Mechanical Design*, *143*(4), 040802.

Vicentini, F. (2020). Terminology in safety of collaborative robotics. *Robotics and Computer-Integrated Manufacturing*, *63*, 101921.