OR in the industrial engineering of Industry 4.0: experiences from the Iberian Peninsula mirrored in CJOR

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Abstract
Industry 4.0 (I4.0) implies a group of technologies, organisational concepts and management principles to improve the performance of manufacturing companies or supply chains driven by production cost optimisation, mass customisation requirements, connectivity and digitisation of factories. The purpose of this paper is to relate Iberian Peninsula advances in I4.0 from Spanish and Portuguese research works published in CJOR papers. Hence this paper reviews the Spanish and Portuguese operations research (OR) and industrial engineering-based papers published in CJOR from 2011, when the I4.0 concept emerged, to the present-day. Here 47 papers are reviewed according to classification criteria based on the following elements: (1) objectives; (2) application context; (3) modelling approach; (4) development or software tool; (5) I4.0 technologies. The main outcomes, limitations and further research are also identified for recent papers. Finally, research trends and future directions in industrial engineering, OR and I4.0 are discussed.

Keywords Industry 4.0 · Industrial engineering · Iberian Peninsula · ICIEM · ADINGOR

1 Introduction

Industrial engineering studies are the branch of engineering studies concerned about the analysis, design, organisation and control of production and service systems. In these first studies, researchers work on the challenges of manufacturing plant analysis, designing and control by considering mostly the operating efficiency of human
resources and machines. These studies include these activities: production planning, organisation and control; quality statistics and control; inventory optimisation and warehouse design; equipment and maintenance; optimal plant layout and workstation design.

Operations research (OR) methods and models as applied mathematics lie in implementation areas in many disciplines, and also in industrial engineering. As a multidisciplinary applied science, it utilises algebra and optimisation, probability and statistics, analyses in real and transformed spaces which, in industrial engineering, have led to many new approaches; for example, machine learning and other methods. Today’s industrial engineering challenges are more broadly spread but concentrate on productivity and all the technical problems of production management and control, as well as financial and general economic consequences. OR methods can be found in all kinds of the industrial organisation from manufacturing to distribution, transportation, other logistics, and services. Industrial engineers’ duties are wide-ranging, from the design of single operations to that of the management and control of complete production, logistics and other service systems. Their systems not only involve physical issues but also integrate them into financial, general economic and environmental components. One important challenge is engineering solutions in benefit of human resources by designing their working places and combining their activities with collaborative robots, modernised workstations and others. Then there are ergonomic solutions for which OR methods and models are essential for organisations to make profits and provide workers with benefits.

In Spain, PhD programs oriented to industrial production and engineering with solid OR support are based mainly on previous Bachelor (Mula et al. 2012) and/or Master studies in Organization Engineering. There are currently 17 Master degrees in Spain in the engineering and architecture branch related to production, logistics and/or supply chain engineering. Four Polytechnic Universities offer seven of these Master’s degrees: Polytechnic University of Cartagena (1), Polytechnic University of Madrid (2), Universitat Politècnica de Catalunya (2) and Universitat Politècnica de València (2).

About ten main PhD programs that focus on industrial production and engineering are offered by Spanish universities. The Spanish Association for the Development of Organization Engineering (ADINGOR) is integrating and disseminating Organization Engineering knowledge through, among others, the annual International Conference on Industrial Engineering and Industrial Management (ICIEIM) or CIO (Congreso en Ingeniería de Organización) conferences, whose selected better results obtained since 2017 are published in CJOR special issues (Mula and Bogataj 2020). In Portugal, there are five main PhD programs about industrial engineering and OR methodologies: Industrial Engineering and Management (Aveiro); Leaders for Industrial Techniques (Lisbon); Industrial and Systems Engineering (Minho); Engineering and Industrial Management (Porto); and Advanced Engineering Systems for Industry (Minho). The overall objective of these Master’s and PhD degrees is to train practitioners and researchers in advanced production engineering, logistics and supply chains by orienting their training toward company requirements or choosing a research itinerary. Advanced planning, programming and sequencing techniques are addressed in both an
industrial and supply chain context. Supply and distribution logistics techniques, logistics and supply chain engineering, and their strategies, are also studied. Finally, process management, performance measurement systems, and modelling and simulation techniques for production, logistics and supply chain systems are investigated and applied.

Regarding the international development of industrial engineering and OR solutions, according to the Journal Citation Report 2019, the Engineering, Industrial scientific category, with 48 journals, has an aggregate impact factor of 3.893, while Operations Research & Management Science, with 83 journals, has one of 3.176. Here it is essential to highlight that 18 of 48 Industrial Engineering journals also belong to the Operations Research & Management Science category, which shows that the growth of both disciplines is closely related.

From an operations management perspective, Industry 4.0 (I4.0) is a connection of technologies, organisational concepts and management principles that underlies a cost-efficient, responsive, resilient and sustainable supply chain (Ivanov et al. 2020; Cañas et al. 2020; Fortuny-Santos et al. 2020). The main enabling technologies for I4.0 development are: additive manufacturing, artificial intelligence and machine learning, autonomous vehicles and mobile robots, big data and data analytics, blockchain, cloud computing and cloud manufacturing, cyber-physical systems (CPS), cybersecurity, digital twins, Internet of Things (IoT) and Industrial Internet of Things (IIoT), optimisation, real-time communication, RFID, simulation, social media analytics and tracking and tracing systems (TTS). While I4.0 focuses on practice and research, Ivanov et al. (2020) argue that operations management studies in this area are not progressive enough. Therefore, with their paper, they intended to understand the current I4.0 research state in different disciplines and to gain insights and opportunities for future research in operations management. They provided a focused analysis to examine state of the art and learned about researchers’ perspectives in I4.0 by offering a global survey on I4.0 topics with researchers in operations management, OR, industrial engineering and control and data science, which was presented at the 9th IFAC MIM 2019 conference, where the current state of knowledge and research opportunities for I4.0 was discussed.

OR and industrial engineering are two main research disciplines involved in I4.0, together with control, data science, mechanical engineering and supply chain operations management. Cañas and Mula (2020) identify that the majority of research works published in the I4.0-based production management and engineering context centre on the production programming of flow workshops and supply chain planning. In this paper, we provide an overview of recent results from I4.0-based OR and industrial engineering applications carried out in the Iberian Peninsula and mirrored in CJOR articles. The main motivation is to identify current trends and new research to be conducted in Spain and Portugal in relation to industrial engineering, OR and I4.0.

The rest of the paper is organised as follows. Section 2 and Sect. 3 present a short literature review about Iberian Peninsula CJOR articles and relate them to I4.0 technologies. Section 4 discusses the main findings of the review. Section 5 presents the conclusions and further research.
2 Iberian Peninsula mirrored in CJOR articles: the contributions before 2021

Before 2011, when the first idea about I4.0 came about, only five Spanish and three Portuguese articles were published in CJOR, and studied the efficiency and competitions of football teams, from the data envelopment analysis (DEA) (Garcia-Sanchez 2007; Guzman and Morrow 2007; Picazo-Tadeo and Gonzalez-Gomez 2010) to game-theoretical approaches, by comparing Shapley and Owen values (Lopez and Saboya 2009) and also discussing business technical efficiency matters (Garcia-Sanchez 2010). Additionally, the first CJOR papers from Portugal were more orientated to routing and location problems (Craveirinha et al. 2008; Dias et al. 2008) by presenting the proposal of a multiobjective routing optimisation framework for multiprotocol label switching (MPLS) networks and a capacitated dynamic location problem. Witte and Marques (2010) strike a balance between economies of scale and a sufficient number of remaining comparable utilities using DEA by comparing the efficiency of the drinking water sector in the Netherlands, England and Wales, Australia, Portugal and Belgium. Since 2011, ideas about I4.0 are also reflected in some CJOR articles. During the 2011–2021 period, we identified 47 Spanish and Portuguese papers published in CJOR (Table 1).

Table 2 provides a general review of the articles published during the 2011–2020 period, along with their modelling approaches and major outcomes. These papers have been reviewed and classified according to the following criteria: objectives of the paper; application context; modelling approach; software tool used; I4.0 technologies contributed.

3 Recent results toward Industry 4.0

The papers published in 2021 are mostly written on the bases of presentations at ICIEIM conferences before 2020 and further developed for CJOR. They were reviewed and classified according to the following criteria (Table 3): objectives of the paper; research area; application context; research methodology and approach modelling; software tool used; I4.0 technologies contributed; major outcomes, limitations and further research, identified by the authors.

| Table 1 Spanish and Portuguese papers in CJOR since 2011 |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | 2011–2015       | 2016–2020       | 2021            | Total           |
| Spain           | 7               | 19              | 12              | 38              |
| Portugal        | 7               | 1               | 1               | 9               |
| Total           | 14              | 20              | 13              | 47              |
| Authors          | Year          | Objectives                                                                 | Application context | Modelling approach                     | Software tools | I4.0 technologies contributed |
|------------------|---------------|----------------------------------------------------------------------------|---------------------|----------------------------------------|----------------|-------------------------------|
| Belen et al.     | 2011          | To explain rumour spreading in continuous time                              | Rumours             | Differential equations                  | MAPLE          | Simulation                     |
|                  |               |                                                                           |                     |                                        |                |                               |
| Simoes and Marques | 2011        | To measure the efficiency or congestion of Portuguese hospitals            | Health              | DEA                                    | Not mentioned  | Optimisation                   |
|                  |               |                                                                           |                     |                                        |                |                               |
| Baptista and Oliveira | 2012   | To evaluate dispatching rules for the Lisbon emergency medical system       | Health              | Queuing theory                         | Visual basic—excel | Simulation                     |
|                  |               |                                                                           |                     |                                        |                |                               |
| Pedamallu et al. | 2012         | To model HIV/AIDS transmission                                             | Health              | Cross impact analysis—dynamical system  | Not mentioned  | Simulation                     |
|                  |               |                                                                           |                     |                                        |                |                               |
| Pinto et al.     | 2012          | To model a financial market under uncertainty                              | Financial market    | Random game matching—dynamical system   | Not mentioned  | Simulation                     |
|                  |               |                                                                           |                     |                                        |                |                               |
| Ros-McDonnell et al. | 2012   | To maximise the efficiency of using different means of transport and loading | Logistics           | Branch and bound heuristics            | Not mentioned  | Optimisation                   |
|                  |               |                                                                           |                     |                                        |                |                               |
| Volkovich et al. | 2012         | To propose a minimal spanning tree approach for the cluster validation problem | Data mining          | Clustering methods                     | Not mentioned  | Machine learning              |
|                  |               |                                                                           |                     |                                        |                |                               |
| Garcia-Sanchez et al. | 2013 | To analyse the efficiency of police forces in Spain                        | Police services     | DEA                                    | FEAR           | Optimisation                   |
|                  |               |                                                                           |                     |                                        |                |                               |
| Lopez-Perez and Rodriguez-Ariza | 2013 | To analyse the governance structure of capital international joint ventures | Spanish-Moroccan SMEs | Exploratory cross-sectional Questionnaires and statistics | Not mentioned  | Data analytics                 |
| Authors (year)          | Objectives                                                                 | Application context                         | Modelling approach                                         | Software tools                              | I4.0 technologies contributed |
|------------------------|----------------------------------------------------------------------------|---------------------------------------------|-------------------------------------------------------------|--------------------------------------------|---------------------------------|
| Alvarez-Diez et al. (2014) | To assess executive stock options (ESO)                                    | Financial market                           | ESO analytic models: Black–Scholes (BS) and Cvitanic–Wiener–Zapatero (CWZ) | ExecuCom and Compustat databases         | Data analytics                  |
| Castro et al. (2014)   | To solve real size stochastic slack PERT or SPERT problems                  | Project management                         | Polynomial algorithms                                       | Not mentioned                             | Data analytics                  |
| Dias et al. (2014)     | To find the best set of angles, beam angle optimisation, for intensity modulated radiotherapy treatment (IMRT) planning | Health                                     | Genetic algorithms and neural networks                      | MATLAB CERR DICOM RT                      | Optimisation                    |
| Freixas and Pons (2015) | To compare the success and decisiveness of a voter in symmetric games for different consensus levels | Voting systems                             | Cooperative games                                           | Not mentioned                             | Blockchain algorithms           |
| Kovačič et al. (2015)  | To evaluate, by the extended MRP (EMRP) theory, the impact of location and lead time on the net present value of all activities in a supply chain | Food supply chain                          | Input–output analysis                                       | Not mentioned                             | Simulation                      |
| Albizuri and Alvarez-Mozos (2016) | To propose a new family of cost-sharing rules                              | Cost-sharing problems                      | Axiomatisation                                              | Not mentioned                             | Data analytics                  |
Table 2 (continued)

| Authors (year)       | Objectives                                                                 | Application context | Modelling approach                                  | Software tools                                      | I4.0 technologies contributed |
|----------------------|-----------------------------------------------------------------------------|---------------------|------------------------------------------------------|-----------------------------------------------------|-------------------------------|
| Cordero et al. (2016) | To estimate the differences in efficiency between Spanish public and private schools | Education           | Free disposal hull (FDH), robusts approach and metafrontier approach | Not mentioned                                      | Data analytics                |
| Fragnelli et al. (2016) | To measure the importance of factors contributing to the occurrence of an event | Ocurrence of events | Cooperative games                                   | Not mentioned                                      | Blockchain algorithms         |
| Amaro-Mellado et al. (2018) | To obtain a \( b \)-value, that represents the relation between small and large earthquakes. A map for the Iberian Peninsula | Seismic activity    | Clustering methods                                 | ZMAP NGIS                                           | Machine learning              |
| Pastor et al. (2018)  | To extend the use of bounds, initially proposed exclusively for additive models, to the family of directional distance function models | Agricultural data   | DEA                                                  | Not mentioned                                      | Optimisation                  |
| Ligardo-Herrera et al. (2019) | To assess stakeholders’ influence on a research project in the responsible research and innovation context | Information and Communication Technology (ICT) business sector | Multicriteria decision analysis (MCDA) analytic network process (ANP) | SuperDecisions©                | Data analytics                |
| Authors (year)                   | Objectives                                                                                                                                                                                                 | Application context      | Modelling approach                                                                 | Software tools                                      | I4.0 technologies contributed |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------|-------------------------------|
| Zapata et al. (2019)            | To study a duopolistic competition model in an uncertain environment where attitudes of firms toward uncertainty are incorporated                                                                        | Duopoly market           | Two scenario Cournot game                                                           | Not mentioned                                     | Blockchain algorithms        |
| Arroyo et al. (2020)            | To analyse the effect of carbon pricing policies in battery electric vehicle (BEV) penetration in the city of Madrid                                                                                          | Transportation           | Mixed-integer linear programming (MILP)/48A heuristic algorithm Monte Carlo simulation | Not mentioned                                     | Optimisation simulation      |
| Babiloni and Guijarro (2020)    | To calculate the fill rate at a continuous review reorder point, order quantity (s, Q) policy in a lost sales and discrete demand context                                                                       | Inventory management     | Mathematical formulations                                                           | Not mentioned                                     | Simulation                   |
| Bautista-Valhondo and Alfaro-Pozo (2020) | To propose two MILP models to extend two flow shop scheduling problems (FSP) with an overall demand plan                                                                                               | Automotive               | MILP                                                                                | IBM ILOG CPLEX                                     | Optimisation                 |
| Bildosola et al. (2020)         | To obtain the characterisation of big data technology, which facilitates understanding and identifies its potential                                                                                         | Big data                 | Bibliometric analysis, text mining, principal component analysis (PCA), time series   | Vantage-point R software                           | Big data, data analytics, machine learning |
### Table 2 (continued)

| Authors (year)                  | Objectives                                                                 | Application context                  | Modelling approach          | Software tools                          | I4.0 technologies contributed |
|--------------------------------|-----------------------------------------------------------------------------|--------------------------------------|-----------------------------|-----------------------------------------|---------------------------------|
| Civantos and Garcia-Algarra (2020) | To study the incident management of three live services in Europe and Latin America: IPTV, Cloud Infrastructure and managed IoT connectivity | Telecom services                     | Time series                 | Prophet, causal impact                   | Data analytics                  |
| del Rosario et al. (2020)       | To highlight contributions to achieve Sustainable Development Goals          | Sustainable development              | Editorial review            | Not identified                          | Optimisation RFID simulation    |
| Leon et al. (2020)              | To propose a methodology for designing maintenance systems and estimating costs | Moroccan photovoltaic rural electrification | MILP, rule-based expert system (classification tree and linear regression model) | GAMS/CPLEX                | Optimisation simulation          |
| Martin et al. (2020)            | To model and solve a master production schedule (MPS) problem with uncertainty related to manufacturing times | Automotive                           | Robust optimization         | GAMS/Gurobi                            | Optimisation                    |
| Mateo et al. (2020)             | To develop a decision support system to determine the number of hired workers by taking into account supplement characteristics, ergonomic issues and production rates | Staff planning for a printing plant  | MILP, linear regression     | Not identified                          | Optimisation                    |
| Authors (year)          | Objectives                                                                 | Application context                      | Modelling approach       | Software tools                  | I4.0 technologies contributed               |
|------------------------|----------------------------------------------------------------------------|------------------------------------------|--------------------------|---------------------------------|---------------------------------------------|
| Mula and Bogataj (2020) | To provide an overview of industrial engineering and management problems from an OR perspective | Engineering digital transformation       | Editorial review         | Not identified                  | Big data, data analytics, machine learning, optimisation, simulation |
| Rius-Sorolla et al. (2020a) | To propose a procedure to solve generic materials and operations planning (GMOP) problem with different materials and process lists | Operations planning                      | Lagrangian relaxation    | C, Excel, GUROBI                 | Optimisation                                 |
| Rius-Sorolla et al. (2020b) | To offer a systematic review of collaborative planning for coordination mechanisms in mathematical programming models | Collaborative planning                   | Literature review         | Not identified                  | Optimisation                                 |
| Saez-Mas et al. (2020)  | To model and solve an assignment problem on an assembly line on which 70 sequencing cells have to be located in a new facility | Automotive                               | Discrete event simulation, local search optimisation heuristics | C, SIMIO                        | Optimisation simulation                      |
| Authors (year) | Objectives | Application context | Modeling approach | Software tools | I4.0 technologies contributed | Major outcomes | Limitations | Future research |
|---------------|------------|---------------------|-------------------|---------------|----------------------------|----------------|-------------|----------------|
| Acebes et al. (2021) | To propose a new metrics to be used with both the scheduling risk analysis (SRA) and dynamic scheduling frameworks for risk analyses | Project management | Monte Carlo simulation | Not mentioned | Simulation | A new sensitivity metrics called the activity risk index (ARI), which informs about what activities contribute the most to a project’s uncertainty | An educational project, considered as an example | Studying the network’s configuration and its influence on ARI for each activity |
| Alvarez-Gil et al. (2021) | To model and solve a flexible job-shop scheduling problem (FJSP) in a customer-centric production system | FJSP in a make-to-order production system | Multiobjective discrete firefly algorithm (MO-DFA) | MATLAB | Optimisation | A framework that allows product customisation and customer-centric manufacturing | The potential and limitations of MO-DFA require further analysis | Studying the scalability of MO-DFFA and its combinations with other local search procedures |
| Authors (year)            | Objectives                                                                                                                                                                                                 | Application context          | Modeling approach | Software tools      | I4.0 technologies contributed | Major outcomes                                                                                                                                                                                                 | Limitations                                                                                                                                                                                                 | Future research                                                                                                                                       |
|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|-------------------|---------------------|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Dias et al. (2021)        | To use choice-based questions and MCDA to study the preferences of a population for vehicle technologies                                                                                               | Vehicle technologies        | MCDA MILP         | Not mentioned        | Data analytics optimisation | The use of simple mathematical formulations to obtain the most typical value-function shapes and a post-optimisation step to avoid extreme cases | The results are based on a single study about a specific situation                                                                                                                                           | Simulating the diffusion of new products and technologies with system dynamics or multiagents                                                                                      |
| Garcia-Arca et al. (2021) | To propose a methodology to support decision making in packaging system design to reduce costs                                                                                                          | Sustainable packaging logistics (SPL) | PDCA (Plan-Do-Check-Act) heuristics | Not mentioned | Data analytics              | To define, compare and select an efficient and sustainable packaging range in terms of purchase, logistics and environmental costs | A few method implementations (only one company)                                                                                                                                                               | Extending this methodology to three-level packaging systems                                                                                                                                                           |
| Authors (year) | Objectives | Application context | Modeling approach | Software tools | I4.0 technologies contributed | Major outcomes | Limitations | Future research |
|---------------|------------|---------------------|-------------------|----------------|-------------------------------|----------------|-------------|----------------|
| Manresa et al. (2021) | To analyse the relation between implementing new technologies and organisational practices in operational performance | Digitisation | Exploratory cross-sectional questionnaires and statistics | Not mentioned | Data analytics | Showing how digitisation and organisational practices differ from operational performance instead of focusing on financial performance | Low response rates and focusing on a single country: Spain | Testing the relations between the number and extent of using digitisation and organisational practices and other firm performance aspects to carry out a cross-country study |
| Monteiro et al. (2021) | To sequentially maximise the number of pairs to be transplanted with those that have been waiting longer | Health | MILP Greedy algorithm | Python GUROBI | Optimisation Simulation | Using waiting time as a criterion to select pairs to be matched cuts the maximum waiting time by slightly reducing the total number of transplants | The use of only simple Greedy algorithms | To test more complex solution algorithms |
| Authors (year)                     | Objectives                                                                 | Application context | Modeling approach                                                                 | Software tools                  | I4.0 technologies contributed | Major outcomes                                                                 | Limitations                                                                 | Future research                                                                 |
|----------------------------------|----------------------------------------------------------------------------|---------------------|---------------------------------------------------------------------------------|---------------------------------|--------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Munoz-Villamizar et al. (2021)   | To present a toolkit that adapts lean tools to technological devices, training strategies and optimisation to enhance and speed up environmental and production improvement | Agri-food           | Serious games, e—VSM (environmental value stream mapping), OEE (overall equipment effectiveness), OGP (overall greenness performance), multiobjective approach | Pizz@green plug&Glean          | Optimisation Real-time communication                                           | Adding environmental language to traditional improvement systems to simultaneously improve production and environmental efficiencies | Validation results are not presented                                                                              | To validate the proposed framework in real-world companies                      |
| Novais et al. (2021)             | To propose a methodology for strategic simulation where system dynamics models use results from structural equation models (SEM) | Community cloud, information technology integration and lean/just-in-time practices | System dynamics                                                                 | Vensim                          | Simulation                      | The inclusion of a dynamic analysis to the traditional SEM methodology     | A few tests and applications have been carried out                                                                 | To do new tests in more complex SEMs based on real-world companies            |
| Authors (year)          | Objectives                                                                                                                                                                                                 | Application context                                                                 | Modeling approach | Software tools                                                                 | I4.0 technologies contributed | Major outcomes                                                                                           | Limitations                                                                                       | Future research                                                                                       |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Rius-Sorolla et al. (2021) | To present a test bed generator and an instances database for a rolling horizon analysis with alternatives processes, multi-stroke and multicapacity                                                  | Multiechelon and multiproduct operations planning                                   | MILP               | GUROBI, Statgraphics Centurion XVII®                                         | Optimisation Simulation                                                                 | The analysis of how different demand patterns influence the costs of operations planning and service level | Uncertainty factors have not been considered                                                            | To consider independent or dependent variables, such as instability and contemplate co-products or more complex products |
| Uribetxebarria et al. (2021) | To study the effect of participation on employee well-being and organisational performance                                                                                                                | Human resource management                                                          | Exploratory cross-sectional Questionnaires and statistics | Not mentioned                                                                 | Data analytics                                                                   | Empirical results about the positive impact of HR participation in management performance indicators. Company size and productivity have provided correlations to be further studied | The nature of the considered variables and how they are measured, and the existence of alternative mechanisms working between variables | To use multiple data sources and respondents to mitigate the common method variance (CMV) issue, measurement separation in time to better evaluate causality, and to test endogenous variables at these levels |
| Authors (year) | Objectives | Application context | Modeling approach | Software tools | I4.0 technologies contributed | Major outcomes | Limitations | Future research |
|---------------|------------|---------------------|-------------------|----------------|-----------------------------|----------------|-------------|-----------------|
| Vazquez-Noguerol et al. (2021) | To propose a model to optimise the allocation of online orders to stores based on minimising e-fulfilment costs, and also picking and delivery costs. A weighted sum method is applied to compute the optimal solution | e-grocery | MILP | MPL/GUROBI | Optimisation | Consolidating workloads by avoiding idle times and reducing resources. Substantial savings made by testing in one of the largest grocery sellers | It focuses on allocating orders to vehicles, rather than managing logistics routes to travel the minimum possible kilometers | The proposed model can be adapted to other logistics configurations and decentralised approaches can be modeled |
Table 3 (continued)

| Authors (year) | Objectives | Application context | Modeling approach | Software tools | I4.0 technologies contributed | Major outcomes | Limitations | Future research |
|----------------|------------|---------------------|--------------------|----------------|-----------------------------|----------------|-------------|----------------|
| Verdecho et al. (2021a) | To propose a methodology based on MCDA for supplier selection decisions by considering sustainability performance, supply chain performance and supplier assessment criteria | Agri-food | MCDA AHP multicriteria approach | SuperDecisions© | Data analytics | To integrate the supplier selection process with supply chain sustainability management | Uncertainty factors have not been considered | To validate the proposed methodology in other real-world applications |
| Verdecho et al. (2021b) | To assess and manage the achievement of transversal competences at different levels of University studies (Bachelor and Master’s degrees) | Education | MCDA ANP | SuperDecisions© | Data analytics | The proposal of a new approach based on integrating four components: a methodology, a performance management framework, graphical diagrams and quantitative techniques | Pairwise comparison matrices established by consensus, although there are other methods that can be applied, such as the aggregation of individual judgments or voting | To develop new tools to align the management of all study levels |
4 Discussion

Regarding the papers from 2011 to 2020, we identified that optimization (Simoes and Marques 2011; Ros-McDonnell et al. 2012; Garcia-Sanchez et al. 2013; Dias et al. 2014; Pastor et al. 2018; Arroyo et al. 2020; Bautista-Valhondo and Alfaro-Pozo 2020; Leon et al. 2020; Martin et al. 2020; Mateo et al. 2020; Rius-Sorolla et al. 2020a, b; Saez-Maz et al. 2020), simulation (Belen et al. 2011; Baptist and Oliveira 2012; Pedamallu et al. 2012; Pinto et al. 2012; Kovačič et al. 2015; Babiloni and Guijarro 2020; Saez-Mas et al. 2020), data analytics (Lopez-Perez and Rodriguez-Ariza 2013; Alvarez-Diez et al. 2014; Castro et al. 2014; Albizuri and Alvarez-Mozos 2016; Cordero et al. 2016; Ligardo-Herrera et al. 2019; Bildosola et al. 2020; Civantos and Garcia-Algarra 2020) and machine learning (Volkovich et al. 2012; Amaro-Mellado et al. 2018; Bildosola et al. 2020) were the main I4.0 technologies contributed by Spanish and Portugese CJOR papers. Indeed MILP (Arroyo et al. 2020; Bautista-Valhondo and Alfaro-Pozo, 2020; Mateo et al. 2020) and DEA (Simoes and Marques 2011; Garcia-Sanchez et al. 2013; Pastor et al. 2018) were the most widely used modeling approaches in these reviewed papers. On the application context, automotive (mainly Spanish authors: Bautista-Valhondo and Alfaro-Pozo 2020; Martin et al. 2020; Saez-Mas 2020), health (mainly Portuguese authors: Simoes and Marques 2011; Baptist and Oliveira 2012; Pedamallu et al. 2012; Dias et al. 2014) and financial market (Pinto et al. 2012; Alvarez-Diez et al. 2014) applications were the most addressed ones.

In the more recent 2021 papers, optimisation (Alvarez-Gil et al. 2021; Monteiro et al. 2021; Munoz-Villamizar et al. 2021; Rius-Sorolla et al. 2021; Vazquez-Noguerol et al. 2021) and data analytics (Garcia-Arca et al. 2021; Manresa et al. 2021; Uribetxebarria et al. 2021; Verdecho et al. 2021a, b) were the main I4.0 technologies contributed, followed by simulation (Novais et al. 2021) and real-time communication (Munoz-Villamizar et al. 2021). The application context is very diverse, but agri-food (Munoz-Villamizar et al. 2021; Verdecho et al. 2021a) and technological (Manresa et al. 2021; Novais et al. 2021) applications were mainly studied. As for the solver software for optimisation, CPLEX was mainly used in the 2011–2020 papers, and GUROBI was the unique optimisation solver that the reviewed 2021 papers mentioned. Mathematical programming languages MATLAB and GAMS were mostly applied in the 2011–2020 papers, with MATLAB, MP and Python in the 2021 papers.

According to Cañas et al. (2020), I4.0 could lead to growth in industrialisation and disrupt the sustainability of existing manufacturing supply chains in terms of higher resource consumption, global warming, and climate change issues. Mula and Bogataj (2020) refer to I4.0 in relation to the cooperative digitisation and coordination of industrial processes through information technologies. Recently, Manresa et al. (2021) addressed the benefits for firms of digital transformation, which are transforming manufacturing into digital companies integrated into the I4.0 term. Muñoz-Villamizar et al. (2021) integrate lean thinking, I4.0 and mathematical optimisation to improve production and environmental performance in manufacturing companies.
On sustainability, Arroyo et al. (2020) attempt to motivate sustainable mobility through BEVs; del Rosario et al. (2020) relate sustainable development and OR; Leon et al. (2020) address sustainable energy supply in developing countries. Here sustainability is addressed mainly from the environmental perspective. Recently, Muñoz-Villamizar et al. (2021) also contemplate environmental sustainability practices. Uribetxebarria et al. (2021) consider social sustainability from the HR perspective. Vazquez-Noguerol et al. (2021) address sustainable energy supply in developing countries. Here sustainability is addressed mainly from the environmental perspective. Recently, Muñoz-Villamizar et al. (2021) also contemplate environmental sustainability practices. Uribetxebarria et al. (2021) consider social sustainability from the HR perspective. Vazquez-Noguerol et al. (2021) address the economic sustainability of an online order fulfillment system. Recently, Garcia-Arca et al. (2021) deal with packaging from three sustainable perspectives: social, economic and environmental. Veredcho et al. (2021a) study sustainable supplier selection modelling and selection criteria approaches by considering the same three social, economic and environmental perspectives.

5 Conclusion

This paper identified and reviewed the articles published in CJOR by authors from the Iberian Peninsula during the 2011–2021 period to relate their contributions to the advances and implementations of I4.0 technologies. Indeed the sustainable concept was especially contemplated. We reviewed 47 papers that have been classified in terms of objectives, application context, modelling approach, software tools, and I4.0 technologies contributed. For more recent articles (in 2021), major outcomes, limitations and further research were also identified. Papers from the 2011–2020 period contribute mainly to the state of the art of optimisation (13), simulation (10), data analytics (9), machine learning (4), big data (2), cooperative games for blockchain algorithms (2), optimisation simulation (1) and RFID (1). Papers from 2021 contribute mostly to optimisation (5), data analytics (5), simulation (4) and real-time communication (1).

It is essential to highlight that until 2021, the reviewed papers did not explicitly mention making contributions to I4.0 technologies. It was then when the benefits of digital transformation (Manresa et al. 2021) and a framework proposal to integrate I4.0 and lean thinking were addressed (Munoz-Villamizar et al. 2021). Sustainability should be covered in an integrated manner from its three perspectives: social, environmental, and economic (Cañas et al. 2020). The sustainable concept is included in the reviewed papers from 2020, but mainly in relation to environmental aspects. In 2021, more papers contemplate sustainable thinking in their proposals from its three perspectives: social, environmental and economic. Nevertheless, more research that addresses industrial engineering problems by considering OR solutions under the sustainable I4.0 term umbrella is required.

Future research lines should centre on proposing, testing and validating sustainable I4.0 conceptual, analytical, simulation, and artificial intelligence models to enable I4.0 adoption by companies and to bridge the gap between I4.0 strategy and operational implementation. More software tools for I4.0 practical applications by business leaders and decision-makers are necessary. Finally, real-world validations of I4.0 implementations based on OR solutions would be welcomed, among others, that focus on additive manufacturing, autonomous vehicles and
mobile robots, blockchain, cyber-physical systems (CPS), digital twins, Internet of Things (IoT) and Industrial Internet of Things (IIoT), social media analytics and tracking and tracing systems (TTS).

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