How assembly systems are adopting the technologies of I40: a preliminary landscape

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Abstract: The recent revolution connected to the manufacturing and assembly process digitalization, known as Industry 4.0 (I40), is radically changing the way these processes are conducted. Assembly systems are expected to benefit from positive effects, such as significant innovation and improvement in system flexibility, increase in process speed and efficiency, as well as the possibility of extremely customized products. Accordingly, interest in the exploitation of technological improvements introduced by I40 in the design and management of AS is increasing as well. The objective of this paper is to inspect the evolution of research on I40 applied to AS by means of the analysis of the literature on this topic. To achieve this objective, a traditional content-based literature review is combined with quantitative information extracted from bibliographic networks to detect emerging topics, and by revealing the dynamic evolution of the scientific production. This dynamic analysis allowed highlighting research directions and critical areas for the development of the 'assembly I40'. Moreover, the analysis offers insights on the technology improvements that have not been explored yet in order to allow a real transition towards the I40 transformation of AS.

Keywords: Assembly line systems, co-occurrence keywords network, burst detection, Industry 4.0.

1.Introduction

An assembly system performs the final step of the production process that combines component parts and subassemblies together to build the final products. An assembly system is usually organized in line, a set of workstations aligned in a flow-oriented order and connected by transport mechanisms, e.g. conveyors (Boysen et al. 2008; Saif et al. 2014). Workpieces visit workstations where successive tasks are performed, following specific precedence relationships to assemble the final product (Baybars 1986). At the times of the first moving assembly line installed in the Ford plant, assembly lines were targeted to realize high quantity standardized commodities to cope with the needs of mass production. From the '80s on, according to the requirements of mass customization, assembly systems (AS) have been devoted to the low volume of customized products (Boysen et al. 2008) turning into an important manufacturing process for cost-effective product variety (Hu et al. 2011, Rossi et al. 2017).

Since long time, increasing the efficiency of the assembly line by maximizing the ratio between throughput and required costs has been acknowledged as a problem of considerable industrial importance (Rekiek et al. 2002) as, on average, the assembly activities represent a substantial proportion of overall manufacturing cost and time, accounting for up to the 50% the total (Krugh et al. 2017). In light of the high practical relevance that AS has maintained over time, this topic has been intensively studied since the first mathematical formulation of the assembly line balancing problem by Salveson (1955). Assembly line design (i.e. decisions about the number of workstations and type of task to perform in each station) and balancing (i.e. the allocation of the tasks to the workstations so that workloads are as equal as possible) are recognized as playing a vital function (Make et al. 2017) and strongly affect manufacturing process times and costs (Rashid et al. 2012).

In addition to the recent research on traditional assembly line design and balancing (e.g. Cannas et al. 2018), literature is coping with the specific requirements for the AS in the industrial companies to manage the challenges characterizing the today business environment. The market-driven product complexity and increase in variants together with batch sizes reduction are recognized as affecting the complexity and the cost of the assembly process (Dombrowski et al. 2013). Krugh et al. (2017), reporting the specific case of the automotive industry, confirm the threats from a continuous increase in demand for quality and product variety (e.g. the number of variants in one BMW 7 Series product line is projected 10^7) while decreasing product lifecycle. According to Scholer et al. (2017), automation is recognized to be not favourable when applied to assembly process characterized by a high level of complexity or by low batch size, indeed, in these systems, the number of manual tasks is significant. Notwithstanding the benefits from high flexibility, manual assembly tasks imply the possibility of incurring in different individual performances, especially when considering aging and diversity (Hold et al. 2017), turning in the possibility of hidden bottlenecks between manual workstations (Dombrowski et al. 2013) and in operator errors that, in the automotive industry, totals up to the 40% of the product defects (Krugh et al. 2017), resulting unable to cope with increasing requirements (Scholer et al. 2017).

As the human impact on the manufacturing process is high and performing manual tasks is needed to guarantee flexibility, the latest research on AS has been devoted to overcoming the limitations connected to manual activities through the implementation of Industry 4.0 (I40) technologies. In particular, the majority of works dealing with the implementation of I40 to AS focuses on a new generation of AS, Cyber Physical AS (CyPAS), expected to win the challenge of flexibility. CyPAS can be described as a combination of physical processes and computing, i.e. embedded systems, exploiting sensors and actuators and linking single devices into a network through digital communication technologies (Dombrowski et al. 2013; Hold et al. 2017). In this context, the Industrial Internet of Things (IIoT), i.e. the networking of all objects in the factory, powers big data, machine learning, machine-to-machine and human-to-machine communication, creating a connected system (Krugh et al. 2017). Cybernetic loops are able to distribute tasks depending on the status of the upstream and downstream stations (i.e. the operator) harmonizing the resources utilization (Dombrowski et al. 2013). Similarly, flexibility is chased through innovative control approach to job shop scheduling based on individual sets of tasks within the jobs (Ivanov et al. 2017). Ubiquitous data stream provided by IIoT are successfully used to better manage the role of the human in AS towards the most flexible system (Krugh et al. 2017) and the collaborative robot technology is exploited to realize the human-robot cooperation in an automotive underbody assembly process by Scholer et al. (2017).

Notwithstanding in recent research on AS and I40 the human factor has played a central role, according to the work by Bortolini et al. (2017), balancing, sequencing, material feeding, equipment selection, learning effect and ergonomic risk are all variables to be considered when defining the assembly system configuration and management. In the framework proposed by Bortolini et al. (2017), some of the I40 enabling technologies are presented as suitable to deal with these variables, broadening the focus from human factor. The application of IoT, identified as the pivotal technology of I40, big data, real-time optimization, cloud computing, cyber-physical systems (CPS), additive manufacturing, collaborative robots, augmented reality and machine learning would lead to AS 4.0 (AS40). According to the authors, the characteristics of AS40 are clearly the realization of aided assembly, intelligent storage management, self-configured workstation layout, complete product and process traceability, late customization and assembly control system.

The six characteristics of AS40 identified by Bortolini et al. (2017) identify as many directions of research on the application of I40 to AS design and management. The present work aims at inspecting the evolution of research on I40 applied to AS by means of the analysis of the keywords of Scopus paper on this topic. The study of the evolution of research confirms, among the directions identified by literature, which ones have already been considered by research and identifies others, not already recognized, that has been the object of the studies.

The first step of this analysis consists in defining a set of search keywords to identify the papers dealing with AS and I40, second, from this papers the co-occurrence networks of indexed keywords have been extracted to discover research directions and, third, the Kleinberg's burst detection algorithm (Kleinberg 2003), was applied to author keywords to detect the recent developments. Co-occurrence networks of keywords are networks whose nodes are author keywords and the links are the number of papers in which the two keywords appear together. Group of keywords strongly linked represent subjects that often appear together and then on which many researchers are working on. Su and Lee (2010) applied co-occurrence keywords network to map the knowledge structure in the technology foresight area. Burst detection algorithm allows detecting a sudden increase in the use of keywords. This algorithm was used for different purpose in the literature, for example, Parikh and Sundaresan (2008) applied it to study the burst of e-commerce queries.

Strozzi et al. (2017) applied co-occurrence network and burst detection together to perform a literature review on the "Smart Factory" concept.

In Section 2 the search keywords are defined, and the tools to study the keywords of the papers selected, presented. In Section 3 the contents of papers selected are studied using the tools presented in Section 2 with the aim to explore the research directions of AS40. In Section 4 the main conclusions and the future developments of this work are presented.

2. Material and Methods

The papers used in this work were collected in March 2018 from Scopus database, which is the largest database of scientific peer-reviewed literature.

2.1. Research keywords selection

To define research keywords, to avoid not useful trials and incomplete or wrong results, it is necessary to know how Scopus considers our research. The six main things to keep in mind to insert keywords and obtain a complete set of documents are explained in https://blog.scopus.com/posts/6-simple-search-tips-lessons-learned-from-the-scopus-webinar.

In addition to the choice and method of entering keywords, the choice of the field in which the search is done is also very important. The selection procedure of the search keyword for this work was as follow: first we look for "assembly" in Title field since it is the leading concept of this work, then, with the aim to refer only to works that apply this concept to smart factory framework, we added some terms often used to indicate the "smart" and "factory" (Strozzi et al, 2017), to include all the works containing all the combinations of the two concepts. Moreover, since this research area is new, we considered these strings in a more general field i.e. "Title, Abstract, Keywords". With this selection, Scopus returned 1341 documents (conference papers, articles, reviews, articles in press and book chapters) belonging to different subject areas, not always of interest for our analysis. Between them, we selected the works on Engineering, Mathematics, Decision Sciences and Business Management and Accounting and, only works in the English language. The Final search string was:

(TITLE ("assembly") AND TITLE-ABS-KEY (("digital" OR "smart" OR "intelligent" OR "u biquitous" OR "real-time" OR "4.0")) AND TITLE-ABS-

KEY ((factor* OR manufacturing OR industry))) A
ND (LIMIT-
TO (SUBJAREA , "ENGI") OR LIMIT-
TO (SUBJAREA , "COMP") OR LIMIT-
TO (SUBJAREA , "MATH") OR LIMIT-
TO (SUBJAREA , "DECI") OR LIMIT-
TO (SUBJAREA , "BUSI")) AND (LIMIT-
TO (LANGUAGE , "English"))

And a total number of 952 works was selected.

2.2. Author’s and indexed keywords

When the search field includes “Keywords” field, Scopus searches not only between the keywords of the authors but also the indexed keywords, i.e. keywords systematically assigned by Scopus to documents based on their contents.

Figure 1 depicts an example of author keywords referred to one paper belonging to the output set of our research and the indexed keywords that Scopus systematically associates to the paper.

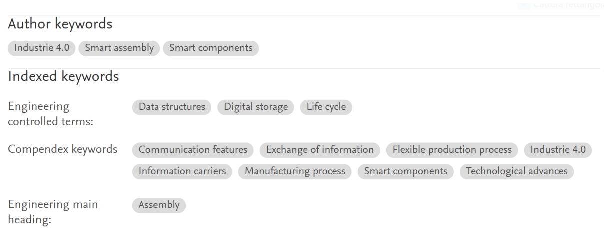

Figure 1. Example of Author’s and indexed keywords

Indexed keywords include Compendex keywords, Engineering controlled terms and Engineering Main Heading.

Compendex keywords are keywords found in Ei Compendex which is an engineering bibliographic database published by Elsevier. The name "Compendex" stands for COMPuterized ENgineering inDEX. Compendex keywords are the equivalent of author keywords but established by Compendex using the Ei Thesaurus. These keywords express what Compendex and, then, Scopus consider important keys of the article contents exactly as the author keywords for the author. Sometimes they coincide with author’s keywords, sometimes they do not. Compendex keywords have the characteristic to reduce ambiguity inherent in normal human languages where the same concept can be given different names and ensure consistency.

The Engineering controlled terms provide a list of subject terms used to describe the content of a document in the most specific and consistent way. These terms are also linked to the abstract to better catch the content of the papers.

The Engineering Main Heading represents the main descriptor or the subject classification that serves to represent the main topic of the document. The Main Headings are also controlled vocabulary terms and they may represent additional concepts found in the article.

In synthesis, the controlled terms define the contents of a document according to Scopus/Compendex criteria while the Main Heading is the more general Engineering topics on the top.

In this work, we use indexed keywords to identify research areas since these terms capture the essence of the topics of the document in a more objective way. The problem of the indexed keywords is that they need to be updated frequently, then, to overcome to this problem and to catch even the most recent trends, we have analyzed the recent bursts in the Author’s keywords.

2.3. VOS Clustering

In Waltman et al (2010) the authors proposed a unified approach for mapping and clustering bibliometric networks. Mapping and clustering are often used together because the two activities have the same goal, which is to provide information on the structure of a network. These techniques are based usually on different principles, however, Waltmant et al. (2010) proposed a new technique that serves both for mapping and clustering avoiding difficulties in the interpretation of the results: the VOS mapping and clustering based on the modularity function proposed by Newman and Girvan (2004). Their approach considers the function “association strength” between node *i* and *j* defined in Van Eck and Waltman (2009) for a network of *n* nodes, *m* links:

$$s_{ij} = \frac{2mc_{ij}}{c_i c_j} \quad (1)$$

where c_i is the weigthed degree of node *i*, and c_{ij} the weigth of the link between *i* and *j*. If the network is a co-occurrence network of author keywords, c_{ij} is the number of papers in which two keywords appear together and c_i the number of papers containing keyword *i*.

Using the strength function is possible to define a new function V:

$$V(x_1, \dots x_n) = \sum_{i<j} s_{ij}\, d_{ij}^2 - \sum_{i<j} d_{ij} \quad (2)$$

where $(x_1, \ldots, x_n)$ are the coordinates of the node *i* in a *p*-dimensional space, in the case of mapping, while they indicate the cluster to which the node i belongs, in the case of clustering. The function *V* represents the difference between an attractive and repulsive force between nodes *i* and *j*. The attraction is greater the more s_{ij} is higher. The attraction and repulsion force depend on their distance too.

Waltman et al. (2010) proved that, in the case of clustering, the partition that minimizes the function V is the same that maximize the modularity function (Newman and Girvan, 2004), i.e. networks with high modularity have dense connections between the nodes within modules (groups of nodes) but sparse connections between nodes in different modules.

The network of co-occurrence indexed keywords (Figure 2) is built using Vosviewer software (Van Eck and Waltman, 2010) selecting only the keywords appearing at least five times (default parameter) together in the same papers. In this way, 402 indexed keywords were selected.

Using Vosviewer VOS clustering method was applied to the co-occurrence network and nine clusters were identified. The keywords of each cluster are in Table 1 while the complete list may be asked to the authors.

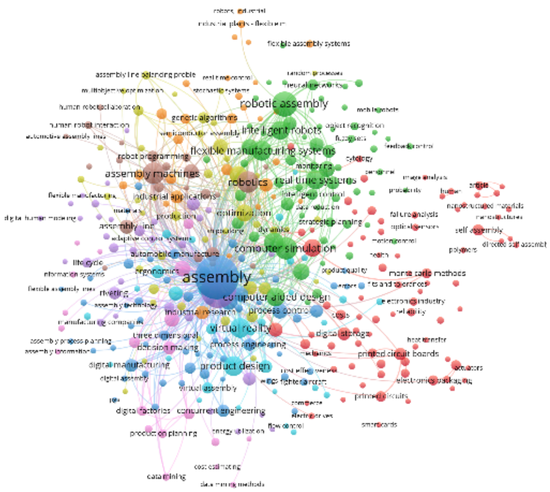

Figure 2: Co-occurrence indexed keywords network.

Table 1. Vos Clustering indexed keywords and research directions

Aided assembly	Complete product and process traceability	Late customization	Assembly control system	Other
Cluster 6: assembly; assembly time; augmented reality; complex assembly; digital assembly; internet of things; product assembly; real time; virtual reality; **Cluster 9**: ergonomics; final assembly; human robot interaction; human-robot collaboration	**Cluster 1**: process monitoring; reliability; wearable computers; **Cluster 8**: flexible assembly lines; radio frequency identification (rfid); real-time data; real-time production; rfid technology	**Cluster 1**: 3D printers; customer satisfaction; design; digital storage; specifications; **Cluster 3**: adaptive systems; flexible manufacturing; reconfigurable hardware; **Cluster 5**: digital mock-up; manual assembly; mockups	**Cluster 2**: Computer control; computer control systems; computer integrate manufacturing; decision support systems; intelligent control; real time control; real time systems; **Cluster 7**: evolutionary algorithms; genetic algorithms; heuristic methods; integer programming; mixed-model assembly lines; multiobjective optimization; scheduling; simulation;	**Cluster 4**: assembly automation; automated assembly; automated assembly systems; automated systems; automation; complex geometries; error prone; image processing; product quality; quality assurance; quality control

2.4. Burst detection

A burst is a sudden increase or "bursts" in the frequency-of-use of keywords over time. The keywords of the papers may be seen as a time series that appear, grow in intensity and then fade away. In this work, we have applied the Kleinberg's algorithm (Kleinberg, 2002).

Rather than using simple frequencies of the occurrences of words, the algorithm employs an automaton that detects the occurrence of a frequency increasing in the use of a keyword by a state transition. The algorithm generates a list of the word bursts, ranked according to the burst weight, together with the intervals of time in which these bursts occurred. The burst weight depicts the intensity of the burst, i.e. how great is the change in the keyword frequency that triggered the burst. Sci2 software (Sci2 Team, 2009) implement the burst detection algorithm on the normalized author's keywords.

The normalization is performed by SCI2 software implement the English Snowball stemmer (http://snowball.tartarus.org/algorithms/english/stemmer.html) and allows to separate text into word tokens, normalizes word tokens to lower case, e.g. it removes "s" from the end of words, removes dots from acronyms, deletes stop words. The sequence of bursts from 1975 to the end of 2017 are presented in Figure 3 and 4.

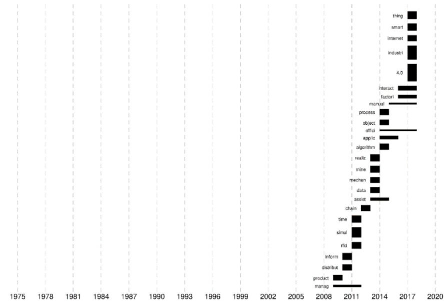

Figure 3: Burst detection of Author's keywords

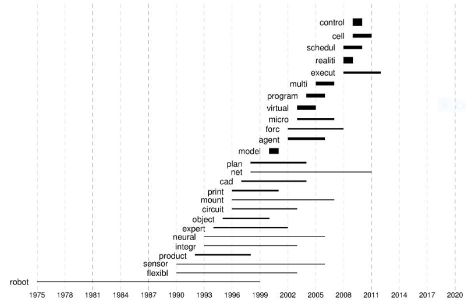

Figure 4: Burst detection of Author's keywords

3. Discussions

This Section is devoted to the discussion of the obtained indexed keywords network and the sequence of bursts of author's keywords. The analysis of the indexed keywords, in particular, is based on the identification, among the obtained clusters, of the directions of research on AS40 identified by Bortolini et al. (2017) (aided assembly, intelligent storage management, self-configured workstation layout, complete product and process traceability, late customization and assembly control system), and of others, not already recognized by literature, but that have already been object of the research. To help the understanding of the resulting indexed networks discussion, the main keywords that constitute the nodes of the network are represented divided into their clusters in Table 1 together with the directions identified by Bortolini et al. (2017). From the 402 indexed keywords that constitute the co-occurrence network obtained through the Vosviewer VOS clustering method, only the ones that are more strictly related to clear research directions are considered in the discussion and listed in Table 1. The sequence of bursts is discussed from the point of view of the timing of bursts appearance, with the aim to provide additional information to the paths identified by the VOS clustering.

3.1. VOS clustering

Among the I40 technologies, IoT is identified as the keystone. The keyword "IoT" appears in cluster 6 of the co-occurrence indexed networks. From other keywords in the cluster, it is possible to state that research on I40 applied to AS has mainly involved, together with IoT, augmented reality, real-time, virtual and different stages and elements of AS design and management (e.g. design, planning, tasks). Among the characteristics of AS40, aided assembly involves IoT in helping the completion of assembly tasks, enabling the use of technologies such as augmented reality, i.e. the improvement of the real surrounding environment of a human with virtual, as the seminal work by Yuan et al. (2008) introduced presenting this technology for assembly guidance as a novel approach. As well, collaborative robots represent a way of assistance to the worker. This technology appears in cluster 9 (as "human-robot collaboration") together with "ergonomics" and "final assembly" confirming that I40 provides tools to help humans in completing complex activities, such as final assembly, that would benefit from their contribution, as recently demonstrated by Tsarouchi et al. (2016). Clusters 6 and 9 of keywords prove the centrality of the human factor as research direction assessed through the review of the literature.

Research on product and process traceability, i.e. the real-time monitoring and detection of any possible failure and non-compliance through continuous monitoring of workers activity, presented by Colledani et al. (2018), is visible in clusters 1 and 8. The keyword "process monitoring" is used together with "reliability", i.e. the extent of the use of technology in the assembly process, and "wearable devices", one of the possible tools to realize constant traceability, as demonstrated by Maekawa et al. (2016) after the seminal work on activity recognition using body-worn microphones and accelerometers by Ward et al. (2006). From cluster 8, the interest in the use of "RFID technology" to gather "real-time data" in "flexible assembly lines" emerges and can be effectively considered as a research direction focused on tools to improve traceability supported by works such as Barenji et al. (2016).

The interest in late customization, i.e. involvement of the customer in the design phase and monitoring, for AS40 can be recognized in keywords from cluster 1: "customer satisfaction", "specifications", "design", "digital storage" and "3D printers". From keywords, it is possible to state that literature has already faced the topic from the design, manufacturing and monitoring sides. Among the others, the work by Lyly-Yrjänäinen et al. (2016) finds evidences of customer responsiveness improvements connected to the combination of product-centric control and direct digital manufacturing. In cluster 3, keywords such as "reconfigurable hardware" and "flexible manufacturing" prove that research on the impact of late customization on the final assembly process has been performed, e.g. Backhaus and Reinhart (2017). From cluster 5, details on the design phase emerge from the connection between keywords such as "digital mock-up" and "manual assembly", as demonstrated by the case of Airbus company presented by Morales-Palma et al. (2017).

Data collected for monitoring can be transformed and used to implement assembly control systems, i.e. the automatic setting of AS40 based on gathered data. Keywords related to such characteristic of an AS40 can be found in clusters 2 and 7. From cluster 2, it is possible to understand that the topic of control has been exploited from the point of view of "computers", connected with "real-time" "decision support systems", as introduced by Jamshidi et al. in 2010. Cluster 7 gives detail about the models and tools studied by literature with the aim to achieve self-configuring, i.e. "simulation", "genetic algorithms", "multiobjective optimization", e.g. Muller et al. (2017).

Two characteristics of AS40 recognized by Bortolini et al. (2017), intelligent storage management and self-configured workstation layout, are not detected from the analysis of the clusters, pointing out that research on I40 applied to AS has not devoted the same attention on materials feeding and on this particular topic related to ergonomics as the consideration devoted to the other commented research directions.

In addition to the directions proposed by Bortolini et al. (2017), another one emerges from the VOS clustering. With reference to cluster 4, attention on product quality, i.e. "product quality", "quality assurance" and "quality control", and on the use of assembly automation, i.e. "assembly automation", "automated assembly", "automated assembly systems", "automated systems" and "automation", are related to "complex geometries", "error-prone" systems and "image processing". According to these keywords, a research path based on assembly automation to ensure quality emerges as significant in case of complex geometries and error-prone systems and image processing appears as the most used tool to reach such objective, as in the works by Gewohn et al. (2017) and .

3.2. Burst detection

From figures 3 and 4, depicting the sequence of bursts from 1990 to the end of 2017, a clear increase in burst appearance and related weight from 2011 is visible. The increase in bursts, i.e. in the number of keywords associated to an increasing frequency in their use, means rise in a number of "new" directions of interest from the point of view of AS immediately after the seminal work by Zuehlke (2010).

One year later than the description by Zuehlke (2010) of the 'SmartFactoryKL' initiative to create and operate a demonstration and research test bed for 'the future factory' technologies, research on AS already deals with "simulation", "real-time" and "RFID", confirming that assembly control systems are among the main studied directions, as suggested by Bortolini et al (2017) and confirmed by the discussion of the co-occurrence network.

In 2013 the author's keyword "assistance" is characterized by an increase in importance. This can be interpreted as an intensification of research activities facing the issue of helping humans in performing assembly tasks. Accordingly, the increasing importance that manual work has gained in customization emerges as the keyword "manual" increases importance, i.e. from 2015. Immediately after, in 2016, attention is given to "interaction", that could be acceptably interpreted as the interaction of human and collaborative robots. These keywords confirm the focus of research on human work in AS assessed by the review of literature in the introduction of the present work.

The most recent keywords, the ones whose burst begins in 2017, i.e. "industri", "4.0" and "smart", demonstrates that great interest is now on the application of the I40 paradigm to AS, not limiting the application to a specific technology.

4. Conclusions and Future Developments

The exploitation of I40 technologies in the design and management of AS, i.e. resulting in AS40, is increasingly recognized by literature as the response to the need of rising system flexibility, process speed and efficiency and extreme customization of products.

According to the revealed importance of AS40, the goal of this paper was to explore the research directions characterizing these newly developed systems using bibliometric and complex networks tools. Through their use, additional temporal view and a degree of depth of the research directions were provided, compared to traditional literature reviews. Hence, the mapping of the research trends through bibliometric and complex networks tools result in effective help in understanding and managing innovations.

The main results of VOS clustering technique applied to indexed keywords, compared with the recent literature review of Bortolini et al. (2017), showed that some directions (aided assembly, complete product and process traceability, late customization and assembly control system) seem to have been actually explored in depth while others (intelligent storage management and self-configured workstation layout) have not received the same attention yet.

The analysis of the author keywords using burst detection algorithm clearly shows a sudden increase of many new author's keywords after 2011, just after the introduction of the I40 paradigm. Moreover, the author's keywords show relevant bursts after 2017 of "industri" and "4.0", "smart", "thing", "internet", confirming that the concept of I40, smart factory and internet of things are the most recent trends in the assembly systems environments.

The bibliometric tools applied in this work are part of a more structured methodology called Systematic Literature Network Analysis (SLNA) applied by Strozzi at. al (2017) to the analysis of the development of the Smart Factory concept. As this study already provides a clear temporal view and a degree of depth of the research directions, the next step will consist in applying all the tools of such methodology and in considering not only keywords but even the citations between papers to extract a series of works representing the backbone of the new development of the theory of assembly systems and research groups working on these topics.

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