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Industry 4.0 Management: Preliminary Design Implications

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Abstract

Industry 4.0 is expected to change competitiveness of manufacturing firms. However, to completely achieve this goal, firms should manage barriers and complexity issues that my hinder its adoption or its effects. For this reason, the study explores, through a literature review, whether and how design theory may be a supporting theory to manage Industry 4.0 adoption and implementation to maximise the opportunities and minimise the risks. The results shows that these research questions require a design approach to innovate not only adopting technologies but reinventing the business practices.

Keywords: industry 4.0, innovation management, design management, digital manufacturing

1. Introduction

In 2011, the German government launches a revolutionary industrial plan named Industry 4.0 (Kagermann et al., 2013) to increase manufacturing productivity and competitiveness through technological adoption. This phenomenon gives rise to the Fourth industrial revolution worldwide, which, like previous industrial revolutions, leads to an economic evolution favoured by a strong component of technological innovation, involving a profound and irreversible transformation from the production system to the economic system as a whole and to the entire social system.

However, more than ten years after Industry 4.0 launch, 4.0 technologies are still little implemented in firms and, most importantly, despite the adoption of 4.0 technologies the strategic organization of many firms remains obsolete. To ensure that the revolution is fully realised, it is necessary to redesign the management of 4.0 firms, creating 4.0 environments and smart factories (Margherita and Braccini, 2021). This implies not only adoption of technologies, but also reorganization of all the rules of the factory. A lack in understanding driving forces and challenges of this phenomenon, may hinder the achievement of the revolution understood as a redesign of every activity inside and outside the firm to create human-centric, sustainable and resilient systems, as required by worldwide institutions such as the European Commission (Breque et al., 2020). This weak and partial implementation of Industry 4.0 is mainly due to: (i) lack in firms' awareness on the phenomenon itself; (ii) a knowledge gap on the understanding of how to manage several barriers and complexity issues (Chauhan, Singh, and Luthra, 2021).

The aim of the paper is to explore new ways to sort out the unknown facets of the fourth industrial revolution to fully realize the transition to Industry 4.0. To do so, it is required to reduce uncertainty, be generative, align technology knowledge structures with social space, institutional rules and cultures, and to create the right ecosystem (Reich and Subrahmanian, 2015).

For these reasons, the following research questions are posed:

RQ1 – Can design theory be useful to improve Industry 4.0 adoption?

RQ2 – How design theory may be useful to improve Industry 4.0 adoption?

To answer these research questions, a literature review is carried out on the joint topic of Industry 4.0 and design theory, to identify: (i) the theoretical foundation of design theory for technological innovation and (ii) the eventual existing applications of design theory to Industry 4.0 systems.
The results show that design theory may help to go beyond the existing tension between perseverating and innovating in Industry 4.0 adoption. Moreover, the study suggests preliminary research proposal for future research in this field, identifying C-K theory as a useful framework to develop creativity in a structured manner.
The paper is structured as follows. Section 2 highlights the main known concepts related to Industry 4.0. Section 3 reports the methodology adopted to answer the research questions. Section 4 summarizes findings and results, answering the research questions. Section 5 discusses the results proposing a framework for future research, and points out the conclusion.

2. Theoretical background

The theoretical background highlights the known aspects of Industry 4.0 and allows to identify the unknown facets of this phenomenon that need to be still explored.
Industry 4.0 is a term coined in 2011 by the German industrial plan "Industrie 4.0" (Kagermann et al., 2013). The term is made by the word "Industry", suggesting that the first field of application is the manufacturing industry, and the suffix "4.0", indicating the fourth industrial revolution caused by this phenomenon. Despite the first field of application is the manufacturing, the phenomenon spread in all economic industries and in all real-life domains. Nowadays, in fact, Industry 4.0 impacts on products (smart products), objects (smart objects), energy systems (smart grid), healthcare (smart health), cities (smart cities), and services (increasing the so-called servitization phenomenon). Moreover, despite the phenomenon started in Germany, several industrial plans exist worldwide in support of this transformation.
Industry 4.0 is based on the adoption by firms of more than 1200 innovations, generally grouped into nine pillars (Rüßmann et al., 2015) of information - or software - technologies and operation - or hardware - technologies: advanced manufacturing, X-reality (virtual/augmented/diminished), big data, Internet of things, cloud computing, additive manufacturing, cyber security, simulation, horizontal and vertical integration. Moreover, 4.0 technologies may be applied to different value chain phases: production, logistics and warehouse, purchases, sales, and administration. For these reasons, the phenomenon is generally measured as adoption or non-adoption of at least one 4.0 technology, or it may be measured as openness to Industry 4.0 (Büchi, Cugno, and Castagnoli, 2020; Cugno, Castagnoli, and Büchi, 2021) intended as breadth - number of 4.0 technologies adopted - and/or depth - number of value chain phases where the technologies are adopted. The technological foundation of Industry 4.0 is highlighted as the only or the most important one by academic literature in the fields of management and industrial engineering and by worldwide industrial plans.
However, in addition to 4.0 technologies adoption, Industry 4.0 requires a reorganization of the factory in a more integrated one, creating the so called 4.0 environment, or smart factory (Braccini and Margherita, 2021). The smart factory requires new lenses to read the existing rules, in order to accomplish the compromise between innovation and status quo (Harlé, Le Masson, and Weil, 2021).
This new kind of factory is expected to be efficient, flexible and automated leading to six main categories of performances: production flexibility; speed of serial prototypes; greater output capacity; reduced set-up costs and fewer errors and machine downtimes; higher product quality and less rejected production; customers' improved opinion of products (Dalenogare et al., 2018; Chauhan, Singh, and Luthra, 2021).
However, to implement Industry 4.0, firms should overcome several barriers upstream to its adoption (Horváth and Szabó, 2019; Raj et al., 2020; Stentoft et al., 2020). These barriers are listed in 15 sub categories grouped in 5 main categories (Castagnoli et al., 2020), and are related to macro and micro levels and depend on both intangible - such as culture, knowledge and skills - and tangible constraints, such as financial resources or infrastructures (Table 1).

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Table 1. Categories and sub categories of barriers

Categories of barriers	Sub-categories of barriers
Cultural aspects	Scarce attitude to innovation
	Inhomogeneity of the Industry 4.0 definition
	Complexity related to the certification of the use of incentives of the National Plans in support to Industry 4.0 adoption
	Lack of an approach 4.0 in the firms' management
	Lack of cultural support from institutions to adopt Industry 4.0
	Relevance of psychological aspects in the perception of the need for innovation
Ecosystems' characteristics	Lack of networks between firms and institutions
	Lack of an integrated supply chain approach
	Little support from the institutions in the early stages of development
	Infrastructural limits
	Traditional dependence of the SMEs on large companies or groups
Firms' characteristics	SMEs' dimensional problems
	Problems of SMEs' location in poorly communicating geographical areas
Human Resource Management	Generational Polarization
	Absence of professionals dedicated to Industry 4.0 within companies
Business model innovation	Relative novelty of the servitization phenomenon

Source: Own elaboration on Castagnoli et al., 2020.

However, other studies verify that the perception of some barriers, related for example to knowledge issues, do not hinder the perception of increased performances (Cugno, Castagnoli, and Büchi, 2021). This interesting result, may depend by an awareness issue related to the fact that firms more aware about the Industry 4.0 phenomenon, are also able to perceive both more barriers and performance, suggesting that the awareness, knowledge or cultural issue is one of the most important in the fourth industrial revolution. This confirms that Industry 4.0 is not only a technological adoption challenge, as managerial literature mainly affirms.

In addition to upstream barriers to Industry 4.0 adoption, to reach the above mentioned performances, firms should manage the increased complexity of Industry 4.0 systems downstream its adoption – generally reported as 70% higher in Industry 4.0 than in traditional systems (Mourtzis et al., 2019). The increased complexity is due to two main issues. The first one is related to a huge amount, variety and velocity of information exchanged among the different integrated systems, which introduces new languages, new knowledge and new kind of interoperability (Ullah, 2020) to be managed. The second one is related to the increased number of components that are involved in products, processes and systems, depending by the rise of connectivity, communication and integration between products, people, machines, systems and realities (virtual and physical realities).

Moreover, literature highlights three main discrepancies between Industry 4.0 opportunities and firms' capabilities to profit from this opportunities, as summarized in Table 2. The first one concerns the possibility given by Industry to collect, analyse and exchange data in real time. This contrasts with rigidities of SMEs' internal management systems that do not allow to really exchange this data in real time. The second one is related to the possibility given by Industry 4.0 to increase communication both inside the firms and along the supply chains. This contrasts with the SMEs problems in internal communication. This problem depends on employee scarce attitude to communicate with employees of other functions of the factory, because operators generally do not possess enough T-shape knowledge. The third complexity issue is related to the geographical

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dispersion of firms which limits the exchange with other employees and stakeholders, even though Industry 4.0 allows to increase it through greater interconnection and increased communication also at distance.

Table 2. Complexity issues

Uncovered needs to manage complexity	Description of the uncovered needs
Real time data exchange issues	Need for more flexible internal management tools. Systems traditionally used by firms for the internal management - MES or ERPs - do not allow the real-time use of data that I4.0 make available in real-time.
Collaboration issues	Need for employees in the company to possess T-shape knowledge, i.e. having a main specialization on a subject but, at the same time, being able to have transversal knowledge in order to work together as a team and be a human resource more adaptable to the various tasks.
Teams dispersion issues	Need for greater interaction between systems geographically dispersed. Geographical dispersion of firms leads to the problem of dispersed teams from which it emerges the need to encourage forms of collaboration and exchange of data within the same enterprise even before the supply chain level.

Source: Own elaboraiton on Castagnoli et al., 2020.

However, despite the great relevance of these issues, it is important to highlight that both barriers and complexity issues might be both an opportunity or a constraint, depending on the readiness of the firms to manage it.

In addition, industrial plans and literature on Industry 4.0 point out the role of incentives in helping firms to adopt Industry 4.0. Incentives are mainly related to fiscal discounts given by governments to promote, from one side, technological adoption and infrastructural development, and, form the other side, awareness and knowledge. This highlights again that Industry 4.0 is not only a technological-adoption process. Moreover, Cugno, Castagnoli, and Büchi (2021) verify that firms adopting increasing number of 4.0 technologies, perceive increased performance, perceive increased barriers and adopt increasing number of incentives. However, firms perceiving greater economic-financial barriers do not adopt more incentives. This highlights a mismatch between real firms' constraints and incentives design.

The above mentioned relationships between Industry 4.0 adoption, performance perception, barriers perception, and incentives adoption are verified by Cugno, Castagnoli, and Büchi (2021) through a quantitative analysis on secondary data from Congiuntura Industriale in Piemonte dataset collected by Unioncamere Piemonte in 2019. The sample is based on 1732 local manufacturing units (500 adopting Industry 4.0) with at least two employees belonging to different size classes and different product sectors in Piedmont. The regression models investigate the relationships between the independent variable openness to Industry 4.0 – measured as number of 4.0 technologies adopted – the dependent variable performance, and the mediation variables: (i) four categories of barriers (related to knowledge issues, economic-financial constraints, cultural issues and system conditions); (ii) incentives. Following this study, the above mentioned results are summarized in Table 3.

Despite the deep qualitative and quantitative analyses carried out by existing literature on Industry 4.0, the role of barriers and complexity, the incentives design, and the management of these concepts, still remain unknown facets of the fourth industrial revolution. These aspects should be deeply explored in order to improve the adoption and the performance of this phenomenon.

For this reason, to integrate the theoretical background unveiling the unknown facets of Industry 4.0, the paper aims to answer the above mentioned research questions.

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Table 3. Empirical evidence on the relationships between Industry 4.0, performance, barriers and incentives

Hypotheses (H) number	Hypotheses short description	Supported or not supported	Coefficient and p-value	Accepted or rejected
H1	Openness to Industry 4.0 increases performance perception	Supported	.148***	Accepted
H2a	Openness to Industry 4.0 increases knowledge barriers perception	Supported	.051***	Accepted
H2b	Openness to Industry 4.0 increases economic-financial barriers perception	Supported	.031**	Accepted
H2c	Openness to industry 4.0 increases cultural barriers perception	Supported	.031*	Accepted
H2d	Openness to Industry 4.0 increases systemic barriers perception	Supported	.075***	Accepted
H3a	The perception of knowledge barriers increases performance perception	Supported	.224**	Accepted
H3b	The perception of economic-financial barriers increases performance perception	Supported	.223**	Accepted
H3c	The perception of cultural barriers increases performance perception	Not supported	.073	-
H3d	The perception of systemic barriers increases performance perception	Not supported	.048	-
H4	Openness to Industry 4.0 increases incentives adoption	Supported	.075*	Accepted
H5	Incentives adoption increases performance perception	Supported	.175***	Accepted
H6a	The perception of knowledge barriers increases incentives adoption	Not supported	.143	-
H6b	The perception of economic-financial barriers increases incentives adoption	Supported	-.266*	Rejected
H6c	The perception of cultural barriers increases incentives adoption	Not supported	-.086	-
H6d	The perception of systemic barriers increases incentives adoption.	Not supported	.009	-

Results *, **, and *** indicate the p-values, which means that the coefficients are statistically significant at the <5%, <1% and 1‰ levels, respectively.
Source: Own elaboration on Cugno, Castagnoli, and Büchi, 2021.

3. Methodology

Having identified that Industry 4.0 is already deeply explored through qualitative and quantitative studies in the industrial engineering and management field, while several unknown aspects still remain uncovered, the research carries out a theory based literature review (Eisenhardt, 1989), analysing the role of design theory in the field of Industry 4.0. This literature review methodology synthetizes and helps advancing a body of literature that uses and/or empirically applies a given underlying theory (Paul and Criado, 2020): design theory.

Design theory is a research field touching a wide range of disciplines, from engineering to humanities. As Hatchuel et al. (2017) say: "design theory is a set of shared problematics". For this reason, it is possible to hypothesize that this approach might be the best one to address the problems highlighted in the managerial literature on Industry 4.0 described in the theoretical background. In particular, design theory helps to overcome the classical opposition between decision theory and creativity theory, introducing the generativity capability, or the the capacity to generate new solutions for emerging problems, identifying new definition of things, new categories, and new values (Hatchuel et al.,

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2011). Moreover, design theory adopts different formal models to increase the generativity capability, such as: axiomatic design (Suh 1978, 1990), coupled design process (Braha and Reich 2003), infused design (Shai and Reich 2004a, b) or C–K design theory.

The review is carried out to identify theoretical foundation of design theory for technological innovation - searching for most useful and feasible frameworks to apply design theory in practice - and eventual existing applications of design theory to Industry 4.0 systems. This approach is adopted based on the assumption that design helps in going beyond problem solving through existing knowledge, concepts and solutions, allowing to identify new and unexpected results on new and emerging problems.

Design theory touches a wide range of research fields, however, since the research is focused on the role of design theory for Industry 4.0 in manufacturing firms, in the analysis are included only articles based on design theory in the research fields of management and/or industrial engineering and are preferred the articles with an industrial application.

The review is based on a search using the keywords, namely ("design theory" AND "Industry 4.0" OR "factory" OR "industrial application"). The search is limited to the period from 2011 (year of the beginning of Industry 4.0 phenomenon) to 2022. Then, an online search using Web of Science database is carried out. From Web of Science, 12 articles are identified: 5 for the engineering manufacturing field, 3 for engineering industrial field, 2 for engineering mechanical, material science multidisciplinary fields and 1 for automation control systems, computer science theory methods, construction building technology, engineering civil, engineering multidisciplinary and engineering electrical electronic fields. 5 out of 12 articles are proceedings while the others are published papers on scientific journals, and in particular 3 articles are published by Springer Editor. From these articles, 4 articles are eliminated because not strictly related to the specific topic of the research. At this stage, the list is composed by the following articles: Rauch, Dallasega, and Matt, (2018); Sanderson, Chaplin and Ratchev, (2019); Hwang et al., (2021); Pessoa and MVP, (2020); Plehn, Stein, and Reinhart, (2015); Harlé et al., (2022); Bi et al., (2021); Egger, et al., (2017).

In addition to the online search on Web of Science, an offline research is carried out using the reference list from different articles. Through this search we added the following articles: Hatchuel et al., (2017); Cabanes et al., (2021). The final sample is therefore composed by 10 articles.

In addition, each article is double checked on the respective journal website. Together, the articles included in this review can be considered as representative of the knowledge accumulated about design theory and Industry 4.0.

4. Findings and results

The literature review highlights that only 10 papers in the industrial engineering and management literature fields identify possible connections between design theory and Industry 4.0. Moreover, articles explicitly focusing on empirical application of design theory for Industry 4.0 are lacking. In fact, the majority of the identified articles is focused on industrial applications of design theory in certain types of business functions, i.e. product design (Pessoa and MVP, 2020), or technologies, such as additive manufacturing (Hwang et al., 2021) or cyber-physical systems (Egger et al., 2017).

Despite the limited number of work focusing on Industry 4.0, from the sample of articles it is possible to identify generalizable assumptions on design theory and industrial application in innovative fields, that may be useful to answer the above mentioned research questions:

RQ1 – Can design theory be useful to improve Industry 4.0 adoption?

RQ2 – How design theory may be useful to improve Industry 4.0 adoption?

The review identifies that design theory may be useful to improve Industry 4.0 adoption in two main ways.

First, design theory helps in the following four key points.

- Exploring the unknown facets of the fourth industrial revolution, that are not only related to technological adoption issues, but mainly linked to knowledge, cultural and awareness issues. In fact, while engineering sciences model known objects, design theories support reasoning on the unknown, exploring and giving new meaning to existing rules (Hatchuel et al., 2013).

- Reducing the uncertainty of the impact of Industry 4.0, through the deeper comprehension of practices, skills and reorganization of Industry 4.0 implementation (Hatchuel et al., 2013).
- Being generative, which means generating new propositions that are made of known building blocks – i.e. 4.0 technologies, skills, knowledge, human resources, economic-financial resources – but are still different from all previous known combinations of these building blocks, including knowledge creation and including independent knowledge from outside (Le Masson, Hatchuel, and Weil, 2011);
- Aligning technology knowledge structures with social space, institutional rules and cultures to create the right ecosystem (Reich and Subrahmanian, 2015).

For this reason, we can assume that design theory is the right solution to go beyond quantitative and qualitative studies carried out so far on Industry 4.0.

Second, design theory may help firms to increase Industry 4.0 adoption and to reach higher performance, overcoming the recurrent tension between preservation and innovation (Harlé, Le Masson, and Weil, 2021). In fact, design theory shows that innovation can be incremental/disruptive/a compromise. This leads to different impacts on the way of combining tradition and innovation and especially on whether or not existing rules remain valid in the factory system. In this direction, it is possible to identify four strategies for implementing an innovation. An innovation can: (i) adapt to previous rules; (ii) require new rules; (iii) adapt to existing rules only in single domains; or (iv) require an extension of existing rules through new perspectives (Harlé, Le Masson, and Weil, 2021).

In the case of Industry 4.0, literature verifies that it adapts differently in SMEs and in large companies. On the one hand, it involves more difficulties in managing complexity in SMEs (Horváth and Szabó, 2019), which might suggest that it is an innovative solution that only fits locally with existing rules (i.e. only in large enterprises). On the other hand, literature empirically verifies that micro firms paradoxically get more benefits from adopting Industry 4.0 than large enterprises (Büchi, Cugno, and Castagnoli, 2020). This second aspect might suggest that Industry 4.0 is rather a solution that changes depending on the contexts in which it is inserted with excellent potential in each of these contexts.

However, given the difficulties that all firms types report in dealing with the barriers (Cugno, Castagnoli, and Büchi, 2021) and complexity issues of Industry 4.0 (Castagnoli et al., 2020), it is possible to assume that it is an innovation that generally does not fit within existing rules.

By consequence, the doubt that may arise is whether Industry 4.0 requires the destruction of existing rules, or new perspectives to re-read existing rules, or even a mix of the two solutions depending on the specific rule systems (on the specific firms' characteristics) and/or on the different technologies adopted.

The answers to these questions and the solutions consequently implemented, might help in the transition to the fourth industrial revolution not only by adopting technologies, but reinventing new uses of the technologies, enriching the interpretation of performances, barriers and complexity, and transforming these concepts into drivers for the success of Industry 4.0 adoption through creativity management instead of only through strategic management.

5. Discussion and conclusion

The research confirms, through a literature review, that design theory might be the right supporting theory for adopting and implementing Industry 4.0 in industrial contexts, allowing to overcome upstream barriers and downstream complexity issues. In particular, this is possible through the capability of design theory to sort out the unknown aspects of emerging phenomenon by integrating different sources, actors and perspectives on a shared problem, generating new solutions.

Moreover, from a critical analysis of the results, the following framework is developed to point out the main tools and methodologies to apply design theory in Industry 4.0 factories.

Concerning the tools for applying design theory in industrial systems, the concept-knowledge tool (C-K) is identified as a good one (Hatchuel et al. 2013), able to increase: (i) creativity (novelty, originality, variety); (ii) feasibility (quality, cost, delay); and (iii) robustness (performance). This is absolutely relevant in Industry 4.0 contexts, since: (i) creativity is required to go beyond known solutions for known problems; (ii) feasibility is essential to reduce uncertainty of technological adoption; (iii) robustness is needed to certify the effectiveness of the revolution.

Concerning methodologies to apply C-K tool in Industry 4.0 factories, the proposed framework follows the methodologies introduced by some of the articles identified through the literature review, describing the application of design theory in industrial contexts (Cabanes et al.; 2021; Harlé et al., 2022). In particular, the suggested methodology is a multiple case-study analysis comparing different firms' types, depending on firms' size and industries. In particular, four case studies on the following firms' types are proposed (Table 4).

Table 4. Proposal of case studies distinguished for firms' types

Case study to be compared	Firms' size	Technological intensity of the industries
1	Big company	High-tech
2	Big company	Low-tech
3	Small firm	High-tech
4	Small firm	Low-tech

Source: Own elaboration.

To collect data from the case studies, a research data triangulation between the following sources is carried out: observation of internal processes; interviews; internal documentation; participation in meeting and working groups. This methodology, moreover, should follow a collaborative management research methodology (Coghlan and Shani, 2008) to produce, from one side, actionable knowledge for firms and, from the other side, new knowledge for scientific community.

In each case study, the C-K tool is developed separately in different teams following four steps:
i. K-K = each member collects data and knowledge;
ii. K-C = members elaborate concept tree based on knowledge shared;
iii. C-C = members think about unexpected issues through partitioning (which may be restrictive or expansive partitioning, which means adding or reducing attributes to the original concepts);
iv. C-K = creation and sharing of new knowledge, by evaluating the relevance of new concepts and identifying absent or non-actionable knowledge in-house.

Moreover, to ensure the widest variety of perspectives and knowledge on the phenomenon under analysis, Harlé et al. (2022) suggest that each team is composed by managers and employees from different business functions and from different hierarchical levels.

It is possible to summarize the proposed framework for future research and industrial applications of Industry 4.0, as follows. First, it is needed to adopt design theory as a supporting theory to guide Industry 4.0 adoption and implementation. Second, it is required to adopt specific tools to implement design theory in industrial contexts adopting Industry 4.0. A possible and effective one may be the C-K tool. Third, to move to the operational plan, the suggested research methodology is a comparison between different single case studies distinguished for firms' size and technological intensity of the industries to which the firms belong to. Moreover, it is suggested an approach of collaborative management research and a data triangulation between different sources to compare different perspectives on the problem under investigation.

This framework is a proposition for future research and future industrial applications that may be useful to reach a deep understanding of: (i) unsolved known problems of Industry 4.0 presented in the theoretical background (namely upstream barriers to Industry 4.0 adoption and downstream complexity issues to Industry 4.0 implementation); (ii) unknown facets of the fourth industrial revolution related to non-technological adoption issues; (iii) best solutions to overcome barriers and complexity issues of the ongoing phenomenon in factories.

The main contribution of this proposal is to integrate the literature on industrial engineering, and in particular the research on design theory, with the management literature, to open up new research lines on Industry 4.0 implementation. This might help academics, policy makers and managers to identify the best solutions to profit from the fourth industrial revolution.

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References

Bi, Z., Zhang, W. J., Wu, C., Luo, C., & Xu, L. (2021). Generic Design Methodology for Smart Manufacturing Systems from a Practical Perspective. Part II—Systematic Designs of Smart Manufacturing Systems. Machines, 9(10), 208.

Breque, M., De Nul, L., Petridis, A. (2020), Industry 5.0: Towards a sustainable, human-centric and resilient European industry. Directorate-General for Research and Innovation, European Commission,

Büchi, G., Cugno, M., Castagnoli, R. (2020). Smart factory performance, Technological Forecasting and Social Change, 150, 119790.

Cabanes, B., Hubac, S., Le Masson, P., & Weil, B. (2021). Improving reliability engineering in product development based on design theory: the case of FMEA in the semiconductor industry. Research in Engineering Design, 32(3), 309-329.

Castagnoli, R., Buchi, G., Cugno, M., & Stal-Le Cardinal, J. (2020). Managing Complexity in Industry 4.0 Based Systems: A Qualitative Analysis. In 11th Complex Systems Design & Management (CSD&M) Conference (pp. 1-11).

Chauhan, C., Singh, A., & Luthra, S. (2021). Barriers to industry 4.0 adoption and its performance implications: An empirical investigation of emerging economy. Journal of Cleaner Production, 285, 124809.

Cugno, M., Castagnoli, R., & Büchi, G. (2021). Openness to Industry 4.0 and performance: The impact of barriers and incentives. Technological Forecasting and Social Change, 168, 120756.

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics, 204, 383-394.

Egger, G., Rauch, E., Matt, D. T., & Brown, C. A. (2017). (Re-) Design of a Demonstration Model for a Flexible and Decentralized Cyber-Physical Production System (CPPS). In MATEC Web of Conferences (Vol. 127, p. 01016). EDP Sciences.

Eisenhardt, K. M. (1989). Building theories from case study research. Academy of management review, 14(4), 532-550.

Harlé, H., Hooge, S., Le Masson, P., Levillain, K., Weil, B., Bulin, G., & Ménard, T. (2022). Innovative design on the shop floor of the Saint-Nazaire Airbus factory. Research in Engineering Design, 1-18.

Harlé, H., Le Masson, P., & Weil, B. (2021). A Model of Creative Heritage for Industry: Designing New Rules while Preserving the Present System of Rules. Proceedings of The Design Society, 1, 141-150.

Hatchuel, Armand, Le Masson, Pascal, Reich, Yoram, et Subrahmanian, Eswaran, "Design theory: a foundation of a new paradigm for design science and engineering," Research in Engineering Design 29 (2017): 5-21.

Hatchuel, A., Weil, B., & Le Masson, P. (2013). Towards an ontology of design: lessons from C–K design theory and Forcing. Research in engineering design, 24(2), 147-163.

Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?. Technological forecasting and social change, 146, 119-132.

Hwang, D., Blake Perez, K., Anderson, D., Jensen, D., Camburn, B., & Wood, K. (2021). Design Principles for Additive Manufacturing: Leveraging Crowdsourced Design Repositories. Journal of Mechanical Design, 143(7).

Kagermann, H., Wahlster, W., & Helbig, J. (2013). Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0 Working Group. Forschungsunion: Berlin, Germany.

Le Masson P, Hatchuel A, Weil B (2011) The Interplay Betwee creativity issues and design theories: a new perspective for design management studies? Creativity Innovation Management 20(4):217–237.

Margherita, E. G., & Braccini, A. M. (2021). Managing the fourth industrial revolution: A competence framework for smart factory. In The Fourth Industrial Revolution: Implementation of Artificial Intelligence for Growing Business Success (pp. 389-402). Springer, Cham.

Mourtzis, D., Fotia, S., Boli, N., & Vlachou, E. (2019). Modelling and quantification of industry 4.0 manufacturing complexity based on information theory: a robotics case study. International Journal of Production Research, 57(22), 6908-6921.

Paul, J., & Criado, A. R. (2020). The art of writing literature review: What do we know and what do we need to know?. International Business Review, 29(4), 101717.

Pessoa, M. V. P. (2020). Smart design engineering: leveraging product design and development to exploit the benefits from the 4th industrial revolution. Design Science, 6.

Plehn, C., Stein, F., & Reinhart, G. (2015). Modeling factory systems using graphs-ontology-based design of a domain specific modeling approach. In DS 80-4 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 4: Design for X, Design to X, Milan, Italy, 27-30.07. 15 (pp. 163-172).

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A. B. L., & Rajak, S. (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 224, 107546.

Rauch, E., Dallasega, P., & Matt, D. T. (2018). Complexity reduction in engineer-to-order industry through real-time capable production planning and control. Production Engineering, 12(3), 341-352.

Reich, Y., & Subrahmanian, E. (2015). Designing PSI: an introduction to the PSI framework.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. Boston Consulting Group, 9(1), 54-89.

Sanderson, D., Chaplin, J. C., & Ratchev, S. (2019). A Function-Behaviour-Structure design methodology for adaptive production systems. The International Journal of Advanced Manufacturing Technology, 105(9), 3731-3742.

Coghlan, D., & Shani, A. B. (2008). Collaborative management research through communities of inquiry: Challenges and skills. Shani AB (Rami), Mohrman SA, Pasmore WA, Stymne B., Adler N.(Eds.) Handbook of Collaborative Management Research, Thousand Oaks (CA): Sage.

Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., & Haug, A. (2020). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning & Control, 1-18.

Ullah, A. S. (2020). What is knowledge in Industry 4.0?. Engineering Reports, 2(8), e12217.

Yin, R. K. (2009). Case study research: Design and methods (Vol. 5). sage.

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