23rd International Conference on Harbor, Maritime and Multimodal Logistic Modeling & Simulation
18th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0339 ISBN 978-88-85741-59-1 © 2021 The Authors.
doi: 10.46354/i3m.2021.hms.009

# Discrete-event simulation in logistics: a critical review and framework for classification

Michela Tosti[1] and Eleonora Bottani[2,*]

[1]University of Parma, Department of Engineering and Architecture, viale delle Scienze 181/A, 43124 Parma, Italy
[2]University of Parma, Department of Engineering and Architecture, viale delle Scienze 181/A, 43124 Parma, Italy

[*]Corresponding author. Email address: eleonora.bottani@unipr.it

## Abstract

This paper has been designed in the form a systematic literature review targeting 164 papers between 2009 and 2020, intended for evaluating the current state-of-the-art of simulation usage in the logistics and supply chain management fields. This study grounds on the previous publication by Manuj et al. (2009), who have provided a detailed 8-step approach to be followed for a rigorous implementation of discrete-event simulation (DES). Starting from this previous study, this paper first of all evaluates the rigor in the application of DES in the logistics and supply chain management literature, in terms of the consistency of the published studies with the guideline proposed by Manuj et al. (2009). A second purpose of this research is to delineate a new method for classifying the published research on DES on the basis of the intrinsic quality of research, besides the more traditional analyses of journals and authors based on number of publications and citations.

**Keywords:** discrete-event simulation (DES); logistics; literature review; classification.

## 1. Introduction

The strong development of simulation in logistics and Supply Chain Management (SCM) literature has made it necessary to have a guide to rely on when producing articles in this area, for making the scientific literature more structured, understandable and consequently believable. One of the most important simulation techniques applied in logistics and SCM is discrete-event simulation (DES), which models the operation of a system as a sequence of discrete events that occur at different time intervals and that can change the state of the system.

A guideline for applying simulation (and in particular DES) in logistics has been proposed more than 10 years ago by Manuj et al. (2009), in their article titled "Improving the rigor of discrete-event simulation in logistics and supply chain research"; this is the basis to which we will refer in this paper.

Starting from the previous publication just quoted, this paper has been conceived to evaluate, through a systematic review of the literature, the current state-of-the-art of simulation usage in the logistics and SCM fields. The primary aim of this study is to evaluate whether, after the publication of the guideline by Manuj et al. (2009), improvements have been made in the rigor of application of DES in the logistics and SCM fields. Such a rigor is evaluated in terms of the consistency of the literature published between 2009 and 2020, with the guideline proposed by Manuj et al. (2009). A second purpose of this research is to delineate a new method for classifying the published research on DES on the basis of the intrinsic quality of research, besides the more traditional analyses of journals and authors based on number of publications and citations. The new classification framework is expected to become a tool for scholars and authors and an approach to follow when carrying out studies on DES models in the logistics and/or SCM contexts.

## 2. Methodology

### 2.1. Sample creation

The chosen approach for this research is the systematic literature review (Dewey & Drahota, 2016), carried out using the Scopus database. Compared to traditional reviews, a systematic literature review (SLR) identifies, selects and critically appraises research, for answering a clearly formulated scope, which in this study, consists in providing a sound evaluation of the literature relating to simulation usage in logistics and supply chain.

A crucial point when carrying out literature review (and SLRs in particular) is the selection of the appropriate keywords (Bottani & Franchi, 2021). Indeed, scientific writing does not impose any specific rule to authors for the usage of keywords in their papers (Hartley, 2008; Murphy, 2010); as a consequence, what frequently happens is that authors can use various terms for indicating similar concepts, all relating to the topic under investigation. An effective way to deal with this issue is to start reading some papers resulting from the query, evaluate their relevant to the targeted topic and then, check the keywords used in these papers to make fruitful queries (Bottani & Franchi, 2021).

Following this procedure, two sets of keywords were used in carrying out the queries:

- Keywords related to the application context, such as "supply chain" or "logistics";
- Keywords related to the tool investigated, such as "simulation model" or "simulation". Some further, more specific, terms (e.g. DES, system dynamics, or agent-based simulation) were introduced later for making addition queries intended to investigate the various simulation types. This choice is motivated by the fact that hybrid approaches are always possible in simulation contexts (Brailsford et al., 2019).

Looking at the query settings, the following rules were adopted:

- Papers must be written in English. Other languages were excluded;
- Papers must be published on international journals, which are recognized as the primary source of scientific studies. Other publication types were excluded;
- The paper type was set at “article” or “review”, to complement the previous setting, as well as to ensure that the fulltext was actually available for download;
- The publication timespan was set from 2009 to 2020, in line with the fact that the reference article for this study (i.e. Manuj et al., 2009) was published in 2009 and that, at the time of the query, articles of 2021 were still only partially available.

Using these settings, 164 results were obtained, which were retrieved and screened by reading the abstract, title and keywords, to ensure that they were relevant to the present study. As far as the criteria for retaining the pertinent studies, the main one refers to the fact that the papers retrieved must focus expressively on DES, which is also the focus of the reference article by Manuj et al., (2009). In line with this, the preliminary screening on abstract, title and keywords led to the exclusion of papers that did not focus on that simulation technique. Hybrid approaches (e.g. DES coupled with a second type of simulation) were instead retained. A final check was made by reading the full texts of the remaining papers to ensure correspondence with the inclusion criterion.

As a result of the above steps, 111 articles were retained for the following analyses. The list of these papers is too long to be reported in full in this manuscript, but interested readers are welcome to ask the authors about this.

### 2.2. Framework of analysis

#### *2.2.1. Descriptive analyses*

The relevant piece of information (i.e. authors, keywords, source title, year of publication and number of citations) about the 111 papers were extracted in .csv format from the Scopus database using the “export” function and imported in MS Excel™ for being elaborated. Descriptive statistics were first made for evaluating the trend of the publications in time, identifying the top-journals and the most prominent authors in the field of DES applied to logistics.

#### *2.2.2. Authors classification*

Authors were then classified on the basis of a revisited Pareto (ABC) analysis, incorporating the number of papers published by each author and the number of citations received by the papers. To be more precise, the following classes were set for authors and citations:

Author classification by number of publications (NP) and first year of publication (FYP):

- Class A: NP≥2 (active authors);
- Class B: NP<2 and FYP>2014 (less active authors but relatively new to simulation studies);
- Class C: NP<2 and FYP≤2014 (no longer active authors).

Author classification by average number of citations per year (ACY):

- Class A: ACY≥2 (prominent authors);
- Class B: 2>ACY≥1;
- Class C: ACY<1 (not well established authors).

The value of ACY was obtained using the following formula:

$$ACY = \left(\frac{sum\ of\ the\ author's\ citation}{NP*publication\ age}\right) \quad (1)$$

In eq.1, NP is the number of publications in the sample written by an author (as defined previously); the numerator, i.e. the sum of citations received by the author, was obtained by adding up the citations received by the NP papers of the sample (citations of each paper were extracted from Scopus); finally, the publication age reflects the number of years from the publication of the paper. By crossing the above categories, a final ranking of authors was obtained, with 9 classes (from AA to CC). Each class was than assigned a score, according to the ranking below:

- Class AA → 4 points (excellent);
- Class AB or BA → 3 points (good);
- Class AC, BB, or CA → 2 points (average);
- Class CB, CC or BC → 1 point (weak).

### *2.2.3. Journal classification*

A similar Pareto analysis was made also on the journals that published the studies about simulation usage in logistics and supply chain. To be more precise, the following criteria were applied for the classification:

Journal classification by NP and FYP:

- Class A: NP≥2 (journal that publishes frequently on the topic);
- Class B: NP<2 and FYP>2014 (journal that publishes less frequently and has started publishing on that field recently);
- Class C: NP<2 and FYP≤2014 (journal that does not published much on the topic).

Classification by journal citations per year (JCY):

- Class A: JCY≥2 (highly cited journal);
- Class B: 2>JCY≥1;
- Class C: JCY<1 (not well established journal).

In this classification, JCY denotes the average number of citations per year received by each study published in the corresponding journal, according to the following formula:

$$JCY = \left(\frac{sum\ of\ the\ citations\ of\ the\ papers\ published}{NP*publication\ age}\right) \quad (2)$$

Once again, by crossing the above categories, a final ranking of journals was obtained, with 9 classes (from AA to CC). Each class was than assigned a score, according to the same ranking used for author classification.

### *2.2.4. Papers classification*

A final classification (and ranking) was also made on the 111 papers reviewed, on the basis of the average number of citations received by per year (PCY), to check the correspondence with the previous analyses. The PCY was simply obtained as the ratio between the total number of citations received and the number of years since the paper has been published, according to the following formula:

$$PCY = \left(\frac{citations\ received\ by\ the\ paper}{(2021-publication\ year+1)}\right) \quad (3)$$

For classification purpose, 4 classes of citations were defined on the basis of the outcomes obtained, namely: class A→PCY≥16 (highly cited paper); class B→8≤PCY<16; class C→3≤PCY<8; class D→PCY<3 (almost uncited paper).

## 2.3. Framework for the critical analysis

The guidelines by Manuj et al. (2009) have identified a set of 8 steps that describe a rigorous process to be followed when applying DES. By reading the papers of the sample, these steps were divided into sub-steps for a better clarification of the single phases of a DES. The full list of steps and sub-steps (for a total of 14 phases) is provided below:

1. Problem formulation;
2. Identification of independent and dependent variables;
3. Development and verification of the conceptual model
    - 3.1. Development of the conceptual model;
    - 3.2. Validation of the conceptual model;
    - 3.3. Definition of the assumptions;
4. Data collection;
5. Development and verification of the computer-based model;
    - 5.1. Choosing the software environment;
    - 5.2. Checking the model;
6. Validation of the model;
7. Simulation run;
    - 7.1. Defining the warm-up time;
    - 7.2. Defining the run time;
    - 7.3. Determining the number of replicates;
    - 7.4. Determining the simulation scenarios;
8. Results analysis.

Obviously, the steps listed above could be performed in various ways by the authors. Following an approach similar to that proposed by Malhotra & Grover (1998) in the field of survey research, for each paper we checked whether each of the above steps was implemented by the authors, and, for each step implemented, a score of 1 was assigned (a score of 0 was instead assigned if the study failed to implement that step). The papers were then classified on the basis of the resulting total score (TS), as follows:

- TS<6 → weak;
- TS between 6 and 8 → average;
- TS between 9 and 11 → good;
- TS≥12 → excellent.

(being 14 the set of phases, i.e. steps and sub-steps, to be implemented in total). Each class of papers was finally assigned an additional score (AS), determined as follows: TS<6→AS=1; 6≤TS≤8→AS=2; 9≤TS≤11→AS=3; TS≥12→AS=4.

The frequency by which each step and sub-steps was implemented in the studies reviewed was also evaluated, with the purpose of checking whether, e.g., some steps are constantly neglected by the authors. The same analysis was made taking into account the year of publication of the papers, to see whether the rigor of simulation studies has improved across the years.

## 3. Results and discussion

### 3.1. Descriptive analyses

As a first analysis, Figure 1 shows the sharing of the papers reviewed by publication year, with the purpose of determining the trend in time of the publications dealing with DES in logistics and SCM. From that figure it can be seen that the number of studies published per year has significantly increased in 2019 and 2020, compared to the previous years, reaching a peak of 17 papers. These last two years include more than 30% of the sample of papers. Overall, the average number of publications per year is 9.25. The dashed read line in Figure 1 confirms a positive trend of the number of studies.

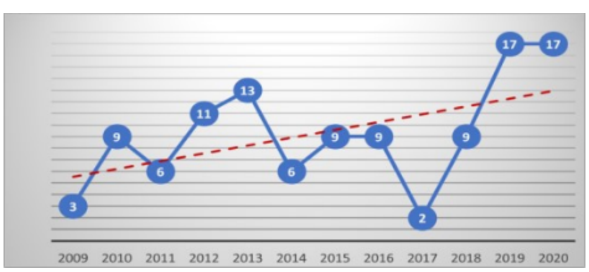


**Figure 1.** publications by year and trend line

The papers reviewed were published overall on 75 different journals, and 57 of these journals (76%) have published one paper only. Focusing on those journals that published more than one paper, *International Journal of Production Research*, *Vaccine* and *European Journal of Operational Research* were the journals that published the greatest number of studies (7, 6 and 4 respectively), and cover more than 15% of the sample of papers. The journal *Vaccine*, however, could seem to be an outlier, as it is classified among the medical journals and not among the engineering ones. On the basis of this consideration, the papers published by that journal were checked accurately, and were found to be almost all related to the usage of DES in vaccine supply chain, which makes them consistent with the intended aim of this review. The relevance of this journal to the DES literature is also confirmed by the recent review carried out by Vieira et al., (2020), that quotes numerous references from *Vaccine*.

Out of the 75 journals, the first one that focuses expressively on simulation is the *Journal of Simulation*, that ranked fourth with 3 papers published.

Overall, these outcomes suggest that DES is a methodology used for the optimization of logistics processes in various contexts, from industrial to medical ones, as reflected by the variety of journals that published studies on that topic.

### 3.2. Authors classification

The studies reviewed were published by 341 authors. The ABC cross-analysis made on these authors led to the results in Table 1, which, for the sake of brevity, provides the aggregated outcomes in terms of the number of authors belonging to each class. Most of the authors were classified as "weak" (classes BC, CC or CB, 39.59% of the sample), followed by "average" (classes AC, BB or CA, 27.27%), "good" (classes AB and BA, 23.75%) and "excellent" (class AA, 9.38%).

**Table 1.** authors classification

| | AA | AB | BA | AC | BB | CA | BC | CB | CC |
|---|---|---|---|---|---|---|---|---|---|
| TOTAL | 32 | 69 | 12 | 38 | 50 | 5 | 18 | 67 | 50 |

### 3.3. Journals classification

The same Pareto analysis made on journals led to the classification of the 75 sources in the classes proposed in Table 2. As this table shows, 10 journals (13.33%) are classified as AA; for the sake of clarity, these journals (which are actually all well-established in scientific literature) are *Applied Energy*, *Transportation Research Part E: Logistics and Transportation Review*, *International Journal of Production Research*, *Sustainability*, *International Journal of Production Economics*, *Biosystems Engineering*, *Computers and Industrial Engineering*, *Journal of Cleaner Production*, *Vaccine* and *European Journal of Operational Research*. The most numerous class, as expected in a Pareto analysis, is the last one (corresponding to categories BC, CB and CC) and includes 45.33% of the journals.

**Table 2.** journal classification

| | AA | AB | BA | AC | BB | CA | BC | CB | CC |
|---|---|---|---|---|---|---|---|---|---|

| TOTAL | 10 | 4 | 8 | 5 | 9 | 5 | 3 | 16 | 15 |
|---|---|---|---|---|---|---|---|---|---|

## 3.4. Papers classification

A further analysis was made of the number of citations received by each paper per year. The resulting classification, shown in Fig.3, highlights that one paper only can be considered a highly cited one, while most of the papers (87, 78.3% of the sample) have a very limited number of citations per year. It is interesting to note that the top-cited paper was published on a journal which is classified in the BB (average) class. This is a somehow counterintuitive result, as it is recognized in literature that there is a correlation between the citations received by an article and the prestige of the journal in which it has been published (Fazel & Wolf, 2017).

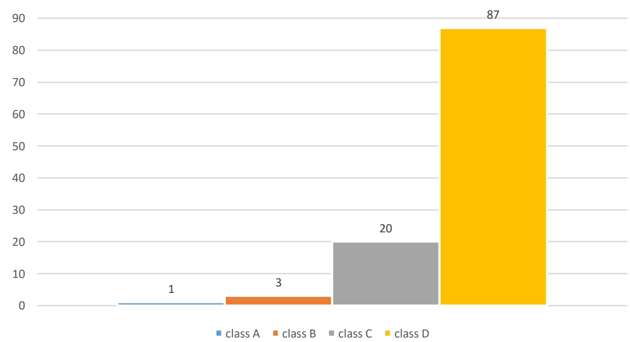


**Figure 3.** citation distribution.

## 3.5. Critical analysis

The critical analysis of the paper aimed at evaluating the extent to which the 14 phases listed in section 2.3 were applied by the papers reviewed. An extract of the classification and resulting TS is shown in Fig.4.

| Title | Year | 1 | 2 | 3 | | | 4 | 5 | | 6 | 7 | | | | 8 | TS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 3.1 | 3.2 | 3.3 | | 5.1 | 5.2 | | 7.1 | 7.2 | 7.3 | 7.4 | | |
| A cost optimisation strategy for a single warehouse multi-distributor vehicle routing system in stochastic scenario | 2011 | X | X | X | NO | NO | X | X | NO | X | NO | NO | NO | X | X | 8 |
| A discrete-event simulation model to test multimodal strategies for a greener and more resilient wood supply | 2019 | x | x | X | x | NO | x | x | X | x | NO | X | X | X | X | 12 |
| A formal method for analysing and assessing operational risk in supply chains | 2012 | x | x | x | NO | NO | X | X | NO | X | NO | X | X | X | X | 10 |
| A hybrid simulation modeling framework for regional food hubs | 2019 | X | X | x | NO | X | X | X | NO | X | X | X | X | X | X | 12 |
| A new simulation modelling approach to continuous berth allocation | 2013 | X | X | X | NO | X | X | X | NO | X | X | NO | X | X | NO | 10 |
| A numerical approach for inventory pre-positioning in emergency management | 2020 | x | x | x | X | X | X | X | no | x | NO | NO | X | X | X | 11 |
| A routing and location model for food waste recovery in the retail and distribution phase | 2018 | X | X | X | NO | X | X | X | NO | X | NO | X | X | X | X | 11 |
| A rule based strategy for cost minimisation in distribution planning | 2009 | x | x | x | NO | NO | X | X | NO | X | NO | X | NO | X | X | 9 |
| A Simulation Model Of Multi-Echelon Retail Inventory With Cross-Channel Product Returns | 2019 | X | X | x | x | x | X | X | X | X | NO | x | x | x | X | 13 |

**Figure 4.** classification of the papers reviewed (extract).

Overall, the 111 papers turned on to be classified as shown in Table 3; as can be seen from that table, most of the papers belong to the "good" class, and 19 papers were classified as "excellent".

**Table 3.** results of paper classification.

| Paper class | Number of papers | Percentage |
|---|---|---|
| weak | 2 | 1.80% |
| average | 21 | 18.92% |
| good | 69 | 62.16% |
| excellent | 19 | 17.12% |

Looking at the single simulation steps (Fig.5), it is immediate to see that steps 1, 2 and 4 are (almost) universally implemented in the studies reviewed, while others steps (e.g. 7.1 or 3.2) are almost systematically neglected by the authors.

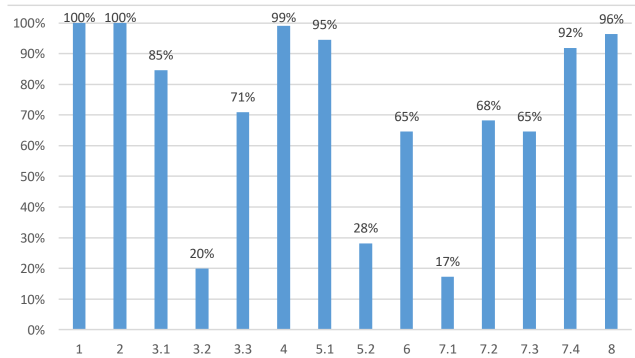


**Figure 5.** percentage of implementation of the simulation phases.

It is interesting to check whether the attention paid by the authors in developing simulation studies has somehow increased in time. Indeed, it is well-known that for a paper to be recognized in literature, some years are typically needed. Hence, it could be expected that, if the methodology proposed by Manuj et al. (2009) has been progressively recognized in literature, studies published in recent years are more likely to apply that approach in full. In line with this consideration, the distribution of the classes of papers in time was evaluated and depicted in Figure 6. What that figure shows, actually, is that there is not a particular trend of the classes as a function of the publication year. Papers classified as "good", for example, were found in all years of the timespan, with higher frequency compared to the remaining classes. Similarly, "excellent" papers span across the whole timespan. These outcomes obviously lead to reject the hypothesis of a trend of the quality of the papers in time, but at the same time, suggest that the average quality of simulation studies in logistics has always been quite high, which is anyway an interesting point.

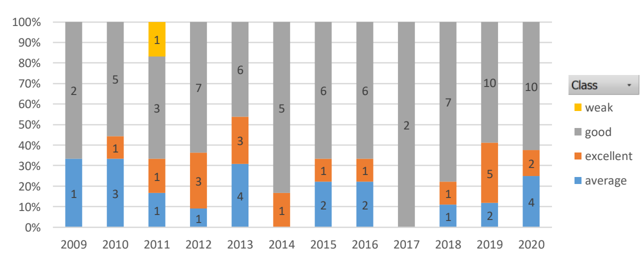


**Figure 6.** distribution of the paper classes in time.

A similar analysis has been made by crossing the paper class with the journal that published the study; the underlying assumption is that a more prestigious journal will probably publish more structured and rigorous papers. As the journals that published the papers reviewed in this study are numerous, for being more effective only journals that published more than 2 studies were taken into account in this analysis.

Results, shown in Figure 7, somehow support the above consideration, as it is immediate to see that here are journals that have published only "good" or a combination of "good" and "excellent" studies. These journals are also very well-established in the literature and publishing on that journals is challenging, which further supports the assumption of the relationship between the paper quality and the publication outlet.

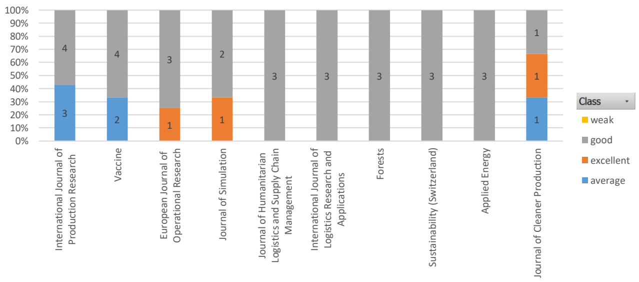


**Figure 7.** distribution of the paper classes as a function of the journal.

## 3.6. Synthesis of the results by matrixes

We now recall (cf. sections 2.2.2 and 2.2.3) that both the authors' and journals' classifications led to 4 classes, to which a score (from 1 to 4) was assigned. On the basis of the scores of the papers published, each author has been assigned a grade computed as the average score of the relating papers and rounded to the closest integer value for simplicity. Again the resulting grades were classified into 4 classes, on the basis of the numerical value; it is immediate to realize that the highest score of this class if 4 and the lowest one is 1. This additional score was combined with that resulting from the authors' classification just recalled, leading to 16 total classes, which were depicted in a matrix such as that proposed in Figure 8. Each cell in the matrix highlights, by colors (best: dark green; worst: dark red), the result of the authors' classification based on Pareto analysis (in rows) coupled with the authors' classification on the basis of the article score. Besides deepening the classification made previously, such a representation is useful for identifying the various paths for improvement, which is highlighted by the dashed lines in the matrix.

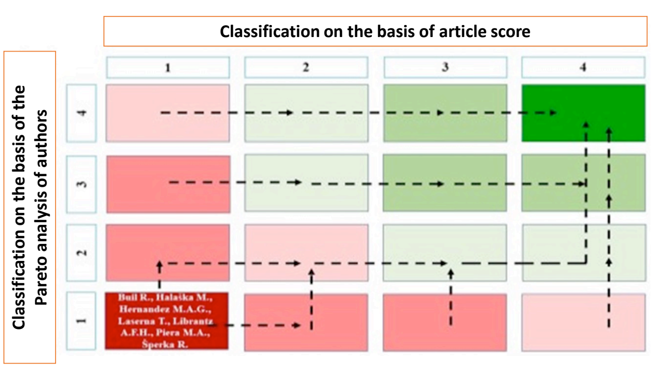


**Figure 8.** authors' matrix.

The same line of reasoning can be easily applied to journals, leading to the results in Figure 9.

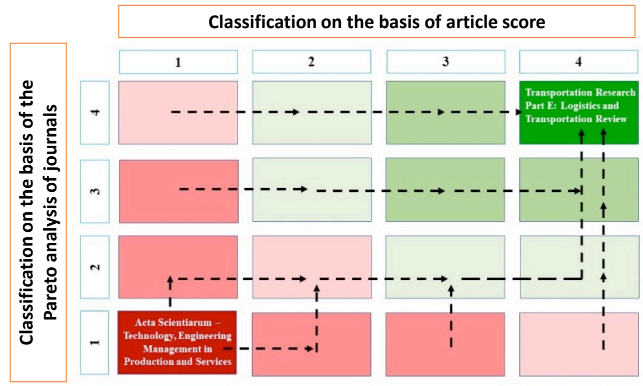


**Figure 9.** journals' matrix.

# 4. Discussion and conclusions

This paper has proposed a comprehensive evaluation of the literature relating to the usage of simulation in logistics and SCM. The analyses made in this paper start from the consideration that simulation had a tremendous development in scientific literature and is more and more used for solving a wide set of problems relating to logistics. The usage of this tool, at the same time, calls for the need for a structured approach to make the study understandable and sound. In line with these considerations, the procedure developed by Manuj et al. (2009), whose aim was exactly the improvement of the rigor of simulation studies, was taken as the reference for evaluating the quality of a sample of 111 studies, all applying DES in the context of logistics. In addition, the papers and authors that have dealt with simulation in logistics have also been classified on the basis of multiple logics, using tools commonly applied in bibliometric analyses (e.g. the number of citations per year or the prestige of a journal).

From a methodological point of view, this paper first of all has deepened the approach proposed by Manuj et al. (2009), by evaluating the single steps and identifying possible sub-steps, also on the basis of the findings available in literature. This analysis led a detailed list of 14 phases for a rigorous implementation of a DES model in logistics. Starting from this outcome, the paper then offers interesting insights in terms of classification methods for simulation studies and could form the basis for developing a structured approach for evaluating simulation studies. From a more practical perspective, the results of our analyses show that the quality of scientific publication relating to simulation usage in logistics and SCM is in general good and has not significantly changed in time. There are, however, some phases that have been frequently neglected by the authors. These findings, overall, lead to the consideration that probably, the structured framework by Manuj et al. (2009) has not (yet?) been taken as a reference when applying simulation to logistics problems. We therefore hope that the present study will also encourage authors to look at that framework when developing simulation studies, to further raise the quality of their research articles on DES application in logistics.

Starting from this paper, future research directions could be undertaken for getting an ever more detailed evaluation of the scientific literature dealing with simulation in logistics. Similarly, this study could be repeated in some years, using a longitudinal approach, to evaluate whether the rigor of scientific papers relating to simulation in logistics has improved in time.

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