Models for the cost-benefit analysis of digitalization and Industry 4.0: a systematic literature review

Leonardo Maretto[1], Maurizio Faccio[1], Daria Battini[1] and Irene Granata[1]

[1] Department of Management and Engineering, University of Padova, Stradella San Nicola, 3, 36100, Vicenza, Italy
leonardo.maretto@phd.unipd.it (corresponding author)
maurizio.faccio@unipd.it
daria.battini@unipd.it
irene.granata@phd.unipd.it

Abstract. Industry 4.0 is a concept that has already reached a certain degree of scientific maturity. However, there are still significant grey areas: one of the topics that most urgently require academic attention is represented by the cost-benefit analysis of Industry 4.0 implementation. In order to address this gap, a systematic literature review was conducted, selecting models for the cost-benefit analysis of Industry 4.0, devoting particular attention to the elements of economic evaluation. Only 9 papers could be identified, confirming the need for more research on the subject. The resulting works are classified, analyzed and discussed, resulting in two main future research directions.

Keywords: Industry 4.0, digitalization, cost benefit analysis, economic, investment assessment.

1 Introduction

Industry 4.0 (I4.0) and digitalization can be seen as two sides of the same coin: according to [1], digitalization is one of the types of technology push that are behind the development of Industry 4.0. Since its introduction at the Hannover Messe in 2011 and its first formalization provided by [2], Industry 4.0 has generated a great amount of attention, both from the academic and non-academic world. Following the example of Germany, several governments worldwide have tried to oversee the Fourth Industrial Revolution by introducing specific national plans, such as [3, 4]. At the same time, international organizations [5] and private companies [6] have provided their own definition of the phenomenon. On the other hand, the academic world has tried to put some order in the great amount of literature on the topic, adopting a more systematic approach to the problem of the definition of Industry 4.0 [7] as well as its enabling technologies and their implementation patterns [8]. Nowadays, Industry 4.0 can be seen as a concept reaching its maturity, thanks to the large number of academic studies focusing on its technological aspect and its application in the industrial sector [9]. However, despite the large body of research, there are still some grey and highly under-research areas.

The results of a survey [10] conducted at the 9th IFAC Conference on Manufacturing Modeling, Management and Control (MIM), held in Berlin in 2019, showed that a large number of areas in Industry 4.0 still require urgent academic attention. One of the areas where this urgency for academic analysis was most strongly felt, is represented by the cost-benefit analysis of the implementation of Industry 4.0, accompanied by a lack of clarity regarding its actual economic benefit. Other works have confirmed the existence of this gap [11, 12] highlighting the significant distance between the interest of practitioners in the cost-benefit analysis of Industry 4.0 and the relative academic neglect of the topic [13]. The absence of clear evidence and dedicated cost-benefit analysis models represents one of the main barriers towards a wider adoption of Industry 4.0 [14], making the examination of this gap even more important. For this reason, we have conducted a systematic literature review (SLR) of the existing models for the cost-benefit analysis of Industry 4.0 in the manufacturing and industrial sector, with specific attention to the economic benefit evaluation. Our review tries to answer the following research questions (RQs):

1. What are the main models for the cost-benefit analysis of Industry 4.0 existing in scientific literature?
2. What are the elements of economic evaluation within these models?

The rest of the paper is organized as follows: Section 2 introduces the adopted methodology for the systematic review, Section 3 illustrates and discusses the results and Section 4 presents the conclusions and the new research directions.

2 Methodology

To guarantee a sufficient degree of scientific rigor and the reproducibility of the results, we decided to adopt the systematic literature review approach [15]. Our review process is summarized in Table 1.

The research was conducted on two databases: Scopus and Web of Science (WoS). We started by searching the set of keywords shown in the second row of Table 1 within title, abstract and keywords. The main target of this review is addressed by the keyword “cost benefit analysis” but since we are also interested in the economic evaluation aspect within the models, we added other related keywords such as “economic evaluation”, “economic assessment” etc. The adopted search string found 356 results in Scopus and 99 in WoS.

We limited the timeframe of the contributions to the interval 2017-2023, in order to select works that were published when the concept of Industry 4.0 had already reached a certain degree of maturity (which is after some of the main articles on the topic had already been published, such as [1, 2, 16]). Then, we filtered the results according to the document type (articles or reviews), source (journals) and language (English). After this filtering process, 146 papers were left from Scopus and 56 from WoS. Since the boundaries of our research are limited to the industrial and manufacturing sector, we decided to include papers coming exclusively from the research areas indicated by Selection Criteria E. This additional filtering step yielded 104 results in Scopus and 39 in

WoS. We then proceeded to eliminate the 19 duplicates between the two databases, resulting in a final list of 124 papers.

Table 1. Review methodology and resulting papers

Step	Description	N.° of papers
1. Database	Scopus, Web of Science	-
2. Keywords (searching in Title, Abstract and Keywords)	("industry 4.0" OR "I4.0" OR "smart manufacturing" OR "digital transformation") AND ("economic evaluation" OR "economic assessment" OR "economic estimation" OR "economic benefit" OR "economic advantage" OR "cost benefit analysis" OR "economic index*" OR "investment assessment" OR ROI OR "return on investment")	356 (Scopus) 99 (WoS)
3. Selection Criteria A	Year: 2017-2023	341 (Scopus) 96 (WoS)
4. Selection Criteria B	Document Type: Article AND Review	154 (Scopus) 56 (WoS)
5. Selection Criteria C&D	Source Type: Journal Language: English	146 (Scopus) 56 (WoS)
6. Selection Criteria E	Subject Area: Engineering, Business Management and Accounting, Decision Sciences, Economics Econometrics and Finance [SCOPUS] Subject Area: Engineering, Business Economics, Operations Research Management Science, Science Technology Other Topics [WoS]	104 (Scopus) 39 (WoS)
7. Excluding Duplicate Papers	(Out of 39 papers in WoS, 19 were duplicates)	124
8. Content Analysis	Criterion 1: Select only papers that include models of cost-benefit analysis that can be classified according to [17] Criterion 2: Select only papers that focus on the implementation of Industry 4.0 in the indus-trial and manufacturing sector	9

Each one of those papers was carefully examined according to two selection criteria:

1. Select only papers that include models of cost-benefit analysis that can be classified according to Meredith and Suresh [17]
2. Select only papers that focus on the implementation of Industry 4.0 in the industrial and manufacturing sector.

After the content analysis, only 9 works remained. This first preliminary result confirms the large gap existing in the literature on the topic of cost-benefit analysis of Industry 4.0. The content of the 9 selected papers is analyzed in the following section.

3 Classification and Discussion

Table 2 collects and classifies the 9 papers selected with the SLR process.

Looking at the publication year, no works were published before 2020 (1 in 2020, 3 in 2021 and 5 in 2022). The upward trend might indicate a small but increasing interest in the scientific community.

The papers were classified according to the classification of investment justification approaches proposed by Meredith and Suresh [17] . The cost-benefit analysis models are divided in three main categories: economic, analytic and strategic approaches. Economic approaches are usually dedicated to stand-alone systems and tend to be more quantitative. Example of economic approaches are the payback period, the Return on Investment (ROI), the Incremental Rate of Return (IRR) or the Net Present Value (NPV). Analytic approaches are dedicated to more linked systems and are able to consider multiple factors as well as subjective judgements. This category can be further divided into value analysis, portfolio analysis and risk analysis. Multi-criteria decision-making methods and mathematical models fall within the portfolio analysis sub-category. Finally, the strategic approach are typical of fully integrated systems and is less technical than the previous two categories since it incorporates firm goals and objectives.

According to the introduced classification, three of nine selected works adopted a purely economic approach: [18–20]. [18] used the Life Cycle Costing (LCC) method to evaluate the economic feasibility of introducing AGVs in a food processing factory. [19] proposed a systematic approach to evaluate I4.0 applications. The second of the three phases of the proposed method requires the transparent evaluation of the investment object, which is conducted using NPV and payback period. [20] introduced an 11-phases long framework, called Integrated Business Process Management, which aims to guide practitioners towards an efficient transition towards I4.0. The cost benefit analysis is performed during the 9th and 10th phase, using ROI, payback period and Benefits to Costs Ratio.

Three other works followed an exclusively analytic approach: [21] used decision trees while [22, 23] adopted mathematical models. In [21], decision trees were exploited to compare corrective maintenance with the investments in sensors and software for the development of a predictive maintenance policy. The element of economic evaluation that was used as term of comparison was the unitary expected cost of each maintenance policy. [22] analyzed data from 116 Chinese industrial companies using a regression model where the return on net assets is used as the explanatory variable, being a proxy for production efficiency. [23] developed a mathematical model that aims to evaluate the impact of the implementation of Internet of Things (IoT) technologies in warehouses that store perishable and deteriorating products. The total profit function is the objective function of the model, and it depends on the length of the product deterioration cycle and the investment cost in IoT.

Two papers adopted a hybrid economic-analytic approach. [24] studied the economic feasibility of multiple RFID implementation projects using a Monte Carlo simulation with six different control variables and three response variables, among which there was the NPV of the profits. Subsequently, an optimization analysis was conducted in order to obtain the best possible NPV of the profits. [25] evaluated nine different I4.0 implementation projects in an agricultural machinery company using the Integrative Investment Index, which combines economic, financial and sociotechnical evaluation. The sociotechnical evaluation is conducted with a multi-criteria decision-making model (the Analytic Hierarchy Process), combining technological, organizational, environmental and social factors, while the economic and financial evaluations are based respectively on NPV and payback period.

Both the analytic and strategic approaches were included by [26].

Table 2. Classification and content analysis of the 9 selected works. E = Economic, A = Analytic, S = Strategic, according to [17]. CS/G: CS = Case Specific, G = General; it refers to whether the model is general and can therefore be adopted in various different applications or if the model is tailored on the specific case study.

Ref	Year	Cit	E	A	S	Economic Evaluation	Other Evaluated Elements	Case study	CS/G
[18]	2022	1	X			Life cycle costing for economic evaluation (LCC)	Life Cycle Assessment (LCA) conducted with EPD and ReCiPe	Food processing	G
[21]	2022	15		X		Unitary Expected Cost of the maintenance policy		Food processing (failure modes of gearbox for roasting oilseeds) Case A: planetary Case B: high speed shaft bearing	CS
[19]	2022	0	X			Net present value Internal Rate of Return		Switchgear manufacturing	G
[25]	2022	2	X	X		Net Present Value (economic evaluation) Payback Period (financial evaluation)	Sociotechnical evaluation using an index that combines 12 different criteria, divided in 4 categories: technology, organization, environment, social.	Machinery and equipment manufacturing for agriculture	G
[22]	2022	8		X		Return on net assets (explanatory variable) Asset liability ratio		NA	G

Ref	Year	Cit	E	A	S	Economic Evaluation	Other Evaluated Elements	Case study	CS/G
[24]	2021	1	X	X		Payback Time Net Present Value of profits	The control variables of the Monte Carlo simulation, mainly the number of RFID projects	Data taken from the Visuwan–Tannock (VT) model: a simulation model of a Thai automaker	CS
[26]	2021	4		X	X	Profit in a production period	Agility and Responsiveness of the manufacturing facility to uncertainty	Wood press manufacturing company	CS
[23]	2021	11		X		Total Profit Function		Warehouse of a small food company	CS
[20]	2020	27	X			Return On Investment Payback Period Benefits to Cost Ratio		NA	G

A mathematical model with the profit in each production period as the objective function was used to assess the possible investment in connectivity with suppliers of a wood presses manufacturing company. The analytic model suggested that not investing in I4.0 was more profitable, but the strategic benefits brought by increased agility and responsiveness to uncertainty forced the choice towards I4.0 implementation.

With regards to the generality of the cost-benefit analysis approaches, five of the nine selected works [18–20, 22, 25] included models that were general enough to be exported to other case studies. The models of the remaining works, instead, were tailored for the specific case study or application under assessment.

4 Conclusions and Future Research Direction

Table 2 lists the main models for the cost-benefit analysis of Industry 4.0 produced by the scientific literature (RQ1) while its “Economic Evaluation” column shows the main elements of economic evaluation adopted by these models (RQ2). The main limitation of our approach is represented by the search string: we did not include keywords related to frameworks or models for technology selection, which can include forms of cost-benefit analysis. This may represent an opportunity for further extension of this work. The analysis of the selected papers allowed us to define two main future research directions (D1 and D2):

D1: Development of new cost-benefit analysis models that combine multiple investment justification approaches.

Given the paucity of contributions on the topic, and the concurrent urgent need for them, any type of new model would be beneficial for the academic debate. However, particular attention should be devoted to cost-benefit analysis models that combine multiple assessment approaches. Industry 4.0, in fact, is a complex phenomenon that drives towards the full integration of the production systems, calling for the adoption of analytic or strategic approaches. The economic evaluation aspect, on the other hand, remains crucial, especially for practitioners: a combination of multiple approaches, possibly with the aid of multi criteria decision making methods, seems the most fitting solution.

D2: Development of new generic cost-benefit analysis models, that can be transferred to different application cases.

New developed models should be generic enough to be applicable to multiple case studies in different sectors. This would allow to gather a larger volume of data, while guaranteeing a standardized approach that could permit the comparison of economic performance of I4.0 technologies in different environments.

References

1. Lasi H, Fettke P, Kemper H-G, et al (2014) Industry 4.0. Business & Information Systems Engineering 6:239–242. https://doi.org/10.1007/s12599-014-0334-4
2. Kagermann H, WW, HJ (2013) Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0.
3. MISE Ministero dello Sviluppo Economico (2016) Piano Nazionale Industria 4.0. In: https://www.mise.gov.it/images/stories/documenti/guida_industria_40.pdf
4. HM Government (2017) Industrial Strategy: Building a Britain Fit for the Future. In: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664572/industrial-strategy-white-paper-print-ready-version.pdf
5. Klaus Schwab (2016) The Fourth Industrial Revolution
6. Rüßmann M, Lorenz M, Gerbert P, et al (2015) Industry 4.0 The Future of Productivity and Growth in Manufacturing Industries
7. Culot G, Nassimbeni G, Orzes G, Sartor M (2020) Behind the definition of Industry 4.0: Analysis and open questions. Int J Prod Econ 226:. https://doi.org/10.1016/j.ijpe.2020.107617
8. Frank AG, Dalenogare LS, Ayala NF (2019) Industry 4.0 technologies: Implementation patterns in manufacturing companies. Int J Prod Econ 210:15–26. https://doi.org/10.1016/j.ijpe.2019.01.004
9. Zheng T, Ardolino M, Bacchetti A, Perona M (2021) The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. Int J Prod Res 59:1922–1954. https://doi.org/10.1080/00207543.2020.1824085
10. Ivanov D, Tang CS, Dolgui A, et al (2021) Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management. Int J Prod Res 59:2055–2078

11. Tabim VM, Ayala NF, Frank AG (2021) Implementing Vertical Integration in the Industry 4.0 Journey: Which Factors Influence the Process of Information Systems Adoption? Information Systems Frontiers. https://doi.org/10.1007/s10796-021-10220-x
12. Agostini L, Nosella A (2019) The adoption of Industry 4.0 technologies in SMEs: results of an international study. Management Decision 58:625–643. https://doi.org/10.1108/MD-09-2018-0973
13. Nazarov D, Klarin A (2020) Taxonomy of Industry 4.0 research: Mapping scholarship and industry insights. Syst Res Behav Sci 37:535–556. https://doi.org/10.1002/sres.2700
14. Kumar S, Suhaib Mohd, Asjad M (2021) Narrowing the barriers to Industry 4.0 practices through PCA-Fuzzy AHP-K means. Journal of Advances in Management Research 18:200–226. https://doi.org/10.1108/JAMR-06-2020-0098
15. Kitchenham B, Pearl Brereton O, Budgen D, et al (2009) Systematic literature reviews in software engineering – A systematic literature review. Inf Softw Technol 51:7–15. https://doi.org/10.1016/j.infsof.2008.09.009
16. Hermann M, Pentek T, Otto B (2016) Design Principles for Industrie 4.0 Scenarios. In: 2016 49th Hawaii International Conference on System Sciences (HICSS). IEEE, pp 3928–3937
17. MEREDITH JR, SURESH NC (1986) Justification techniques for advanced manufacturing technologies. Int J Prod Res 24:1043–1057. https://doi.org/10.1080/00207548608919787
18. Stefanini R, Vignali G (2022) Environmental and economic sustainability assessment of an industry 4.0 application: the AGV implementation in a food industry. The International Journal of Advanced Manufacturing Technology 120:2937–2959. https://doi.org/10.1007/s00170-022-08950-6
19. Joppen R, Kühn A, Förster M, Dumitrescu R (2022) Evaluation of Industry 4.0 Applications in Production. Journal of the Knowledge Economy. https://doi.org/10.1007/s13132-022-00959-2
20. Butt J (2020) A Conceptual Framework to Support Digital Transformation in Manufacturing Using an Integrated Business Process Management Approach. Designs (Basel) 4:17. https://doi.org/10.3390/designs4030017
21. Arena S, Florian E, Zennaro I, et al (2022) A novel decision support system for managing predictive maintenance strategies based on machine learning approaches. Saf Sci 146:105529. https://doi.org/10.1016/j.ssci.2021.105529
22. Zhang T, Shi Z-Z, Shi Y-R, Chen N-J (2022) Enterprise digital transformation and production efficiency: mechanism analysis and empirical research. Economic Research-Ekonomska Istraživanja 35:2781–2792. https://doi.org/10.1080/1331677X.2021.1980731
23. Maheshwari P, Kamble S, Pundir A, et al (2021) Internet of things for perishable inventory management systems: an application and managerial insights for micro, small and medium enterprises. Ann Oper Res. https://doi.org/10.1007/s10479-021-04277-9
24. Elizondo-Noriega A, Tiruvengadam N, Guemes-Castorena D (2021) An economic feasibility study using a system-dynamics-based archetype of RFID implementation in a manufacturing firm. International Journal on Interactive Design and Manufacturing (IJIDeM) 15:187–210. https://doi.org/10.1007/s12008-021-00752-6
25. Almeida RP, Ayala NF, Benitez GB, et al (2022) How to assess investments in industry 4.0 technologies? A multiple-criteria framework for economic, financial, and sociotechnical factors. Production Planning & Control 1–20. https://doi.org/10.1080/09537287.2022.2035445
26. Alami D, ElMaraghy W (2021) A cost benefit analysis for industry 4.0 in a job shop environment using a mixed integer linear programming model. J Manuf Syst 59:81–97. https://doi.org/10.1016/j.jmsy.2021.01.014