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This is an expanded and significantly revised version of a paper presented at the 4th edition in the series of International Conferences on Control, Automation, and Diagnostics. It was held on October 7th-9th, 2020 in Paris, France.

The data that support the findings of this study are available from the corresponding author, Rony.djeunang-mezafack@grenoble-inp.fr, upon reasonable request.

Systematic Literature Review of Repair Shops: Focus on Sustainability

Maintenance activities are crucial for all manufacturing industries. To ensure availability and lifetime of production equipment, operations management and logistics support for maintenance need to evolve year after year. Besides, Centralized Maintenance Workshops are one of the most interesting approaches to reduce the cost and time required to repair faulty equipment. Generally known in the research community as ‘repair shops’, they aim to pool all the resources needed to repair defective equipment provided by different production sites. This paper aims to provide a comprehensive overview of repair shops and to present opportunities for future research with a focus on the circular economy context. The most relevant papers have been rigorously selected and analyzed, providing interesting reference materials on the subject. Repair shops are a set of workstations, operators, and spare parts inventories required to restore a group of failed production equipment. After detecting the origin of the failures, there are two options: either repair the equipment by restoring its defective components or replace the defective components with others in good working order. In the case of non-repairable components/equipment, circular strategies allow identification of components/equipment that could be restored and used to supply the spare parts warehouse.

Keywords: maintenance; circular economy; repair capacity; spare parts; repair by replacement; logistics.

1 Introduction

In almost all manufacturing companies, maintenance operations involve huge costs representing between 15% and 70% of the total production budget (Wang et al. 2008). For example, the U.S. spends more than $200 billion each year to maintain Navy equipment (Sleptchenko et al. 2019). In order to satisfy customers and keep up with the competition, the lives of industries depend on the availability of high-value capital assets to provide their services or to manufacture their products (Driessen et al. 2020). The last decades have been characterized by an exceptional change in the regulation of maintenance actions and associated budgets (Tiemessen and van Houtum 2013). Thus, many companies improved continuously and progressively their maintenance department (Basten and van Houtum 2014). Maintenance activities then became more complex than ever, prompting manufacturers to develop and implement new strategies for maintenance, better suited in the current context.

The main objective of maintenance is to reduce production equipment downtime in order to ensure good manufactured products or services using as few resources as possible (Chan and Prakash 2012). This study of defective production equipment with a process-oriented methodology is part of a broad approach called Zero-Defect Manufacturing (Psarommatis et al. 2020). Besides, in the case of a set of failed production equipment from different sites, pooling all the maintenance facilities in optimal locations called ‘repair shops’ is an intuitive approach which could help reduce maintenance costs and time (Guide et al. 2000). The literature review under study concerns repair shops also known as ‘Centralized Maintenance Workshops’, illustrated in Figure 1 and more adapted to companies with several production sites in different locations. This concept could be cost-effective when the distance between repair shops and production sites is not too great. For instance, repair shops have been set up in the French railway sector at the SNCF (Société Nationale des Chemins de Fer) (Hani et al. 2007) and in the UK aeronautical sector at CENTRAL (Center for Transport and Logistics) (Sanchez et al. 2020). In some cases, it would be better to outsource maintenance to each production site instead of relying on a repair shop to reduce the cost of transporting failed equipment. In this paper we are concerned with those cases where centralizing all the maintenance facilities is the best option (Driessen et al. 2020).
[t]Figure 1 near here [/t]

In the same context of economic growth, the circular economy aims to replace the ‘end-of-life concept’ by closing material loops and extending product life (Batista et al. 2019). It is one of the recent, promising solutions to deal with the limitations of repair shops, allowing the reuse (Smith and Dekker 1997), the remanufacturing (Abbey et al. 2018) or the recycling (Bressanelli et al. 2019) of some components in a repair shop. Indeed, one of the biggest challenges of repair shops is to reduce waste in terms of time and resources used in maintenance activities (Basten and van Houtum 2014). Unfortunately, existing frameworks simply consider equipment supplied by multi-site production to be defective or not. However, defective equipment may have components in different states of availability. Hence, these frameworks do not yet consider the opportunity to reintegrate some components of this defective equipment into the value chain (Simeu Abazi et al. 2012; 2014).

To better understand implementation of the repair shop, two interesting research questions are: first, how are repair shops developed? And second, what is the influence of the circular economy context? From this, four sub-questions can be identified, namely:

(1) Organization: How should be design a better model for a repair shop?
(2) Operation: What are the different operations involved in a repair shop?
(3) Material Flow: What is the material flow inside repair shops?
(4) Circular Economy: How could circular strategies be implemented in a repair shop?

To answer these questions, our study aims at conducting a literature review of repair shops with a focus on sustainability. This paper provides a synthesis and an analysis of the state-of-the-art, and presents directions for future research. The methodological approach is detailed in section 2. It consists in, first, defining and combining the relevant keywords from the most highly ranked journals in Industrial and Manufacturing Engineering. Second, in searching papers in defined databases and third, in using filters with inclusion and exclusion criteria, in order to obtain representative and relevant papers of the literature. After filtering, a cross-analysis is conducted throughout the resulting papers. Section 3 presents the results of the literature review, while the opportunities for future research are given in section 4.

2 Research Methodology

2.1 Defining and combining the relevant keywords

2.1.1 Selection of keywords

This step is crucial for the research, as selecting relevant keywords is the foundation of the literature review. First of all, the subject under study has two main keywords: "repair shop" and "centralized maintenance workshops". The aim here is to find the most frequently used and representative keywords related to these two keywords in the literature. For this purpose, it is necessary to choose a database that allows the extraction of keywords from a high number of papers. Google Scholar, for example, does not yet allow this. The Scopus database, on the other hand, offers this possibility. Scopus was therefore chosen as a suitable database to find relevant keywords for the literature review. As detailed in Figure 2, a first search of papers in Scopus with the two main keywords in their full-text yields about 14000 other keywords. To reduce this number and thus allow a more accurate choice of relevant keywords, we use the method of (Dibbern et al. 2004), which proposes to reduce the search to the 25 best-ranked journals in the studied field (Industrial and Manufacturing Engineering). The ranking used is that of (“SJR: Scientific Journal Rankings.” 2020). It reduces the number of keywords to 125.

[t]Figure 2 near here [/t]

The next step is to select a reduced number of relevant keywords from these 125 keywords. This was done manually, with the help of the software Vosviewer (Van Eck and Waltman 2010) which makes it possible to visually represent the relationship network of the 125 keywords. We chose more intuitively those that are relevant to the subject, as illustrated in Figure 3. Other similar software could be suitable as the aim is simply to acquire a broad idea of the keywords most used. The default settings of Vosviewer are maintained. The radius of each circle is proportional to the occurrence of each keyword in the literature. We have represented the keywords with at least two occurrences. From Figure 3, it can be observed that Remanufacturing and Spare parts are the main clusters of the keywords. The first is more related to circular strategies and sustainable development (Reuse, Recycling, Reverse logistics, Sustainability), while the second relates more to repair shop activities (Inventory, Maintenance, Repair). Evolution of the keywords related to the two clusters is pretty much the same in terms of years from 2005 to 2020. However, in terms of numbers, the group containing the circular economy has more new keywords than the group containing repair shop activities. Table 1 presents the 15 keywords manually selected from the 125 keywords according to the four topics of repair shops obtained from our above research sub-questions (Organization, Operation, Material Flow; and Circular Economy).

[t]Figure 3 near here [/t]

[t]Table 1 near here [/t]

2.1.2 Combination of keywords

After obtaining keywords, they are combined to better focus the exploration of repair shops. Presented in Table 1, coupling of keywords led to 39 different combinations by using the operators ‘AND’ and ‘OR’ as shown in Figure 2. In fact, combining keywords allows to better specify the research. The expected papers must always talk about "repair shop" or "centralized maintenance" or "maintenance workshops" which are the focal point of the subject. This is the reason why the expression: 'AND (Centralized Maintenance OR Maintenance Workshop OR Repair Shop)' is used in all the combinations. To obtain keywords representing as far as possible the four research questions, the keywords of each topic (Circular Economy, Organization, Operation and Material Flow) are joined with the previous expression.

2.2 Research databases

While relevant papers can be found in many sources, filters differ from one source to another. Since the search is automatic and is run in a large number of papers, only the sources that allow to filter full texts, titles or abstracts, are considered as presented in Figure 4. For example, using the source Emerald, 113 papers are found containing at least one of the combined keywords in their full text and 18 papers containing these keywords in either their abstracts or their titles. Thus, 6 databases without any restriction of journals were used to search for the papers (Emerald, HAL, IEEE, Science Direct, Web of Science and Wiley).

[t]Figure 4 near here [/t]

2.3 Defining filters

To finally obtain relevant papers for the systematic literature review, the filters presented in Figure 4 are used. Indeed, by progressively using exclusion and inclusion criteria, all the papers concerned by the subject under study and which have at least one of the combined keywords in either their titles or their abstracts are included first. This allows a reduction from 3791 papers to 355 papers found in all unrestricted journals.

Second, all the duplicated items and proceeding papers are removed manually, resulting in 124 remaining items. Finally, papers that do not deal with the process-oriented models are excluded manually. For example, the papers (Sanjuán-Herráez et al 2012; Wagner et al. 2021) contain combined keywords in their abstracts or keywords but they are product-oriented. The quality of restored equipment is studied whereas the literature review under study focuses on the repair shop process. Other papers such as (Parker et al. 2012; Whittaker et al. 2003) have been excluded as they deal with the health and safety of operators. 54 papers are thus retained as presented in Figure 4.

3 Results of content analysis

3.1 Classification and evolution of repair shops over the years

The 54 papers under study were written between 1984 and 2020. To acquire more information on the classification and annual evolution of publications, the papers are grouped according to the 4 main topics of the subject (Circular Economy, Organization, Operation and Material Flow). It should be pointed out again here that a paper is considered to be part of a topic when either its title or its abstract or its keywords contain the keywords related to that topic in Table 1. For example, papers dealing with organization are identified with the keywords: “Centralized Maintenance”; “Maintenance Workshop” and “repair shop”. On the other hand, papers dealing with Operation are identified with the keywords: Maintenance and Repair. As a remark for classification in the topics, the repair process is a part of the circular economy (Riisgaard et al. 2016) and all the 54 papers deal with this process. It may be logical to conclude that all these papers use circular strategies. However, not all the papers clearly specified how the material flow loop is closed. In these cases, the following are considered to be circular: papers that either integrate circular strategies other than repair, and papers with repair processes that clearly describe their closed loops. Then the number of papers published each year in each topic is counted. Figure 5 is thus obtained and it should be noticed that a paper can be part of several topics at the same time. For example, if a paper deals with both circular economy and material flow, in Figure 5 this paper will be counted in both green (circular economy) and yellow (material flow), as half a paper for each color.

[t]Figure 5 near here [/t]

The 54 papers can be classified into three main periods of time. As illustrated in Figure 6, the first period, from 1984 to 1999, shows the first papers addressing repair shop activities, but with a low density of publication in time. The main keywords are scheduling, simulation, batching, and repairables. The second period, from 2000 to 2012, is characterized by an increase in the number of papers published on repair shops, with at least one every 2 years. The central keyword is “spare parts” linking other main keywords: maintenance, inventory and remanufacturing (circular economy). The third period, from 2013 to 2020, is the most productive in terms of publications. The central keyword has become “repair shop”.

These initial results reflect the fact that interest in repair shops has grown significantly over the years. However, even though many keywords related to circular strategies are found in the domain, their implementation in repair shops as yet lacks proper study. Indeed, since 2005, there are only nine relevant papers on the circular economy topic in the literature, which accounts for less than 15% of papers. However, it can be highlighted that almost all the years integrating the circular economy, such as 2005, 2011, 2013, 2019 and 2020, have the highest level of publications.

[t]Figure 6 near here [/t]

3.2 The most cited papers and journals related to repair shops

To measure the impact of repair shop papers in the research community, the average number of citations is evaluated per year for each paper. This is calculated by dividing the total number of citations found in Google Scholar from the year of publication to 2020 by the number of years elapsed. Among the 54 relevant papers, there are a total of 31 papers that have been cited at least once a year, accounting for 57% of papers since their publication. The previous percentage indicates that the papers have real use for research progress. Hence, the development of knowledge about repair shops is strong, and their improvements are certainly reliable. Furthermore, the most cited papers are selected by using the Pareto chart which shows 20% of the papers representing 80% of all the citations. Figure 7 and 8 present the results obtained for the papers addressing repair shops without circular strategies (Figure 7) and with circular strategies (Figure 8). This process leads to 16 papers in Figure 7 representing 3 topics (Organization, Operation and Material Flow) and 4 papers in Figure 8 linked to Circular Economy). Thus, on average per topic, the circular economy is well cited by authors, as often as the other topics, despite the small number of its papers, if we consider the fact that the circular economy was introduced only recently, in 2005, whereas the other topics have been in use since 1984.

[t]Figure 7 near here [/t]

[t]Figure 8 near here [/t]

The journals in which the studied papers are published are presented in Table 2. The 54 papers are distributed into 30 different journals, demonstrating the diversity of publication sources. IJPE with nine papers and EJOR with eight papers are the journals with the highest number of papers in the studied field. Other interesting journals generally contain three relevant papers (for example: AOR) or two relevant papers (for example: IJPR). Most of the other journals have one relevant paper on the subject. In addition, to obtain information on the impact of journal publications, each journal was assigned the sum of the average number of citations per year of all its papers under study (‘c/y’ in Table 2). For instance, IJPE is cited 41 times on average per year. When focusing on circular strategies, IJPE and EJOR are the most-cited journals for repair shops.

[t]Table 2 near here [/t]

3.3 Contribution of the papers

Repair shops aim to reduce downtimes as much as possible in the event of equipment failure (Basten and van Houtum 2014). Over the years, the papers provided by authors and journals have had a significant impact on the improvement of repair shops, as discovered with the previous results. To go further in the study of the contributions of these 54 papers, as the papers were already grouped into the 4 topics (Circular Economy, Organization, Operation and Material Flow), we read the full text of each paper and extracted information that seemed to be important for the subject. This analysis led to Tables 3 and 4. In Table 3, the papers are classified according to the topic they address: organization, operation, material flow and/or circular economy. Table 3 shows, among others, that 51 papers address at least two of the topics we defined, which account for 94% of the papers under study, and that 30 papers (56%) deal with the three topics of the repair shops, whereas only 9 papers (17%) deal with circular economy. Table 4 details the different contributions within each topic. It is worth noting that the contributions of the circular economy, also known as circular strategies, are presented considering the three other topics of the repair shop (Organization, Operation and Material Flow). The different contributions are discussed below, with a focus on circular strategies.

[t]Table 3 near here [/t]

[t]Table 4 near here [/t]

3.3.1 Organization

As shown in Table 4, repair shop organization can be identified by its repair capacity and its spare parts inventory. 39 of the 54 papers deal with this topic, accounting for a percentage of 72%.

A repair capacity is globally considered to be the ability to handle failures throughout two-stage service processes consisting of an inspection and a repair phase (Driessen et al. 2020). Repair shop capacity consists of multiple parallel servers where each server could have diverse skills (can repair different types of failed parts) (Sleptchenko et al. 2019). It allows repair shop activities to be conducted in two workshops: a central maintenance workshop (repair process) and a mobile maintenance workshop (inspections and replacement) (Simeu-Abazi et al. 2011). More basically defined, repair shop capacity is a set of centralized facilities for maintenance in the optimum location (Simeu-Abazi et al. 2014). Centralization mainly considers scheduling and policies such as maintenance activity scheduling, scheduling under emergent failures, priority policies, and overtime policies (increased repair capacity as needed to offset short-term demand fluctuations) (Scudder and Chua 1987; Al-Refaie et al. 2020). Furthermore, a repair shop capacity could be simplified and modeled as a single server, considered finite or infinite depending on the facilities (Sleptchenko et al. 2002). In addition, it is necessary to highlight that the cognitive factors (the characteristics of a person that affect performance and learning) of operators and the deterioration of facilities impact repair capacity (Azadeh et al. 2017).

The spare parts inventory can be considered as a single or a number of warehouses stocking several spare parts, also known as repairables (Turan et al. 2018). It could be for the same or for different types of machines (each machine has many different parts). The aim is to determine the initial spare parts inventory levels, the impacts of limited or unlimited capacity storage, the impact of the priority policies in spare parts networks, spare parts provisioning, and the Economic Order Quantity (EOQ) (Taleizadeh et al. 2016). When the requests for parts are not met from stock, backorders of spare parts could be triggered (García-Benito and Martín-Peña 2020).

From the point of view of the circular economy, organization of repair shops has some extensions. Among the 9 papers concerning circular strategies, 6 deal with the organization problems, accounting for a percentage of 67%. Organization of repair shops integrating circular strategies allows the system loop to be closed with a base stock of spare parts (Spanjers et al. 2005), also called an interchangeable inventory (Li et al. 2013). Indeed, with a circular economy, the spare parts stock is not only made up of new components but also of repaired components. Remaining Useful Life Prediction is a way of studying the deterioration of components or equipment throughout their life cycle (Shi et al. 2020).

3.3.2 Operation

Operation in repair shops concerns preventive maintenance (Simeu-Abazi et al. 2014) or corrective maintenance (Simeu-Abazi and Ahmad 2011). Table 4 shows that all 54 papers deal with operation. However, the authors deal more with corrective maintenance than with preventive. Only 4 papers among the 54 implement the preventive approach (Smith and Dekker 1997; de Smidt-Destombes et al. 2004; Safaei et al. 2011; Buyukkaramikli et al. 2015). Generally, in both cases, the main process used is “repair by replacement”. This consists in replacing a failed component with a functioning spare part (Basten and van Houtum 2014). The term SRU (Shop Replaceable Units) (Sleptchenko et al. 2019) is used to identify the failed component to be replaced, while LRU (Line Replaceable Units) refers to the spare part. Instead of LRU, (Tiemessen and van Houtum 2013) use the term SKU (Stock Keeping Units). When the failure rate of production equipment has reached a certain value, it may be advantageous, for less time and money, to perform preventive maintenance (Smith and Dekker 1997).

In general, a circular economy embeds several strategies. It should be noted here that all 9 papers concerning the circular economy deal with operation. The main operations specific to the circular economy and mentioned in the papers studied are: remanufacturing (Kleber et al. 2011), reuse, and recycling (Turkeli et al. 2019), (Riisgaard et al. 2016). These operations give a second life to components from discarded equipment. Circular strategies allow the recovery of irreparable parts as good as new throughout the remanufacturing provided by the OEM (Original Equipment Manufacturer). (Riisgaard et al. 2016; Turkeli et al. 2019) analyze the business ecosystem of cell phone repair shops that integrate closed-loop design through repair, remanufacturing or recycling. Weibull distribution is applied to analyze the life cycle of the equipment. It is important to note that repair, while fundamental to the repair shop, is considered a circular strategy.

3.3.3 Material Flow

Material Flow mainly consists of spare parts (Driessen et al. 2020) and equipment derived from different production sites (Simeu-Abazi and Ahmad 2011). Table 4 shows that 42 of the 54 papers deal with this topic, accounting for a percentage of 78%. Spare parts are a fundamental element in the repair shop (van Jaarsveld et al. 2015). Without them, it would not be possible to repair by replacement (Buyukkaramikli et al. 2015). However, setting up a spare parts warehouse requires an initial investment (Tiemessen and van Houtum 2013). The demand for spare parts takes place according to the Poisson process at a constant rate (Turan et al. 2018). It requires a supply system and allocation optimization (Li et al. 2013). The demand for spare parts can be state-dependent (this means that it depends not only on the failure rate but also on the state of the failed equipment) (Sahba et al. 2018). The repair shop allows grouping of defective equipment from several production sites (Liang et al. 2013). Collection of failed equipment is coordinated with or without batching policies (batch size is the number of defective parts waiting to be repaired once) (Chua et al. 1993). On different production sites, equipment fails from time to time (irregularity) or regularly (Smith and Dekker 1997). In the case of regular failures, equipment reaches the repair shops according to an exponential distribution with a constant failure rate or an increasing failure rate (Sleptchenko et al. 2003). Multiple failure levels could be observed (Scudder et al. 1984).

The circular economy aims to close the material flow loop and maximize the product lifetime (Turkeli et al. 2019). For example, irreparable components are sent to the OEM for remanufacturing and, after the process, the item is supposed to be brand new (Riisgaard et al. 2016). A buyback of failed parts is offered by the OEM (Kleber et al. 2011). Circular strategies consist of a closed-loop system of spare parts integrating remanufactured items (Luh et al. 2005) and repaired items (Adan et al. 2009).

3.4 Methods used by the papers

In order to minimize the total costs of maintenance activities and increase the availability and maintainability of equipment, repair shops have always been continuously improved (Sleptchenko et al. 2002). Table 5 classify the 54 papers under study according to the method used by the authors (Performance evaluation or optimization). Performance evaluation of repair shops is carried out through analytical or simulation methods. Queuing networks is the methodology most commonly used (20 papers), accounting for 37% of all papers. This method provides decision-support tools for the allocation of maintenance resources. However, it is best suited to a stochastic environment where demands and services are uncertain. Other methods used for performance evaluation are Fuzzy Data Envelopment Analysis (Azadeh et al. 2017), Data Envelopment Analysis (Azadeh et al. 2013), Discrete Event Simulation (Tiemessen and van Houtum 2013), Stochastic Petri Nets (Simeu-Abazi and Ahmad 2011; Li et al. 2013), and Monte Carlo Simulation (Luh et al. 2005). All these methods are mostly uncertain but deterministic and are used to evaluate either the average time of failed equipment in the system (Chua et al. 1993) or the mean sojourn time of each equipment item inside the repair shops (Kim and Lee 2014) or the average waiting time of failed equipment (Azadeh et al. 2013). The average utilization of the repair shops is also measured (Sleptchenko et al. 2002).

[t]Table 5 near here [/t]

Considering the optimization of the performance indicators of the repair shops, it could be observed that Linear or Non-linear Programming (16 papers) are the algorithms most commonly used, accounting for 30% of all papers. The objective is to minimize either the expected waiting time in repair shops (Safaei et al. 2011; Liang et al. 2013; Aramon and Beck 2014; Dreyfuss et al. 2018; Al-Refaie et al. 2020; Driessen et al. 2020) or the spare parts inventory (Adan et al. 2009; Basten and van Houtum 2014; Jaber et al. 2014; van Jaarsveld et al. 2015; Taleizadeh et al. 2016; Arts 2017; Sleptchenko et al. 2019) or the maintenance costs (van Ommeren et al. 2006; Simeu-Abazi and Ahmad 2011; Shivasankaran et al. 2013; Turan et al. 2018; Sanchez et al. 2020). The advantage of both methods is that they are exact, even though the repair shop model needs to be simplified as much as possible to reduce calculation complexity. The other algorithms used are either heuristics or metaheuristics, such as Genetic Algorithm (Sleptchenko et al. 2019), Ant Colony Optimization (Hani et al. 2007), Simulated Annealing Method (Shivasankaran et al. 2013), and Greedy Optimization (Turan et al. 2020). The latter algorithms, although uncertain, make it possible to extend the variables of the repair shops and to build models that reflect reality.

From the circular economy point of view, the methods for both performance evaluation and optimization are the same except in papers (Riisgaard et al. 2016; Turkeli et al. 2019), who are the only ones to survey the implementation of circular strategies in several repair shop companies. The authors (Kleber et al. 2011) and (Shi et al. 2020) use non-linear programming, the first to optimize spare parts inventories and the second to reduce equipment downtime by predicting the remaining useful life of the equipment. Models using a non-linear algorithm are generally simplified, and the simulation results obtained have non-negligible errors that could be reduced with other methods. For instances, (Spanjers et al. 2005) use queuing networks to evaluate spare parts inventory levels maximizing equipment availability. (Li et al. 2013) use Stochastic Petri Nets (SPNs) to evaluate the average utilization rate of servers, the initial inventory level, and the average waiting time of equipment in a repair shop. (Sahba and Balcıog˜lu 2011) carry out optimization of spare parts inventories considering the impact of transportation delay in a closed-loop system using the MVA (Mean Value Analysis) algorithm. Other authors choose to combine several methods to obtain results that can be compared, and work towards a trade-off between model size and results accuracy.

Thus, (Assadi et al. 2019) combine Queuing Networks and the MEBOTT (Modified Extended Bottleneck) algorithm to evaluate and optimize the average utilization of servers and the average waiting time of equipment in spare parts supply system with Closed-Loop. (Luh et al. 2005) combine Monte Carlo simulation and Lagrangian relaxation to measure and minimize Closed-Loop inventory holding costs.

3.5 Industrial application of repair shops

Repair shops are implemented in several industries. Table 6 classifies the papers embedding industrial application with indications on the industry considered, the company, the country and the proposed solutions. The first remark that can be made concerns the diversity of countries involved in the industries represented (Aircraft, Railway, Gas industry, Mobile phone). The aircraft industry is the most present with almost 50% of contributions among the selected papers. The main aims are to manage the spare parts stock and organize maintenance operations. The sectors involved are both private and public. Thus, the real-life case study of repair shops shows that profitable models already exist. However, the majority of these models implemented produce waste that can be optimized through circular strategies. Fortunately, except for the aircraft industry, other industries that have taken up the sustainability challenges, have begun to integrate the circular economy concept, as shown in Figure 9. It is a fact that, in the aircraft industry, the circular economy is more difficult to implement from a safety point of view due to the uncertain quality of equipment in second life. The railway industry and the gas industry are the most balanced in terms of contributions.

[t]Figure 9 near here [/t]

[t]Table 6 near here [/t]

4 Orientation for future research

Since 1984, repair shops have evolved year after year with research development. The aim has always been to restore failed equipment from different production sites as quickly as possible and at minimum cost.

4.1 Sustainable repair shop models

Over the years, researchers have had to improve their repair shop models to deal with time and cost issues. The literature states that centralizing maintenance resources to reduce costs is a successful approach applied in many industries. However, centralization results in new problems related to the designing of a generic model considering an optimal routing of maintenance activities between production sites and repair shops. On the other hand, the grouping of failed equipment offers the opportunity to restore components from end-of-life equipment for use in other functional equipment. Yet, looking at the 54 papers studied, it can be observed that, the majority (83%) of models do not consider the life cycle of components or equipment. Hence, when components/equipment reach their End-Of-Life (Considered to be irreparable), they are discarded, thereby generating environmental and cost issues. Besides, even the seven repair shop models found in the literature with circular economy keywords do not yet really integrate circular strategies. The circular economy remains an under-explored area for repair shops. Improvement of models through performance evaluation and optimization tools could enable development of repair shops. For example, instead of discarding irreparable components, it would be interesting to carry out the remanufacturing process to reintroduce these components into the value chain. With a closed-loop system, repair shop models should integrate the fact that spare parts can be either brand new, repaired, remanufactured or recycled.

4.2 Sustainable operations

All maintenance operations were centralized into repair shops in order to reduce costs by pooling all resources. The papers under study, found with circular economy keywords, suggest some interesting strategies. It would be beneficial to integrate them extensively into the operations of repair shops without circularity:

- Remanufacturing/Refurbishing: when a component is not repairable but when, after the recovery process, it can be used for the same function.
- Recycling/Repurposing: when the product will be used for another function.

Indeed, in a product life cycle, a brand-new component is manufactured with virgin materials (raw material) and, after the assembly process, equipment ready-for-use is obtained. When a piece of equipment fails, the disassembly and repair processes allow it to be reused. As soon as these two processes are no longer able to restore failed equipment/components, remanufacturing could be useful without changing their functions. If remanufacturing is no longer of interest, recycling could be used to convert components into new ones with new functions.

Besides, centralized maintenance operations reduce the number of operators required. The question thus arises of the impact of centralization of repair operators. The emergence of Artificial Intelligence and the Internet of Things could enable efficient management of centralized operations. Maintenance resources could be interconnected to facilitate decision-making in the repair shop.

4.3 Sustainable material flow

Repair shops contain equipment flow, components, and spare parts. A spare part and a component are parts of equipment. The relevant papers integrating circular economy consider that spare parts can be obtained from raw material or restored components. Cost and environmental issues will be reduced if all the repair shops integrate many spare parts supply sources. So, the inventory will contain either new spare parts from the OEM or repaired components or remanufactured components or recycled components. It would be interesting to study the priority rules governing the choice of spare parts depending on their reliability. Indeed, circular strategies have an impact on product quality. It means that a paradigm shift is required regarding the value of components/equipment in second life from a functional and ergonomic perspective.

Moreover, for performance evaluation, instead of using Exponential Distribution to model the behavior of equipment arriving at a repair shop, it would be more realistic to extend it to other distributions to describe the entire lifecycle of spare parts. Questions also arise as to optimizing material flow inside a repair shop, which will probably increase with the loop inserted by circular strategies.

5 Conclusion

This paper provides an overview and an analysis of the literature on repair shops focusing on the circular economy. Obviously, manufactured products have a limited lifetime, and the main purpose of repair shops is to extend this by taking out the failed components and replacing them with ready-for-use components based on their condition. Since 1984, although the objective of the repair shops has remained the same over the years, the repair shop strategies have progressively evolved.

Considering the papers under study and the case studies found during this literature review, it is clear that interest in repair shops is growing. Centralization of maintenance operations is an opportunity already seized by some companies to reduce costs and maintenance time. The circular economy is being progressively integrated and could contribute significantly to the sustainability of repair shops. Authors used performance evaluation and optimization tools to manage the problems arising in repair shops and produce new and more efficient models. Thus, this literature review provides the necessary references to contribute to orientation of research and development of repair shops. Based on the research questions, we conducted a comprehensive overview and a cross-analysis of the literature. This highlighted an emerging concept proving its worth in industry and may well be of increasing interest to the scientific community in the coming decades through the circular economy.

Yet, this study has some limitations. First, the concept studied falls more into the scope of industrial research than that of academic research. However, the databases used to search for papers are closely linked to academia and restrict the relevant papers. A survey conducted in companies could extend the results and provide more relevant data on repair shops. Second, the research questions refer to an inductive approach used as implementation of circular economy in repair shops is new in the studied field. With the growing number of papers published on the subject, an abductive approach in the coming years could yield other results. Finally, it would also be interesting to study to what extent centralization of resources could be associated with the maintenance of other disciplines such as the Internet of Things and Artificial Intelligence.

Acknowledgements

This work was supported by the French government; through the Université Grenoble Alpes and the IDEX Grenoble (Cross Disciplinary Program Circular) under Grant C7H-ID17-PR28-CIRCULARWP1.

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Table 1. Combination of keywords used in the study field

	Circular Economy	Repair shop		
		Organization	***Operation***	***Material Flow***
Keywords	Remanufacturing; Circular Economy; Recycling; Sustainability; Reverse Logistics; Reuse; Sustainable;	Centralized Maintenance; Maintenance Workshop; Repair shop	Maintenance; Repair	Inventory; Logistics; Spare parts
Combination of keywords	(Remanufacturing OR Circular Economy OR Recycling OR Sustainability OR Reverse Logistics OR Reuse OR Sustainable) AND (Centralized Maintenance OR Maintenance workshop OR Repair shop)	Model AND (Centralized Maintenance OR Maintenance workshop OR Repair shop)	(Maintenance OR Repair) AND (Centralized Maintenance OR Maintenance workshop OR Repair shop)	(Inventory OR Logistics OR Spare parts) AND (Centralized Maintenance OR Maintenance workshop OR Repair shop)

Table 2. Journals with the studied papers

References	Journals	Circular Economy	c/y
(Sleptchenko et al. 2002, 2019; de Smidt-Destombes et al. 2007; Kleber et al. 2011; Tiemessen and van Houtum 2013; Jaber et al. 2014; Taleizadeh et al. 2016; van Ooijen et al. 2019 ; Driessen et al. 2020)	International Journal Of Production Economics (IJPE)	●	41.4
(Basten and van Houtum 2014)	Surveys In Operations Research And Management Science (SORM)		17.9
(Chua et al. 1993; Smith and Dekker 1997; Sleptchenko et al. 2005; Hani et al. 2007; Sahba and Balcıog˘lu 2011; Arts 2017; García-Benito and Martín-Peña 2020; Sanchez et al. 2020)	European Journal Of Operational Research (EJOR)	●	14.6
(Safaei et al. 2011; Liang et al. 2013; Buyukkaramikli et al. 2015)	Annals Of Operations Research (AOR)		10.3
(de Smidt-Destombes et al. 2004; Simeu-Abazi and Ahmad 2011)	Reliability Engineering & System Safety (RESS)		9.4
(Kim and Lee 2014)	Applied Mathematical Modeling (AMM)		5.9
(Mabini and Christer 2002; Sleptchenko et al. 2003)	Journal Of The Operational Research Society (JORS)		5.5
(Riisgaard et al. 2016)	European Journal Of Sustainable Development	●	5.2
(Scudder and Chua 1987; van Jaarsveld et al. 2015)	Omega		5.1
(Adan et al. 2009 ; Li et al. 2013)	Asia-Pacific Journal Of Operational Research	●	3.6
(van Ommeren et al. 2006; Dreyfuss et al. 2018; Turan et al. 2020)	Computers & Operations Research		2.8
(Luh et al. 2005)	IEEE Transactions On Automation Science And Engineering	●	2.7
(Aramon and Beck 2014)	Journal Of Artificial Intelligence Research		2.6
(Lin et al. 2014 ; Guide et al. 2000)	International Journal Of Production Research (IJPR)		2.2
(Azadeh et al. 2013)	Journal Of Loss Prevention In The Process Industry		1.8
(Sahba et al. 2013)	IIE Transactions		1.4
(Scudder 1984)	Management Science		1.3
(Turkeli et al. 2019)	Energies	●	1.0
(Shivasankaran et al. 2013)	International Journal Of Computational Intelligence Systems		1.0
(Spanjers et al. 2005 ; Sahba et al. 2018)	Or Spectrum	●	1.0
(Sanchez et al. 2020)	Transportation Research Part B		1.0
(Keizers et al. 2001)	Naval Research Logistics		0.8
(Turan et al. 2018)	Computers & Industrial Engineering		0.7
(Azadeh et al. 2017)	International Journal Of Advanced Manufacturing Technology		0.5
(Scudder 1985)	Journal Of Operations Management		0.5
(Simeu-Abazi et al. 2014)	Journal Of Manufacturing Technology Management		0.4
(Öztürk 2020)	European Journal of Industrial Engineering		0.0
(Assadi et al. 2019)	IEEE Transactions On Reliability	●	0.0
(Al-Refaie et al. 2020)	Journal of Civil Engineering and Management		0.0
(Shi et al. 2020)	Mathematical Problems in Engineering	●	0.0

c/y = Average number of citations per year

Table 3. Classification of the studied papers within each topic

Repair Shops				Results		
Organization	***Operation***	***Material Flow***	**Circular Economy**	***Nb.***	***%***	***References***
●	●	●		25	46%	(Scudder 1984, 1985 ; Chua et al. 1993 ; Smith and Dekker 1997 ; Guide et al. 2000 ; Sleptchenko et al. 2002, 2005, 2019 ; Mabini and Christer 2002 ; de Smidt-Destombes et al. 2004, 2007 ; Adan et al. 2009 ; Simeu-Abazi and Ahmad 2011 ; Sahba et al. 2013 ; Jaber et al. 2014 ; Lin et al. 2014 ; Simeu-Abazi et al. 2014 ; Basten and van Houtum 2014 ; Buyukkaramikli et al. 2015 ; Van Jaarsveld et al. 2015 ; Taleizadeh et al. 2016 ; Arts 2017 ; Driessen et al. 2020 ; Turan et al. 2020 ; García-Benito and Martín-Peña 2020)
	●	●		9	17%	(Scudder and Chua 1987; Sleptchenko et al. 2003; Van Ommeren et al. 2006 ; Liang et al. 2013 ; Tiemessen and van Houtum 2013 ; Turan et al. 2018 ; Dreyfuss et al. 2018 ; Sahba et al. 2018 ; van Ooijen et al. 2019)
●	●			8	15%	(Keizers et al. 2001 ; Hani et al. 2007 ; Safaei et al. 2011 ; Azadeh et al. 2013, 2017 ; Aramon and Beck 2014 ; Al-Refaie et al. 2020 ; Öztürk 2020)
●	●	●	●	5	9%	(Luh et al. 2005 ; Spanjers et al. 2005 ; Sahba and Balcıog˘lu 2011 ; Li et al. 2013 ; Assadi et al. 2019)
	●	●	●	3	6%	(Kleber et al. 2011 ; Riisgaard et al. 2016 ; Turkeli et al. 2019)
	●			3	6%	(Shivasankaran et al. 2013 ; Kim and Lee 2014 ; Sanchez et al. 2020)
●	●		●	1	2%	(Shi et al. 2020)
39	54	42	9 (Luh et al. 2005 ; Spanjers et al. 2005 ; Kleber et al. 2011 ; Sahba and Balcıog˘lu 2011 ; Li et al. 2013 ; Riisgaard et al. 2016 ; Assadi et al. 2019 ; Turkeli et al. 2019 ; Shi et al. 2020)	54	100%	

Table 4. Contributions in the three main research topics

References	Organization			Operation			Material flow		
	Repair shop capacity	*Spare parts inventory*	*Circular strategies*	*Corrective Maintenance*	*Preventive Maintenance*	*Circular strategies*	*Spare parts*	*Failed equipment*	*Circular strategies*
Simeu-Abazi et al. 2014; Sleptchenko et al. 2019; Turan et al. 2020	•			•			•		
Scudder 1985; Simeu-Abazi and Ahmad 2011	•			•				•	
Aramon and Beck 2014	•			•					
de Smidt-Destombes et al. 2004	•				•		•		
Smith and Dekker 1997	•				•			•	
Safaei et al. 2011	•				•				
Sleptchenko et al. 2002; de Smidt Destombes et al. 2007; Lin et al. 2014; Driessen et al. 2020	•			•			•		
Keizers et al. 2001; Hani et al. 2007; Azadeh et al. 2013; 2017; Al-Refaie et al. 2020	•			•					
Mabini and Christer 2002; van Jaarsveld et al. 2015; Taleizadeh et al. 2016; García-Benito and Martín-Peña 2020		•		•			•		
Chua et al. 1993		•		•				•	
Öztürk 2020		•		•					
Buyukkaramikli et al. 2015		•			•		•		
Guide et al. 2000; Sleptchenko et al. 2005; Adan et al. 2009; Sahba et al. 2013; Basten and van Houtum 2014; Jaber et al. 2014; Arts 2017		•		•			•		
Scudder 1984		•		•				•	
Luh et al. 2005; Spanjers et al. 2005			•	•		•	•		•
Sahba and Balcıog˘lu 2011; Li et al. 2013; Assadi et al. 2019			•	•		•	•		•
Shi et al. 2020			•	•		•			
van Ooijen et al. 2019				•				•	
Sanchez et al. 2020				•					
Kleber et al. 2011; Riisgaard et al. 2016; Turkeli et al. 2019				•		•	•		•
Turan et al. 2018; Dreyfuss et al. 2018; Sahba et al. 2018				•			•		
Scudder and Chua 1987; Sleptchenko et al. 2003; Tiemessen and van Houtum 2013; Liang et al. 2013				•				•	
van Ommeren et al. 2006				•			•		
Shivasankaran et al. 2013; Kim and Lee 2014				•					

Table 5. Methods used by the authors

Repair shops		Methods		
Without Circular Economy	***With Circular Economy***	***Performance evaluation***		***Optimization***
		Analytical	***Simulation***	
(Scudder 1984, 1985 ; Scudder and Chua 1987 ; Chua et al. 1993; Smith and Dekker 1997; Guide et al. 2000; Keizers et al. 2001; Sleptchenko et al. 2002, 2003, 2005; de Smidt-Destombes et al. 2004, 2007; Azadeh et al. 2013, 2017; Tiemessen and van Houtum 2013; Kim and Lee 2014; Simeu-Abazi et al. 2014; van Ooijen et al. 2019; García-Benito and Martín-Peña 2020)	(Spanjers et al. 2005 ; Li et al. 2013)	•	•	
(Mabini and Christer 2002 ; van Ommeren et al. 2006 ; Hani et al. 2007 ; Adan et al. 2009 ; Liang et al. 2013 ; Sahba et al. 2013, 2018 ; Shivasankaran et al. 2013 ; Aramon and Beck 2014 ; Basten and van Houtum 2014 ; Jaber et al. 2014 ; Lin et al. 2014 ; Taleizadeh et al. 2016 ; Arts 2017 ; Turan et al. 2018 ; Öztürk 2020 ; Al-Refaie et al. 2020 ; Sanchez et al. 2020)	(Kleber et al. 2011; Sahba and Balcıog˘lu 2011; Shi et al. 2020)			•
(Safaei et al. 2011 ; Simeu-Abazi and Ahmad 2011 ; Buyukkaramikli et al. 2015 ; van Jaarsveld et al. 2015 ; Dreyfuss et al. 2018 ; Sleptchenko et al. 2019 ; Driessen et al. 2020 ; Turan et al. 2020)	(Assadi et al. 2019 ; Luh et al. 2005)		•	•

Table 6. Industrial application of repair shops

Industry	Percentage of papers	Reference	Company (Country)	Circular economy	Proposed solutions
Aircraft	50%	(Mabini and Christer 2002)	McClellan Air force Base (USA)		A model for determining stock levels of repairable items
		(Sleptchenko et al. 2005)	Commercial airline (Netherlands)		Repair priorities to reduce stock investment in spare parts networks
		(Safaei et al. 2011)	Military (Canada)		A maintenance scheduling with workforce constrained
		(van Jaarsveld et al. 2015)	Fokker Services (Netherlands)		A novel method to solve the pricing problem for spare parts inventory control
		(Taleizadeh et al. 2016)	Military (Unspecified)		An Economic Order Quantity inventory model with partial backordering and repair of imperfect products
		(Azadeh et al. 2017)	Unspecified (Iran)		A unique fuzzy multivariate modeling approach for performance optimization
		(Sanchez et al. 2020)	Center for Transport and Logistics, CENTRAL (United Kingdom)		An optimization framework with tail assignment considerations
		(García-Benito and Martín-Peña 2020)	Spanish Army (Spain)		A redistribution model with minimum backorders of spare parts
Railway	19%	(Li et al 2013)	Unspecified (China)	●	A generalized stochastic petri-net model for performance analysis and allocation optimization
		(Shi et al. 2020)	Unspecified (China)	●	A Centralized Maintenance Time Prediction Algorithm Based on Remaining Useful Life Prediction
		(Hani et al. 2007)	SNCF (France)		A hybrid ant colony optimization approach coupled with a guided local search, applied to a layout problem
Gas Industry	19%	(Smith and Dekker 1997)	Unspecified (Netherlands)		The expected uptime, downtime and costs of Preventive Maintenance
		(Kleber et al. 2011)	Unspecified (Italy)	●	A Case-based framework to offer insights into the opportunity of recovering parts
		(Azadeh et al. 2013)	National Iranian Gas Transmission Company (Iran)		A new approach for layout optimization with safety factors
Mobile phone	12%	(Riisgaard et al. 2016)	Unspecified (Denmark)	●	An analysis of the business ecosystem of cell phone repair shops on large global circles addressing recycling of materials rather than the “inner circles” that address maintenance/repair and reuse
		(Turkeli et al. 2019)	Unspecified (Netherlands, Poland and China)	●	An analysis of the business ecosystem of cell phone repair shops that integrate closed-loop design through repair, remanufacturing or recycling.

Figure 1 Caption: Repair shop concept (Simeu-Abazi et al. 2014)

Figure 1 Alt Text: Several geographically distributed production sites supply defective spare parts, a repair shop centralises overhauls and produces ready-to-use spare parts.

Figure 2 Caption: Methodology to find the 39 keyword combinations

Figure 2 Alt Text: The research questions combining the 15 keywords filtered through the topics studied, from both the top 25 journals in industrial and Manufacturing Engineering and from the papers dealing with repair shops.

Figure 3 Caption: Keyword network for repair shops

Figure 3 Alt Text: Two linked clusters describe the organisation of the keywords in the literature, on the one hand, spare parts centred operations related to maintenance and, on the other hand, remanufacturing related to sustainable development strategies.

Figure 4 Caption: Methodology to obtain the 54 relevant papers from the combined keywords

Figure 4 Alt Text: A step-by-step process to extract the most relevant papers from 6 databases related to repair shops, A gradual filter of 3791 papers, then 355 papers and finally 124 papers using inclusion and exclusion criteria.

Figure 5 Caption: Classification and evolution of the papers over the years (up to the end of October 2020).

Figure 5 Alt Text: A histogram showing the positive evolution of the number of publications related to repair shops, distributed between 1984 and 2020, the topics studied are circular economy, material flows, operation and organisation.

Figure 6 Caption: Keyword network from 1984 to 2020 of the 54 papers

Figure 6 Alt Text: The three main periods of repair shop studies, from 1985 to 2000 on sizing, then from 2004 to 2012 on spare parts and finally from 2014 to 2020 on combining all dimensions of a repair shop.

Figure 7 Caption: The most cited papers without Circular strategies

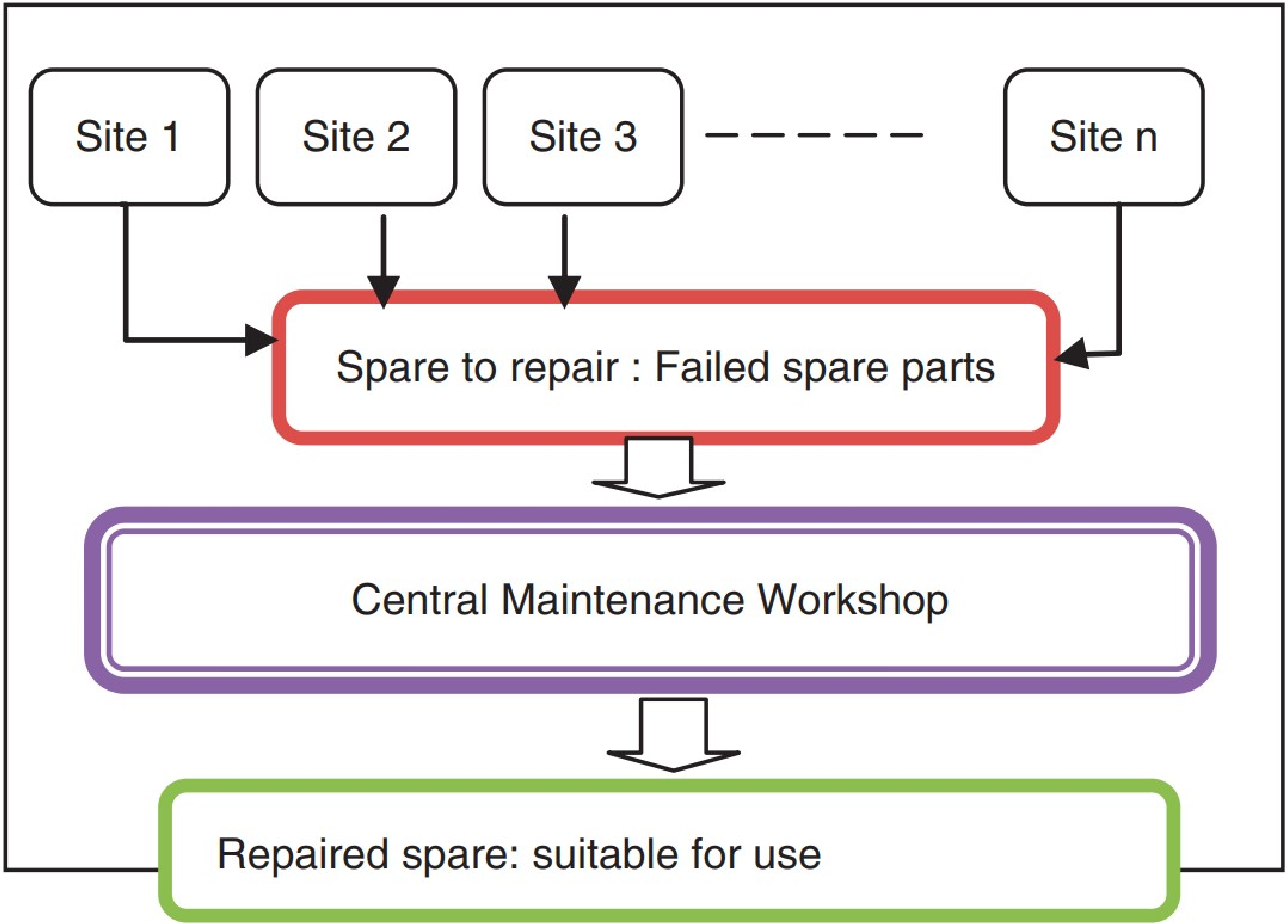
Figure 7 Alt Text: A histogram showing the average number of citations per year of the most relevant papers, Basten and van Houtum's paper published in 2014 comes first with more than 17 publications per year, then 15 other papers are cited at least three times per year.

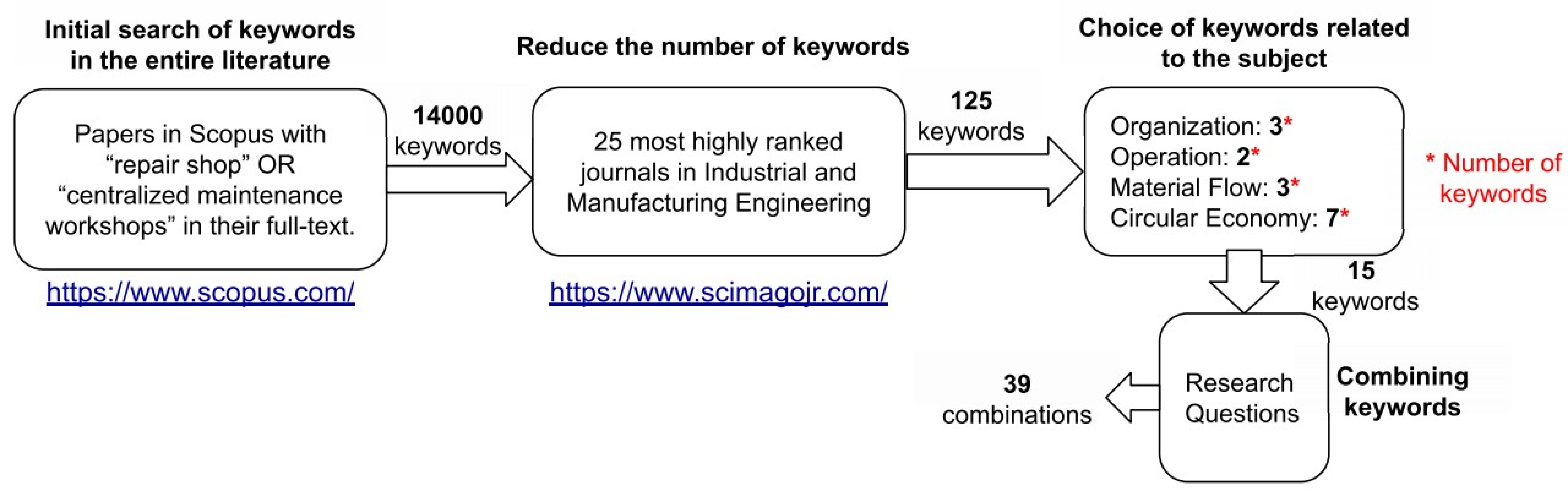
Figure 8 Caption: The most cited papers with Circular strategies

Figure 8 Alt Text: A histogram showing the average number of citations per year of the most relevant papers dealing with the circular economy, the paper by Riisgaard et al. published in 2016 comes in the first position with more than 5 publications per year, then 3 other papers are cited at least 2 times per year.

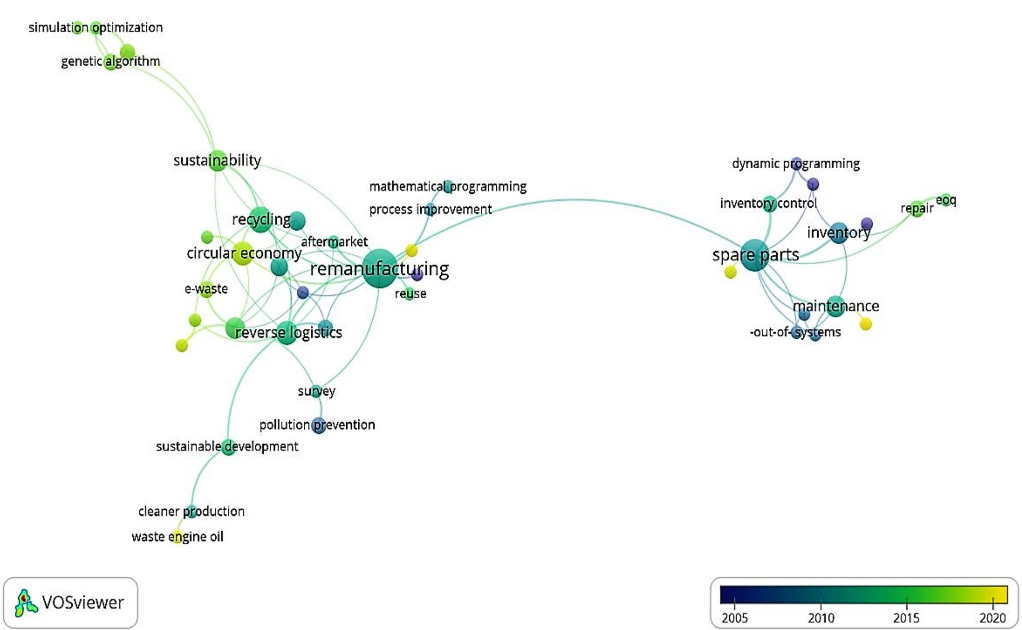
Figure 9 Caption: Topics distribution for specific industries

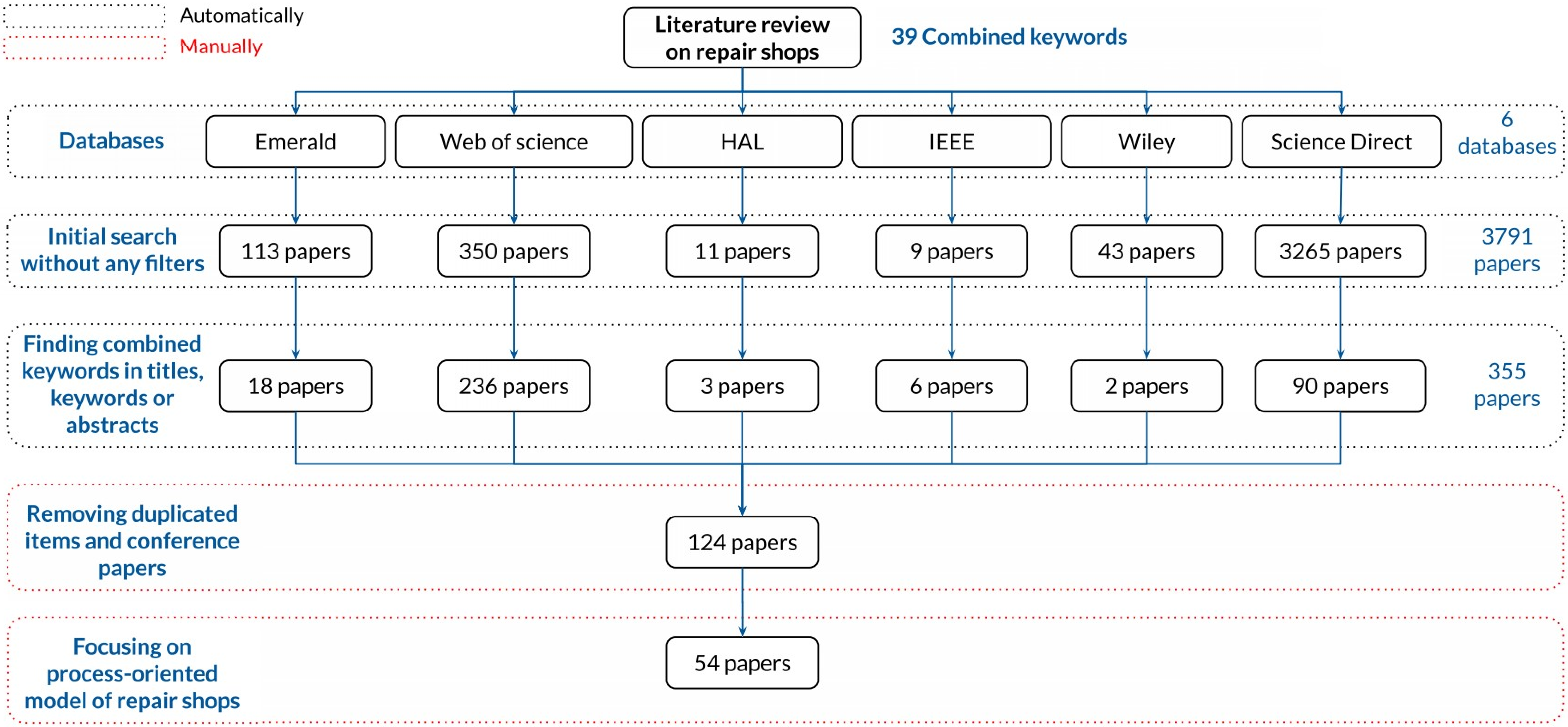
Figure 9 Alt Text: A histogram showing the percentage of repair shop application areas, Aircraft, Gas Industry, Mobile phone and Railway, Aircraft being the only area not yet investigating the circular economy.

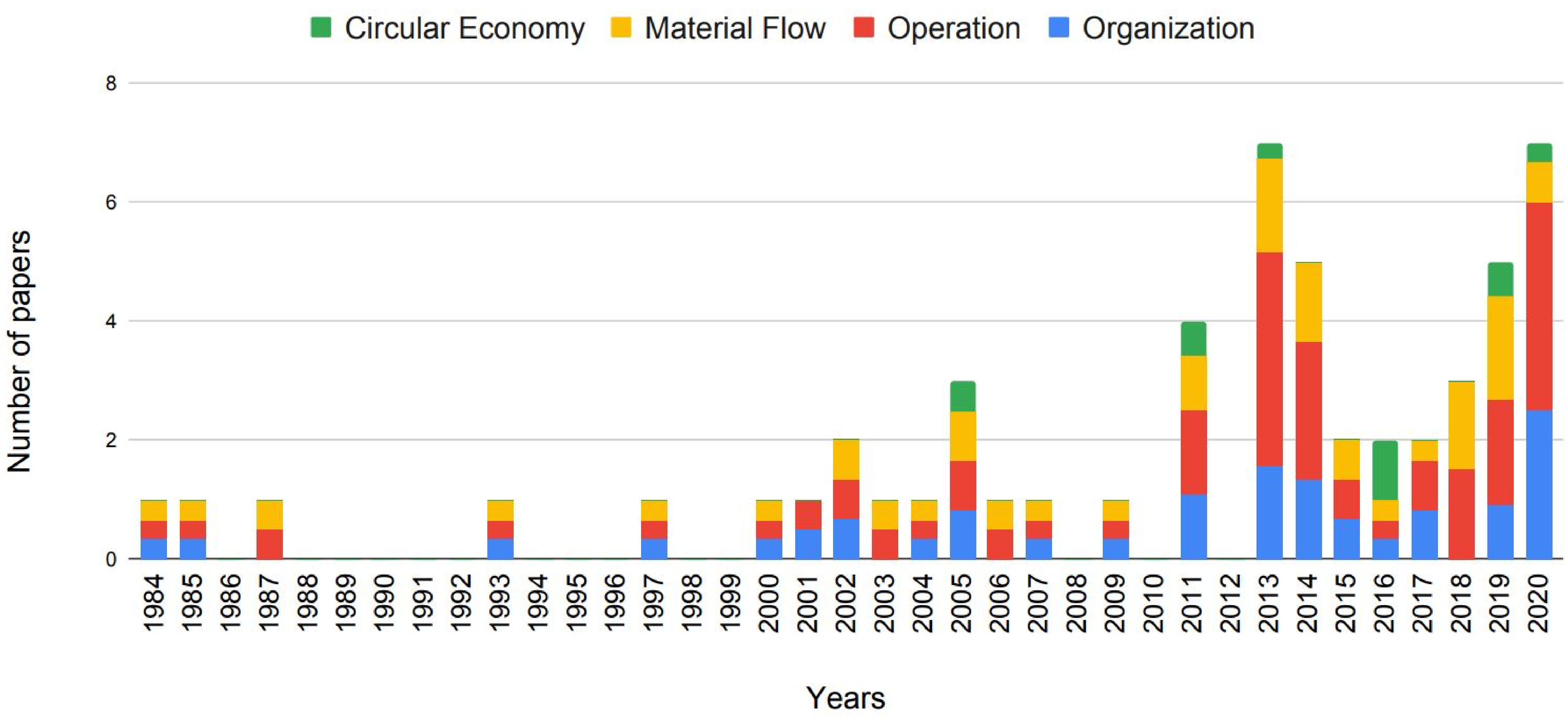

Site 1
Site 2
Site 3
Site n
Spare to repair : Failed spare parts
Central Maintenance Workshop
Repaired spare: suitable for use



Initial search of keywords in the entire literature
Papers in Scopus with "repair shop" OR "centralized maintenance workshops" in their full-text.
https://www.scopus.com/
14000 keywords
Reduce the number of keywords
25 most highly ranked journals in Industrial and Manufacturing Engineering
https://www.scimagojr.com/
125 keywords
Choice of keywords related to the subject
Organization: 3*
Operation: 2*
Material Flow: 3*
Circular Economy: 7*
* Number of keywords
15 keywords
Research Questions
Combining keywords
39 combinations


simulation optimization
genetic algorithm
sustainability
recycling
aftermarket
circular economy
remanufacturing
e-waste
reuse
reverse logistics
mathematical programming
process improvement
survey
pollution prevention
sustainable development
cleaner production
waste engine oil
dynamic programming
inventory control
inventory
repair
eoq
spare parts
maintenance
-out-of-systems
VOSviewer
2005
2010
2015
2020


Automatically
Manually
Literature review on repair shops
39 Combined keywords
Databases
Emerald
Web of science
HAL
IEEE
Wiley
Science Direct
6 databases
Initial search without any filters
113 papers
350 papers
11 papers
9 papers
43 papers
3265 papers
3791 papers
Finding combined keywords in titles, keywords or abstracts
18 papers
236 papers
3 papers
6 papers
2 papers
90 papers
355 papers
Removing duplicated items and conference papers
124 papers
Focusing on process-oriented model of repair shops
54 papers


Circular Economy
Material Flow
Operation
Organization
8
6
4
2
0
Number of papers
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
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2013
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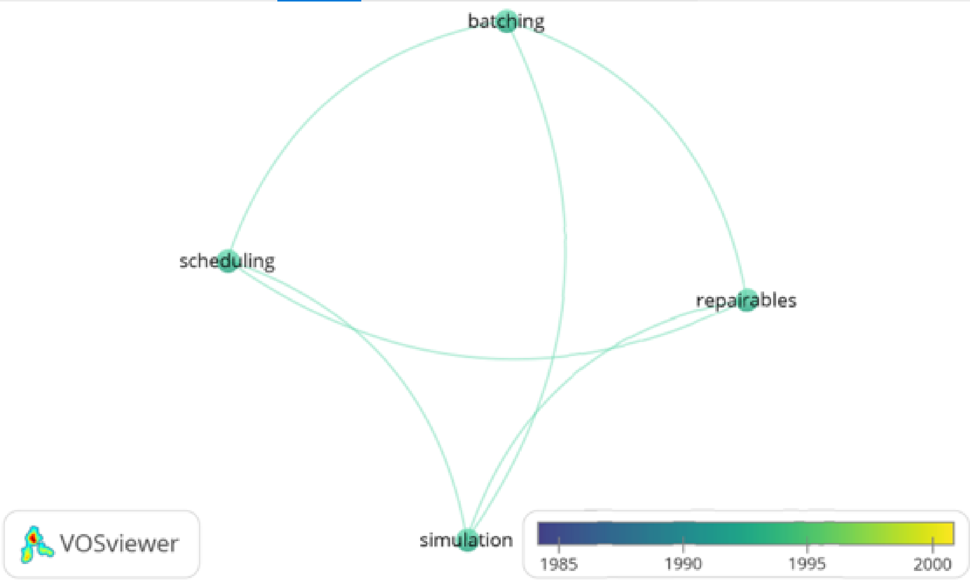
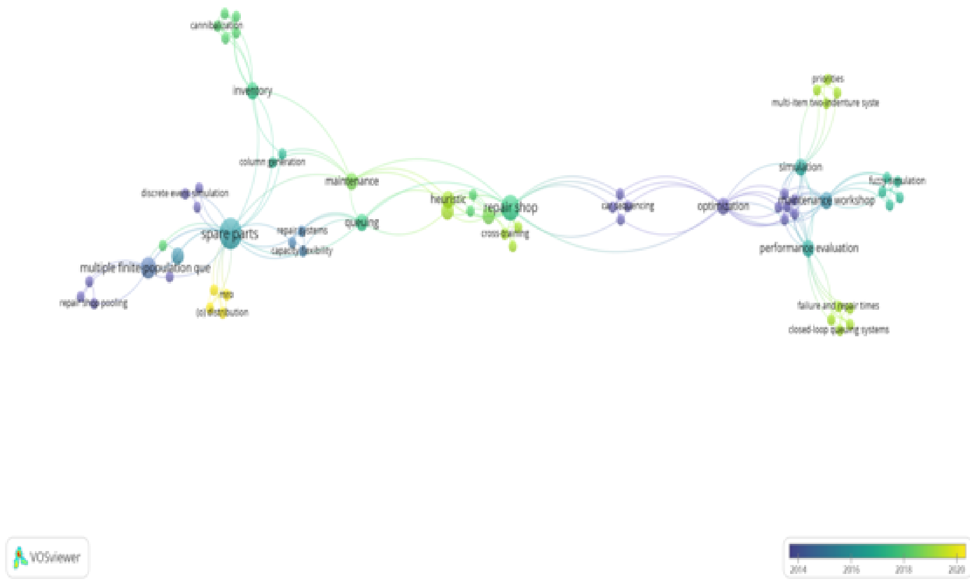
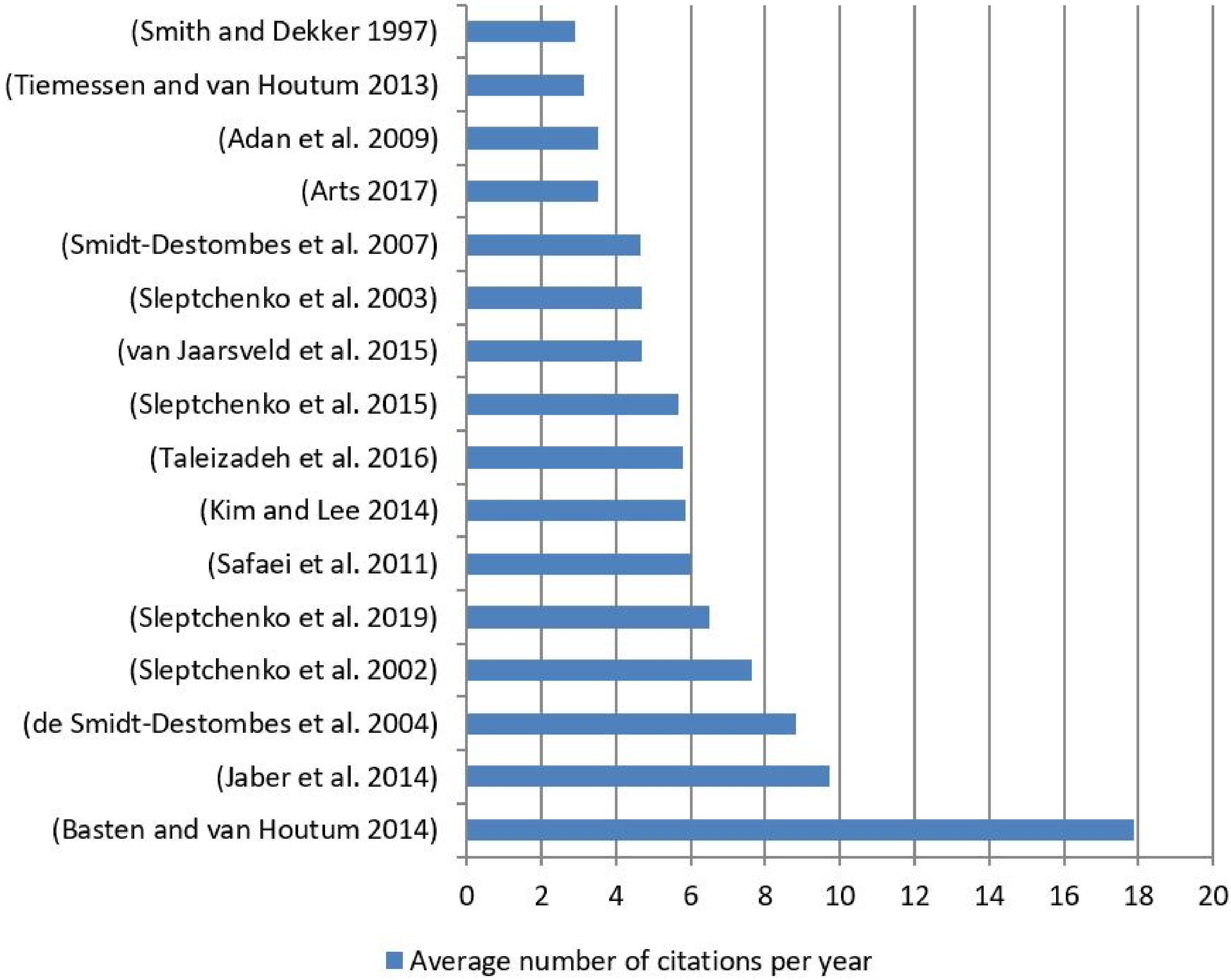
2015
2016
2017
2018
2019
2020
Years

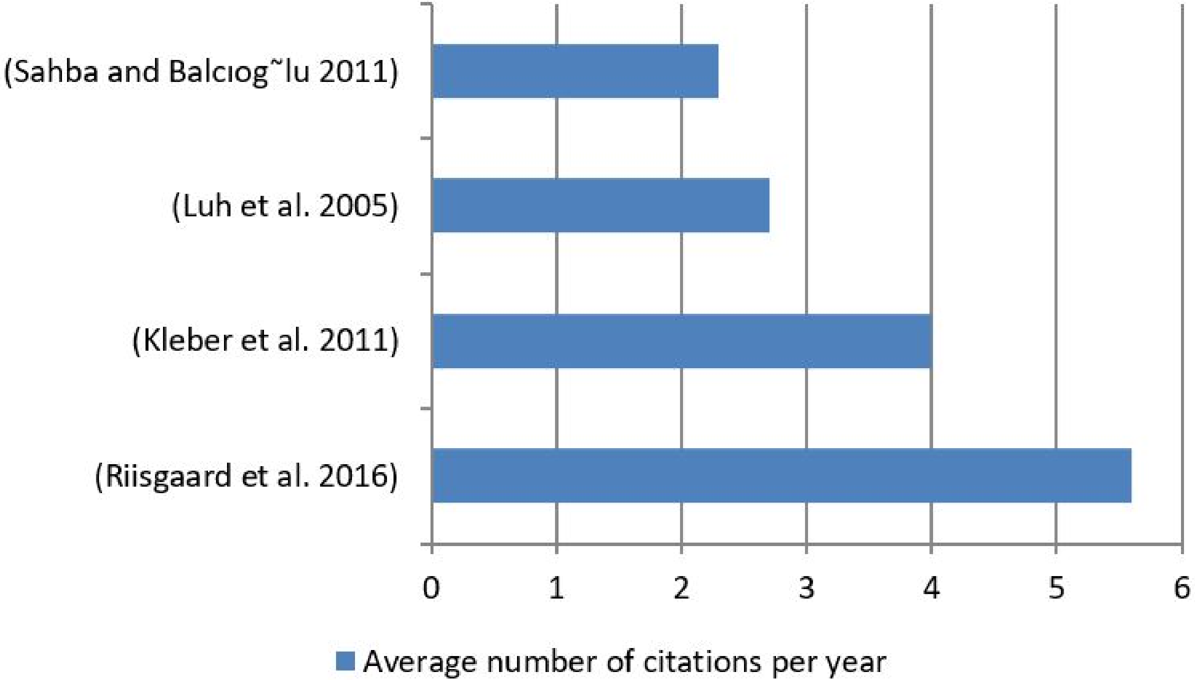

batching
scheduling
repairables
simulation
VOSviewer
1985
1990
1995
2000


inventory/production control
mean-value analysis
static priorities
transportation delays
multi-echelon inventory
skilled-workforce
spare parts
mixed-integer programming
maintenance
k-out-of-n systems
queuing
availability
scheduling
logistics
inventory
buyback
distributed maintenance
overhaul and repair services
remanufacturing
cost evaluation
lagrangian relaxation
VOSviewer
2004
2006
2008
2010
2012

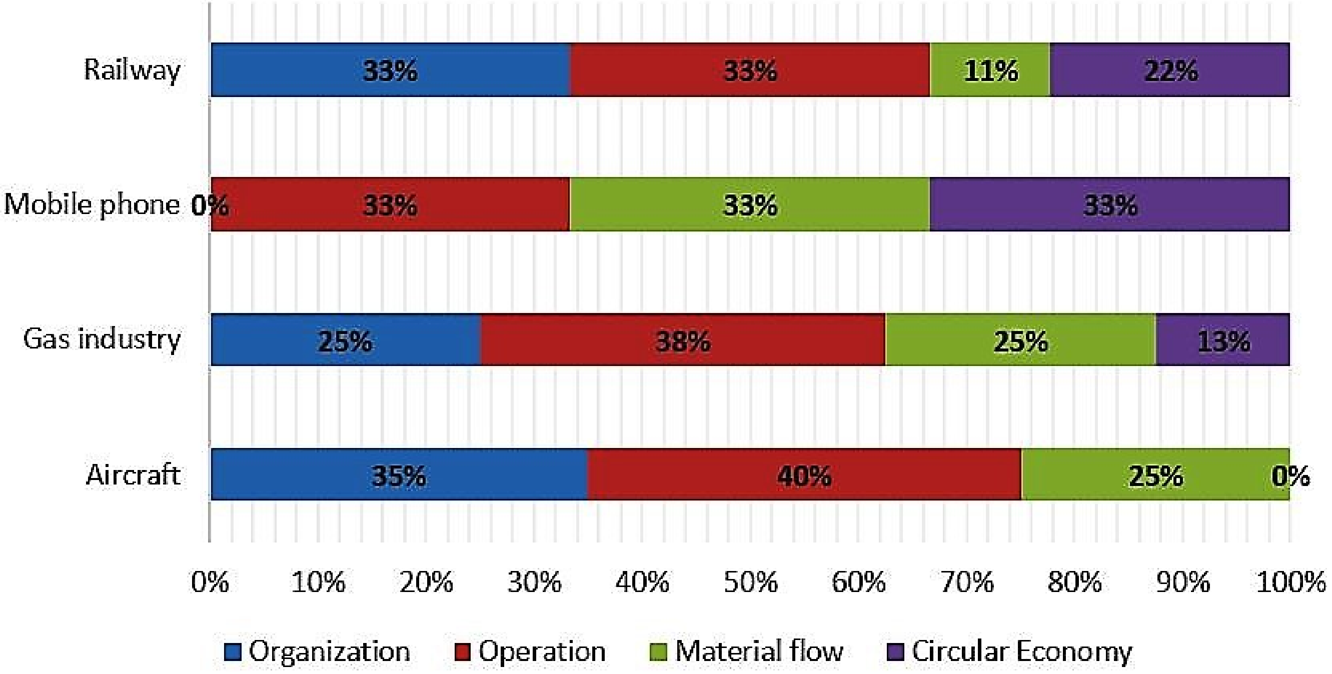

inventory
multi-item two-indenture syste
column generation
simulation
maintenance
discrete event simulation
heuristic
repair shop
optimization
maintenance workshop
spare parts
queuing
repair systems
capacity flexibility
cross-training
performance evaluation
multiple finite-population que
failure and repair times
closed-loop queuing systems
VOSviewer



(Smith and Dekker 1997)
(Tiemessen and van Houtum 2013)
(Adan et al. 2009)
(Arts 2017)
(Smidt-Destombes et al. 2007)
(Sleptchenko et al. 2003)
(van Jaarsveld et al. 2015)
(Sleptchenko et al. 2015)
(Taleizadeh et al. 2016)
(Kim and Lee 2014)
(Safaei et al. 2011)
(Sleptchenko et al. 2019)
(Sleptchenko et al. 2002)
(de Smidt-Destombes et al. 2004)
(Jaber et al. 2014)
(Basten and van Houtum 2014)
0
2
4
6
8
10
12
14
16
18
20
Average number of citations per year



(Sahba and Balcıog˜lu 2011)
(Luh et al. 2005)
(Kleber et al. 2011)
(Riisgaard et al. 2016)
0
1
2
3
4
5
6
Average number of citations per year



Railway
33%
33%
11%
22%
Mobile phone
0%
33%
33%
33%
Gas industry
25%
38%
25%
13%
Aircraft
35%
40%
25%
0%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Organization
Operation
Material flow
Circular Economy