Digital Twin relationship with Virtual Reality and Augmented Reality: a bibliometric review

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Abstract: The interest of the literature in the last few years around the theme of Digital Twins (DT) and its connection with the pillars of Industry 4.0 (I 4.0) paradigm, in particular relating with Virtual Reality (VR) and Augmented Reality (AR) technologies has strongly grown. As a matter of fact, since 2018 it can be noticed a steady increase in publications that relates to these technologies, especially DT and VR. However, even if the body of the literature is rich in journal papers, conference papers and book chapters, it lacks specific literature reviews that connects these technologies. Therefore, the main aim of this paper is to provide a clear overview of the applications of VR and AR concerning the brand-new concept of Digital Twins. In doing so, this study conducts a bibliometric review carried out with a Systematic Literature Network Analysis (SLNA) on the relationship between VR, AR and DTs. Firstly, by analysing the literature, this article describes the main contributions to the research on VR and AR-related DT applications. Secondly, this paper aims at identifying the main topics to which DTs have been related when matched with VR and AR concepts, and therefore to identify the importance of these technologies on DTs applications. Finally, the paper provides an analysis of the past, present and future trends of DT applications in the literature when related to VR and AR. In doing so, a new visual analysis and representation of keywords trend in time, based on the co-word network analysis typical of the SLNA, is presented, i.e. the Keyword Trend Detection (KTD). The study leads to two main conclusions. The first is related to contributions branches identification. Indeed, two main branches of contributions have been identified; the first is related to the concept of virtualization of manufacturing resources, while the second is focused on the applications of DT and VR. Secondly, as a result of the application of keyword clustering techniques, this research identified five clusters of research streams, i.e., *AR-*, *Robotics-*, *Virtual-*, *I 4.0 pillars-* and *DT- related* clusters.

Keywords: Digital Twin; Manufacturing; Industry 4.0; Systematic Literature Network Analysis; Bibliometric Review; Keyword Trend Detection

1.Introduction

The interest in the theme of Digital Twins (DT) of the literature in the last years has heavily grown, also led by the innovative technologies of the Industry 4.0 (I4.0) paradigm (Havard *et al.*, 2019). The first definition of Digital Twin can be referred to NASA that in 2012 defined it as "*an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin*". Therefore, DT can be seen as integrated simulation technology, with the aim of developing a high-reliable model of the behaviour of an environment. The use of the DT can lead to great insights to the users as well as feedbacks on the simulated object or environment (Saporiti et al. 2020, Tao, Qi, *et al.*, 2019). However, to develop a reliable Digital Twin, a huge amount of data gathered by sensors and a massive computation and transmission capability is requested to ensure a real-time connection between the physical and the digital twin (Negri, Fumagalli and Macchi, 2017).

Virtual Reality (VR) and Augmented Reality (AR) could represent powerful tools to enhance the capability and the interactions in a Digital Twin system. As a matter of fact, these technologies could enhance interactivity providing intuitive and efficient ways to manage the physical system simulated and emulated through the DT. VR, as well as AR, are key technologies in the Industry 4.0 paradigm, i.e. pillars. VR is a technology that aims at accurately replicating the physical world, mainly through CAD models and then provide an immersive experience inside the created virtual environment (Pérez *et al.*, 2020). The general idea in VR systems is to totally replicate not only the environment but also the animations, the movements that are usually performed inside the physical environment as well as the entire whole of sensorial feedbacks, i.e. images, videos and sounds (Burghardt *et al.*, 2020). VR systems are exploited to achieve several targets, which ranges from programming to design and training, as a cost-effective technology (Oyekan *et al.*, 2019). The main difference between VR and AR systems is the level of immersiveness in the virtual environment. As a matter of fact, in AR systems the main concept is related to an overlap of virtual information on the view of the user, generating in this way a virtual layer mainly exploited to provide better information about the daily routine job of the user.

However, an overview of the joint applications of VR and AR within Digital Twins is still missing from the literature. Nevertheless, understanding the relationship between these three technologies could be of great interest to the literature. As a matter of fact, it could be interesting to

reorganize the research carried out so far by identifying the main contributions, future trends in the topic, as well as possible joint applications of VR and AR within Digital Twins.

Therefore, this paper aims at providing a general view of the main contributions to the research on Digital Twins applications related to VR and AR technologies through a Systematic Literature Network Analysis (SLNA). Through the analysis of the literature, this paper aims at providing answers to the following research questions:

- RQ1: What are the main contributions in the literature on Digital Twins applications related to VR and AR, using citation network analysis?
- RQ2: What are the main themes that Digital Twin, VR and AR joint concepts have been related to?
- RQ3: What have been the main trends over time in the literature on Digital Twin concerning VR and AR and what are the recent research streams?

This paper is structured as it follows. Firstly, the next section presents the general description of the materials collected as well as the methodology that has been applied in the SLNA. Secondly, Sections 3 presents the analysis of the paper citation network, describing all the categories and critically analysing all the papers contributing to them. Thirdly, Co-word network analysis of the author keywords is performed in Section 4, while Section 5 presents a trend analysis of research streams in the literature based on keywords utilization score, providing a new graphical method that could be exploited in order to analyze keyword trends, i.e. Keyword Trend Detection (KTD). Finally, in Section 6 conclusions, limitations and future research directions are presented.

2.Materials and Methodology

2.1 Materials

The main database used in this study has been Scopus, as it is considered the best one regarding scientific journal coverage (Mongeon and Paul-Hus, 2016). The research has been firstly performed using Digital Twin, Virtual Reality, Augmented Reality and their main synonyms or abbreviations, i.e. Digital Shadow, DT, VR and AR as keywords. The search has been performed considering papers that present the selected keywords in the title, abstract or keywords (i.e. using the TITLE-ABS-KEY operator in Scopus). The resulting search query is the following:

TITLE-ABS-KEY ("digital twin") OR TITLE-ABS-KEY ("digital shadow") OR TITLE-ABS-KEY (dt) AND TITLE-ABS-KEY (vr) OR TITLE-ABS-KEY ("Virtual Reality") OR TITLE-ABS-KEY (ar) OR TITLE-ABS-KEY ("Augmented Reality")

This leads to 837 papers found. Secondly, to exclude some subject areas that are not related to the topic of the research, some filters have been added. In detail, the following subject areas had been excluded: Medicine, Earth and Planetary Sciences, Pharmacology, Toxicology and Pharmaceutics, Agricultural and Biological Sciences, Neuroscience, Arts and Humanities, Immunology and Microbiology, Health Professions, Dentistry, Nursing and Veterinary. This leads to a total number of 588 papers found. Thirdly, only journals and conference proceedings papers have been considered, leading to 536 papers as a result. Fourthly, papers have been filtered to consider only English written papers. Finally, the considered time span of the papers has been set from 2011 to 2021, as 2011 is considered to be the starting year of the Industry 4.0 paradigm in the Hannover fair. This leads to a final number of 324 considered papers. The extraction date is 30/12/2020. In order to provide some general analysis of the considered papers, some descriptive analytics have been computed. Firstly, from a general line chart of the number of publications through the years of the papers it could be easily noticed that there is a sturdy increase in publications from 2018 to 2020 (**Figure 1**).

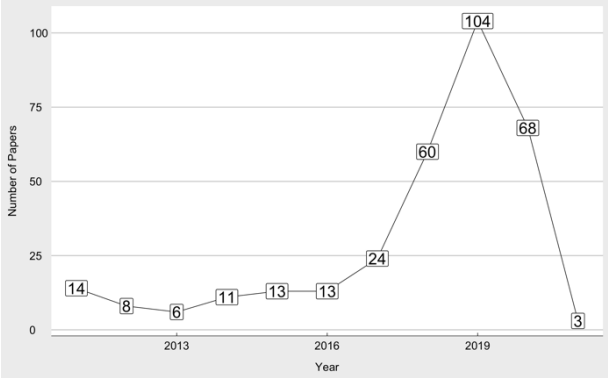

Figure 1: Temporal Distribution of Papers

As a matter of fact, in this period 232 papers have been published, representing 72% of the total number of publications from 2011. Secondly, a general analysis of the geographical distributions of the papers has been carried out through a histogram, where the top 10 countries for the number of papers published are listed (**Figure 2**).

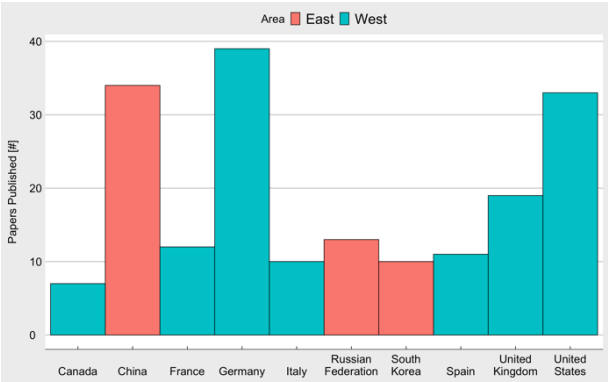

Figure 2: Geographical Distribution of Papers

Furthermore, countries are classified as belonging to East or West countries. From the chart is clear that West countries contributed more than East ones considering the total number of publications. Moreover, it can be noticed that Germany, China, United States and the

United Kingdom are the main contributors to the topic of this research, with respectively 39, 34, 33 and 19 publications. Thirdly, an analysis of the contributions by journals and conferences has been carried out. In doing so, Procedia CIRP has been detected as the most interested in the topic, with a total of 17 contributions in the sample. However, ACM International Conference Proceeding Series, IEEE Access, Applied Sciences (Switzerland), International Journal of Computer Integrated Manufacturing and Journal of Manufacturing Systems have been detected as interested in the topic, with a total of contributions respectively of 9, 7, 6, 5 and 5.

2.2 Methodology

The method used in this study to provide a complete overview of the relationship between Digital Twins, Virtual Reality and Augmented Reality is based on the bibliometric network analysis method. In particular, using the SLNA and considering aspects related to citation and keywords analysis, a wide area of relevant contributions will be considered based on a strong analytical and reliable method (Strozzi et al., 2017).

In order to answer the first research question, the analysis of the main development trajectory, i.e. the main path of the research in Digital Twin when related to AR and VR has been conducted. The most relevant papers from the main path have been carefully analysed. Another parameter taken into consideration for this analysis has been mainly the total citation score. As a matter of fact, the papers with the highest number of citations according to Scopus have been analysed as well. The main tools used in this part of the research have been VoSViewer and Pajek. The former software has been exploited to build the general network file to be able to perform analysis with the latter.

The second research question has been addressed through an analysis of co-occurrence in the author keywords of the considered papers (Waltman, van Eck and Noyons, 2010). Again, for this part of the research both VoSViewer and Pajek have been used, the first to generate network, partition and vector data for the second to read and elaborate.

As far as the third RQ is concerned, a trend analysis of the occurrence of the main keywords identified while addressing the second research question is carried out.

Table 1: Methodology Summary

Method Summary				
Research Question	Data	Graphical Representation	Tool	Software
What are the main contributions to the research on Digital Twins applications related with VR and AR and what do these contributions address?	Citations (References and Citations count)	Citation Network	Key-Route Main Path (on the connected component)	Pajek/VosViewer
What are the topics the Digital Twin concept has been related to and what is the importance of VR and AR among them?	Author Keywords	Co-occurrence keywords network	VoS Clusterisation of nodes	Pajek/VosViewer
What have been the trends in research on Digital Twin in relation with VR and AR and what are the recent research streams?	Author Keywords	Bar chart	Self-build function	RStudio

3.Paper citation networks

The paper citation network has been computed starting from the general network exported by VoSViewer. The network has been then imported and elaborated on in Pajek. Firstly, in order to identify the connections between the papers more clearly, a partition related to the weak connected component has been created. From the starting sample of 324 papers, 249 components have been identified. However, for analysis purposes, only the largest connected component has been considered, as it represents the most solid and steady elements of the analysed literature (**Figure 3**). This component presents 70 vertices (i.e. 70 papers connected), that is corresponding to 21.6 % of the total number of the considered papers.

From the biggest connected components, an analysis of the main path can be performed. Indeed, with a key-route global search performed in Pajek software, a main path composed of 15 nodes has been extracted (**Figure 4**).

The time span of the papers in the main path goes from 2017 to 2020, which is in line with the recent development in the field showed also in the publications trend (**Figure 1**).

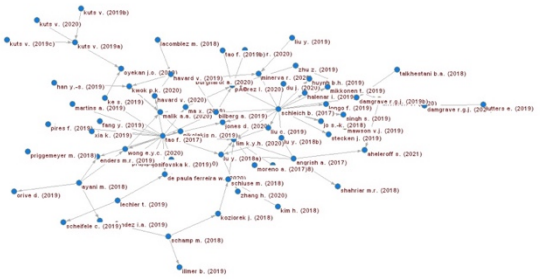

Figure 3: Largest Connected Component Network

The main path presents a two-branches structure.

The core of the first branch is mainly represented by the papers by Lu and Xu, 2018 and Angrish *et al.*, 2017. In the former, the authors propose the concept of DT as resource virtualization, providing a methodology to virtualize manufacturing assets. Similarly, in the latter is proposed the virtualization of manufacturing machines to external manufacturing systems. The other two elements of the first branch are both brand-new papers. The first one is by Lim, Zheng and Chen, 2020. Here is presented a survey on the theme of DT, where Virtual Reality is considered as an integrative technology in a future perspective. The last paper of this first branch is the one by Zhang, Yan and Wen, 2020; the authors here describe VR as a tool that can be exploited in order to successfully enable the interaction between the physical and virtual world.

The second branch of the main path is characterized by a concentration of papers which core is a joint application of DT and VR. As a matter of fact, Bilberg and Malik, 2019, Kuts *et al.*, 2019, Oyekan *et al.*, 2019 and Burghardt *et al.*, 2020 propose works that explore in a practical way the relationship between human and robots, and how Virtual Reality could actually help in enhancing the programming method as well as boost the general safety in a human-robot collaborative environment. In a more general way, Pérez *et al.*, 2020 propose an application of

VR in a DT aimed at providing a testbed to be used before the physical implementation of manufacturing elements. One of the predecessors of these papers in the main path is the one by Tao and Zhang, 2017. Here, the authors provide a general model of a DT based shop-floor, where DT is seen as a way to converge both the physical and virtual world in the manufacturing environment. Finally, also in this branch, a survey paper is detectable, i.e. the one by Minerva, Lee and Crespi, 2020. In this work, the authors propose VR as a new technology that should actually be taken into consideration to determine the main expected properties of a Digital Twin.

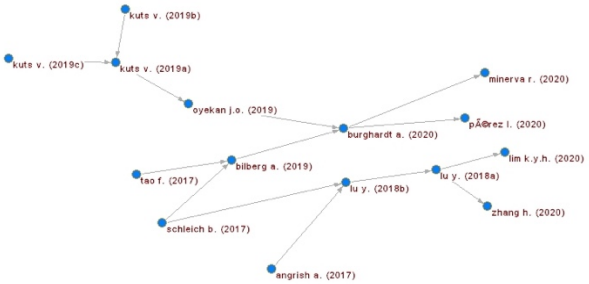

Figure 4: Main Path Network

In order to enhance the completeness of the study, an analysis of the top-cited papers has been performed. In particular, the papers at the top 10 in citation score have been further analysed, with particular attention to the ones not present in the main path analysis (**Table 2**). In the following, a brief description of the concept of each paper that is not included in the main path is presented.

Table 2: Top Cited Papers

Top 10 Cited Papers			
Authors	Year	Citations	Main Path
Schleich B. et al.	2017	291	Yes
Tao F. et al.	2017	247	Yes
Tao F. et al.	2019	100	No
Schluse M. et al.	2018	88	No
Lee J. et al.	2011	75	No
Zhang B. et al.	2014	73	No
Xie H. et al.	2014	69	No
Lu Y. et al.	2018	55	Yes
Chatterjee P. et al.	2020	50	No
Olea A. et al.	2013	49	No

For what it concerns the first three papers in our list, i.e. the ones from Lee, Post and Ishii, 2011, Schluse *et al.*, 2018 and Tao, Sui, *et al.*, 2019, there is still a weak connection to the themes of this study. However, their absence from the main path is justified by the fact that they are all not centred on the connection between DT, VR and AR. The last four in the list, i.e. Olea *et al.*, 2013; Xie *et al.*, 2014; Zhang, Xiu and Bai, 2014 and Chatterjee P. *et al.*, 2020, instead are not connected at all the theme of this research and have been correctly excluded from the main path by the key-route algorithm.

4.Co-word network analysis

The co-word network analysis has been addressed in order to determine what are the main topics the Digital Twin, VR and AR joint concept has been related to. Firstly, an analysis of the keywords has been carried out using VoSViewer. The minimum number of occurrences of a keyword to be considered eligible as one of the main keywords has been set to three, leading to a total number of 30 keywords that meet the threshold. A thesaurus has been used in order to perform some substitutions of keywords that would have been otherwise considered separated (**Table 3**).

Table 3: Keywords Substitutions

Keywords Substitutions	
Keyword	Replaced by
Automationml	Automation
Digital Twin *	Digital Twin
Virtual Reality (Vr)	Virtual Reality
Vr	Virtual Reality
Augmented Reality (Ar)	Augmented Reality
Ar	Augmented Reality
Internet Of Things (Iot)	Internet Of Things
Cyber-Physical System	Cyber-Physical Systems
Cyber Physical System	Cyber-Physical Systems
Cyber-Physical Systems (Cps)	Cyber-Physical Systems
Cyber-Physical Production System	Cyber-Physical Systems
Cyber Physical Systems (Cpss)	Cyber-Physical Systems
Cyber-Physical Manufacturing	Cyber-Physical Systems
Cyber-Physical Production Systems	Cyber-Physical Systems
Cyber-Physical System (Cps)	Cyber-Physical Systems

Afterwards, the data have been exported to Pajek (network, partition and vector files) and analysed within it. From this very general analysis, it can be noticed the importance of some keywords with respect to others. Indeed, the size of the nodes in the co-word network represents the importance of the keywords, i.e. the number of keywords with which each keyword is connected (**Figure 5**). In particular, it can be seen that Digital Twin, Virtual Reality, Augmented Reality and Industry 4.0 are the most used keywords.

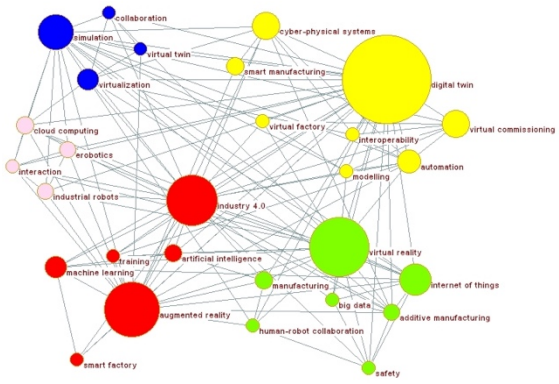

Figure 5: Keywords Network and Communities

Furthermore, another interesting analysis is the one that concerns communities of keywords. Indeed, with a VoS Clustering algorithm (Multi-Level Coarsening and Single

Refinement) with three restarts, 20 maximum levels in each iteration, 50 maximum repetitions in each level and 1 as resolution, the result of the algorithm provides 6 distinct clusters with a VoS quality of 0.434. Anyway, one of them has been ignored as not connected with the other ones, i.e. the *decision tree* keyword. This leads to a final number of 5 connected clusters of keywords (**Figure 5**, **Table 4**). In particular, these groups have been classified as follows.

Table 4: Keywords Clusters

Keywords Clusters				
AR-related	Robotics-related	Virtual-realated	I 4.0 pillars-related	DT-related
Augmented Reality	Industrial Robots	Virtual Twin	Virtual Reality	Modelling
Training	Cloud Computing	Virtualization	Manufacturing	Virtual Factory
Smart Factory	Erobotics	Collaboration	Internet Of Things	Virtual Commissioning
Machine Learning	Interaction	Simulation	Safety	Interoperability
Artificial Intelligence			Big Data	Smart Manufacturing
Industry 4.0			Additive Manufacturing	Digital Twin
			Human-Robot Collaboration	Automation
				Cyber-Physical Systems

The first cluster is related to the theme of Augmented Reality and Industry 4.0. In this group are included 6 keywords, i.e. *Augmented Reality, Industry 4.0, Training, Machine Learning, Artificial Intelligence and Smart Factory*. The links between these keywords are explained both as the utilization by AR technologies need algorithms taken from artificial intelligence and machine learning, as well as some of the main applications of AR systems (e.g. *Training* keyword). In this cluster, an interesting fact can be noticed. Indeed, here the presence of Augmented Reality as a keyword is quite strong and relevant in the overall network and communities structure, while in the main path analysis this topic seemed to be quite neglected. This can lead to the interpretation that the connection between AR and the other elements of the research could be quite fresh and young. As a matter of fact, the non-presence in the main path of AR-related papers, opposed to the heavy weight of this keyword in the co-word network analysis, is a clear signal of the fact that the Augmented Reality theme has not been connected with VR and DT in a way sufficiently deep to become part of the main path, even if the presence of the topic is strong in the overall network.

The second cluster is instead related to the robotics component. As a matter of fact, all the keywords concern robots or the connection between them. In this group, we find 4 keywords, i.e. *Industrial Robots, Interaction, Cloud Computing and ERobotics*.

The third group concerns the "virtual" section of a Digital Twin. Indeed, in this cluster, we find keywords that are all strictly connected with the aim in the virtual world of a DT implementation. In this set 4 keywords are identified, i.e. *Virtual Twin, Virtualization, Collaboration and Simulation.*

In the fourth cluster, Industry 4.0 pillars-related keywords are identified. As a matter of fact, in this group, we find 7 keywords that represent mostly the technologies that are the base of some I4.0 pillars, i.e. *Virtual Reality, Manufacturing, Internet of Things, Safety, Big Data, Additive Manufacturing and Human-Robot Collaboration.*

Finally, in the fifth group can be found 8 keywords strictly linked to the general idea of DT, from enablers and prerequisites to applications, i.e. *Modelling, Virtual Factory, Virtual Commissioning, Interoperability, Smart Manufacturing, Digital Twin, Automation and Cyber-Physical Systems.*

5.Keyword Trend Detection

In order to identify the past and present trends in the theme of DT when related to AR and VR, an analysis of the influence of the main keywords has been carried out. In doing so, for each of the considered keyword, three elements have been considered. Firstly, the year of the very first appearance of the topic as a keyword has been recorded. In this way, a tracing of a possible start of a new research stream could have been identified. Secondly, the year of the last appearance of the topic as a keyword has been taken into consideration. This was done to possibly identify the end of a considered research stream based on a certain keyword. Finally, the utilization score of the keyword in the considered time span has been recorded. In this way, it is possible to notice the magnitude of a certain research stream represented by the considered keyword. These three elements, i.e. the first year of appearance, the last year of appearance and utilization score, have been then exploited to create a visual representation of the trends in the literature. In doing so, a bar chart of keywords vs years have been built, where the height of the bars represent the utilization score of the considered keyword in each year, while the green and the red dots represent respectively the year of the first appearance of the keyword and the year of the last appearance of the keyword. Additionally, bars have been coloured according to the membership of clusters, to ease the comparison between keywords trend in the same cluster. Finally, the bars were ordered firstly by cluster and then by total decreasing utilization score (**Figure 6**). However, in order to provide a readable visual representation of this method, the utilization score has been transformed using a base 2 logarithmic scale.

The first aspect that appears from this analysis is regarding the connection between the very core of this research, i.e. *Virtual Reality, Augmented Reality* and *Digital Twin* keywords. Indeed, VR and AR are present as keywords since the very first year considered in the analysis, but become hot topics in 2017, where DT begins to have importance. Furthermore, from the thickness of the bars in the visual representation is quite evident that the trend of growth of VR, AR and DT in this research is quite connected. This can represent the fact that a strong connection between these themes is actually present in the literature. However, it must be noticed that DT presents the highest utilization score as a keyword, confirming the steady growth in the interest of the literature on this topic.

There is a second interesting aspect that emerges from the keywords' trend identification analysis, i.e. the birth of new research streams. As a matter of fact, some keywords seem to represent a starting point in the field concerning the joint use of DT, VR and AR. The themes of robotics, collaboration and safety for instance are at their infancy when connected to DT topics, but could represent major

future research streams. However, this kind of representation could help in analysing the developing and the internal dynamics of a cluster. Indeed, for each of the clusters is quite easy to identify the main keywords and above all the joint growth of some keywords inside the same cluster. For instance, in the AR-related cluster, is possible to notice that Augmented Reality and Industry 4.0 presents a very similar trend in growth. This element, when considered with the cluster analysis, can lead to the consideration that these two keywords have been actually used together and above all have been used in a growing trend together. Similar considerations could be taken in almost all the other clusters, even if in a slighter measure. As it is possible to notice, the use of this new kind of analysis can enhance the overall comprehension of the co-word analysis, adding time as an important component to identify trends. From here the name of the technique, i.e. *Keyword Trend Detection (KTD).*

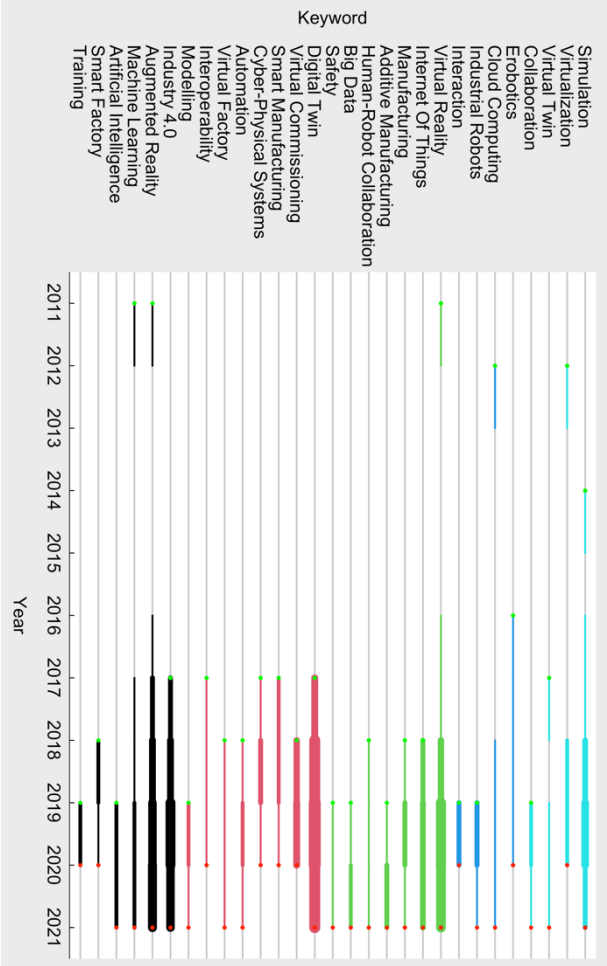

Figure 6: Keyword Trend Detection

6.Conclusions

In this paper, three major questions have been addressed.

Firstly, for what it concerns the theme of the main contributions to the research on Digital Twins applications when related to VR and AR, two main branches of contributors have been identified through a paper citation network. The first is mainly related to the concept of virtualization of manufacturing resources, even if it ends in a brand-new study that analyses the theme of DT with a survey. However, in these papers, VR is seen as an interesting technology that could be possibly exploited in the near future along with DTs. The second branch is instead more focused on the applications of DT and VR. As a matter of fact, VR is seen as a helpful technology to exploit together with DTs as a testbed for possible future configuration, with emerging interesting attention to the human-robot safety theme.

Secondly, through a co-word network analysis the main topics that jointly consider the presence of DT, VR and AR have been identified. Furthermore, through a VoS Clustering algorithm, 5 keywords clusters have been identified. While in three of them DT, VR and AR are the main nodes and therefore can be considered somehow representatives of the group, two additional clusters have been identified, one related to the theme of industrial robots and the other one to the topic of virtualization. Thanks to the co-word communities network analysis, research streams that have been neglected by the main path analysis have been identified, e.g. the AR-related stream.

Finally, through an analysis of the trends in the main keywords, i.e. the KTD, a general time and impact study of the hot topics in the literature has been carried out, considering both research streams in the present as well as in the past. This analysis leads to a threefold consideration. Firstly, while AR and VR have first appeared in 2011, they become hot topics from 2017, jointly with DT, which began to gain importance steadily from the same year. Secondly, some keywords can be considered as the starting point of promising new research streams (e.g. safety, industrial robots and collaboration themes). Finally, the KTD can help in identifying the internal dynamics of a cluster, as well as the developing of keywords through time.

This research presents several limitations. Firstly, only journal and conference papers have been considered. Secondly, the choice of the considered time span of the study has been made only according to the birth of the Industry 4.0 paradigm. Thirdly, an experimental new method has been introduced to determine the present and past trends of the research in the literature. Fourthly, only the authors' keywords have been considered while performing both co-word analysis and trend identification analysis. Finally, the review covers only a few years of intensive contributions. However, although the topic is extremely new, the interest and number of contributions in the literature are sufficiently high to justify a SLNA.

This study proves that the connection between Digital Twin, Virtual Reality and Augmented Reality is quite consistent. However, while VR is clearly mentioned as a promising technology to exploit the characteristics of a DT, especially in a design phase, AR applications are scarcely raised. This fact, connected with the heavy presence of AR as a keyword in the network, could lead to the interpretation that this theme is still quite fresh and young when connected to DT and VR so that it still couldn't be relevant enough to become part of the main

path. However, deepening into the reason that brings poor exploitation of AR technology in the DT could represent an interesting future research direction.

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