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# Cloud manufacturing developments: a review

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**Abstract:** Many scholarly articles have presented meaningful research on cloud manufacturing (CM), but over the past years, new paradigms of CM have emerged. This has brought diverse and interesting developments. The study presents the growth, developments and latest changes in literature in the past 11 years. The reviewed papers were based on the Scopus database (Elsevier springer, SAGE, Emerald, Francis, IJIMS and Wiley). Results on the first dimension show the number of publications between 2010 and 2021 covering 145 to 5,307 journal papers. According to the outcomes on the second dimension based on origin publications related to origin, China has 46% CM research publications. The third dimension focused on CM journal publications in IEEE Access as the most publication. The fourth dimension shows CM growth over the years. The significance of the findings is in the interest of CM as being evident that research is growing from concept to realisation.

**Keywords:** cloud manufacturing definitions; radical manufacturing; key technologies; application cloud manufacturing.

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**Biographical notes:** Mikateko Nonceba Baloyi is a Masters candidate in the Department of Industrial Engineering at Tshwane University of Technology. Her study is focused on the development of cloud manufacturing framework

implementation for small, micro and medium enterprises (SMMEs): a case in South African. She has identified a gap that shows that the lack of sustainability in South African's SMMEs and a resistances to adopt Industry 4.0 technologies. She holds a Bachelor of Technology in Industrial Engineering from Tshwane University of Technology. She is an entrepreneur in the aluminium industry. She is also a member of the Southern African Institute Industrial Engineering (SAIIE) and working on obtaining the Engineering License with the Engineering Council of South Africa (ESCA).

Khumbulani Mpofu is a seasoned Industrial Engineering Professor currently serving as the DSI NRF SARChI in Future Transport Manufacturing Technologies and Gibela Research Chair in Manufacturing and Skills Development. Driven by the need to bridge the innovation chasm he has established the Rail Manufacturing Centre for Entrepreneurship Rapid Incubator so that university innovations see the light of day. He is a leading researcher in advanced manufacturing focusing on various technologies to ensure manufacturing is aligned to the industrial revolutions that are continually evolving. To date, he has over 150 publications and raised US$10 million for research, innovation and commercialisation activities.

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## 1 Introduction

The concept of cloud manufacturing was introduced in China during the 12th Five Year Science and Technology Seminar in 2010. During the seminar, several experts and researchers in the Chinese manufacturing field engaged in conversation that led to new ideas of cloud manufacturing (Wan et al., 2020). During the past 11 years, cloud manufacturing has evolved as a new manufacturing paradigm, which had drawn attention, evident by the number of published articles from 2010 to 2021, and with more than 5,000 based on journal papers.

At conception, when the cloud manufacturing concept was established many advanced manufacturing modes were explored, such as agile manufacturing (Sharifi et al., 2001), network manufacturing (Mitsuish and Nagao, 1999), virtual manufacturing (Bremer and Evershein, 2000) and the manufacturing grid (Tao et al., 2008). The proposed study by the listed authors centred on collaborative manufacturing, network and resource-sharing played a huge role in the development of cloud manufacturing; the transformation of the traditional manufacturing system to a service-oriented manufacturing system.

The manufacturing industry is rapidly growing and has been engaging in an ongoing search for the most cost-effective, efficient, sustainable, and flexible manufacturing systems and technologies. Cloud manufacturing (CM) was developed for the manufacturing industry to be able to achieve the most cost-effective, efficient, sustainable, and flexible manufacturing systems and technologies. The concept of CM is an enabler to solve more complex manufacturing problems and carrying out larger-scale collaborative manufacturing.

According to Huang et al. (2013), cloud manufacturing is a new model that is developed using all the existing advanced manufacturing systems. The support of enterprise information technologies and cloud computing can enable the ability of a manufacturing system, company to meet customers' demands and respond to the unpredictable dynamic environment. According to Mittal et al. (2019, p.5), the new technologies and innovations are driving the industry towards the fourth industrial revolution (4IR); the internet of things (IoT) and artificial intelligence (AI) which make it possible to create a platform for resource sharing. Globally, we can see the growth of cloud manufacturing and how it made the global more competitive, as filter down locally to see what has been happening in South Africa, the work is based on developing frameworks for cloud computing adoption and noting based on the cloud manufacturing implementation framework. The application of cloud manufacturing varies from infrastructure as a service (IaaS), software as a service (SaaS), platform as a service (PaaS) and data as a service (DaaS), which combines the new generation information technology, big data, IoT and mobile internet with the manufacturing industry to build a cloud platform to optimise the allocation of resources.

The advancement of technology made it possible for the manufacturing industries to supply and meet the demands of the dynamic environment. In the future, the possibilities of adoption of smart and sustainable manufacturing as new trends of manufacturing have emerged due to globalisation, individualisation, customisation, and deep customer involvement. In this paper, we looked at the challenges faced by SMME's and the failure rate of SMME's in the entrepreneurial space. We identify the use of these emerging technologies from industry 4.0 to create sustainability for SMME's. CM is introduced as

a new paradigm that enhances manufacturing resources and capabilities sharing of the whole product lifecycle between manufacturing structures and enterprise systems. Cloud computing (CC) is promoted to be adopted by manufacturing enterprises to share resources and capabilities to enhance their response to market requirements and increase cost-effectiveness.

The paper examines what is achieved on CM, the challenges faced with CM, implementation and improvements around CM. The method adopted for the study is a survey methodology where the authors investigated changes and progress based on the available literatures on CM across the different applications in industry and academia.

The rest of the paper is structured as follows. Section 2 presents the literature review in cloud manufacturing including theoretical background, radical manufacturing ideas and key technologies contributing to CMfg and cloud platform and application. Section 3 presents the methodology which is divided into research design and research methodology. Section 4 covers the results and discussion where the authors analysed the developments in CM from 2010 to 2021, followed by the number of publications in year, moving through the origins of publications in CM and finally looked at journal publications on CM. Section 5 concludes this paper based on the findings and highlighting the possible future work.

## 2 Literature review

### *2.1 Theoretical background*

Several experts and researchers analysed network manufacturing and identified key technologies such as cloud computing, the Internet of things, cloud security, high-performance technology, which became an enabler to cloud manufacturing that will be able to solve the challenges that are faced in the manufacturing industry. Li et al. (2010) were the first authors to define what is cloud manufacturing stated as follows "cloud manufacturing is a new, networked manufacturing model that uses network and CMfg service platforms is to arrange online manufacturing resources according to users need and provide users with various on-demand manufacturing service".

In 2011, the new manufacturing model was starting to gain attraction as another definition emerged. According to Tao et al. (2011), the authors states that "CM is a computing and service-oriented manufacturing model that is developed from the advanced manufacturing model such as (AM, NM and MG) and enterprise information technologies under the support of cloud computing, IoT, virtualisation and service-oriented technologies, and advanced computing technologies".

Furthermore, we note that Xu (2012) identifies some different aspects to CM which define cloud manufacturing as a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction.

Additionally, as event evolved with time we can see how the definition of cloud manufacturing changes and expand as stated by Wu et al. (2013) "cloud-based design and manufacturing refers to cloud-based design and manufacturing refers to a product realization model that can foster knowledge and resource sharing and rapid product

development with reduced cost through a social networking and negotiation platform between service providers and consumers".

Similarly, Ren et al. (2017) see a completely different perspective with regards to definition of cloud manufacturing, the authors defined more by observing the technical and the benefits of cloud manufacturing. According to Ren et al. (2017), "cloud manufacturing is a smart networked manufacturing model that embraces cloud computing, aiming at meeting growing demands for higher product individualization, broader global cooperation, knowledge-intensive innovation, and increased market-response agility". Despite the different definitions we have research for cloud manufacturing, we know realised that cloud manufacturing does not only embrace the ability of cloud computing, but some other key technologies and the concepts of advanced manufacturing, therefore, we can see that there is no solid or standard definition of cloud manufacturing as literature shows different definition from different researchers.

## *2.2 Radical manufacturing ideas and key technologies contributing to CM*

CM does not depend on cloud computing only, there are other technologies and unconventional manufacturing ideas that made CM come to the realisation of these manufacturing ideas, which have been proposed in the past. Mitsuishi and Nagao (1999) explain that network manufacturing is a manufacturing system that allows decentration and enabling global competition, furthermore, Zhan et al. (2003) and Leitão (2009) state that network manufacturing or distributed manufacturing was advancing due to the thriving of the internet technology. The purpose of networking manufacturing is to link and integrating resources over the internet.

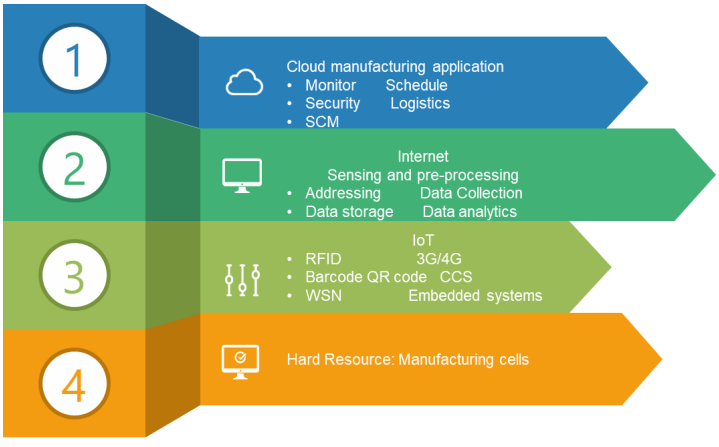
In addition, networking manufacturing is not the only radical manufacturing idea, there are several more of these manufacturing concepts. According to Fan et al. (2004), the manufacturing grid (MGrid) uses grid computing technology to assign tasks over grid notes. Furthermore, Tao et al. (2008) explain the idea of MGrid is to use the manufacturing resources that are distributed in various systems and different places to create collaborative manufacturing system for products and services in the markets demands.

Service-oriented manufacturing approved the concept of a service-oriented architecture (SOA) with purpose of employing combined and standard access to heterogeneous computer aided design/process planning/engineering/manufacturing (Cax) software in IT-base manufacturing stated (Erl, 2005).

Virtual manufacturing allows the user allows to engage to a virtual environment, in this insistence it will be a virtual manufacturing environment and in most cases, there are three dimensions in virtual manufacturing: firstly the convince of simulating the activities and functions of a real manufacturing environment. This can be achieved by means of integrating technologies for modelling and simulation stated (Cottet, 2008), virtual and augmented reality states (Ren et al., 2017).

According to Ren et al. (2017), cloud computing are other technologies that realises cloud manufacturing, cloud computing can be summarise in three basic components which are IaaS, PaaS and SaaS according to Buyya et al. (2009) as shown in Figure 1.

**Figure 1** Cloud manufacturing architecture and framework (see online version for colours)




*Source:* Adopted from Ren et al. (2017)

### *2.3 Cloud platform and application*

Many scholars have proposed a variety of CM platform models and architectures that are suitable for different industries and environments and have conducted in-depth research on the key technologies involved. In addition, advanced technologies, such as cloud computing, IoT and big data have been analysed and discussed at length. Research on the theory and technologies of CM have gradually developed and matured; hence, many enterprises and research institutes have applied the CM platform mode. Following the continuous development of CM, several enterprises in China, such as Shenyang Machine Tool, China Aerospace Science and Industry Group, and Haier Group, are gradually turning CM-related concepts and technologies into reality.

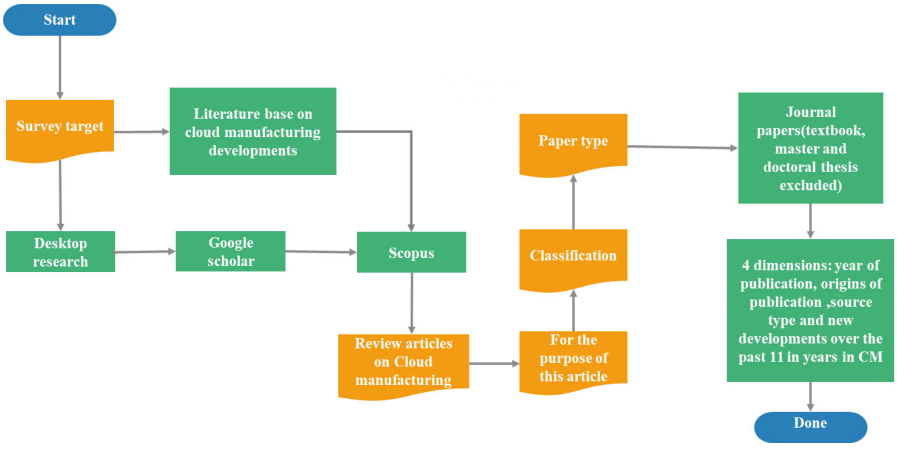
## 3 Methodology

### *3.1 Research design*

Figure 2 indicates the process that the author followed in conducting the study. The author searched for literature based on CM on Google Scholar, then Google Scholar redirected the scholar based on the publication source. Furthermore, the scholar used the Scopus database to collect the data required for the purpose of the article. In Scopus advanced search there, scholars applied the limits according to the dimensions of the paper, where the author specifically searched for journal articles from 2010 to 2021 and observed articles based on the type of journal papers. The paper was further classified under 4 dimensions: year of publication, publication source type, origins of publication and new developments over the past 11 years in CM.

### *3.2 Research methodology*

**Figure 2** Research methodology (see online version for colours)




## 4 Results and discussion

The objective of the study was to evaluate the progress that has been made in the past 11 years on CM. Figure 3 shows that in 2010 the concept of CM was introduced with the key technologies when the author analyses the development in CM. Before CM was explored, network manufacturing was studied to solve more complex manufacturing problems and perform larger-scale collaboration. When network manufacturing was investigated the new model that was developed after that was name CM as stated by Li et al. (2010). From 2011–2013, the research area grows to the cloud platform and service evaluation where the researcher was no longer seeking more understanding in the concept, but more on how to optimise human interaction and resource allocation. From 2014–2016, there was a gap in this new technology and scheduling problem. The growth and development in CM have been great, and more opportunities arise as the research area grows. In other areas, researchers sought a solution to solve CM and understand the benefits and challenges.

Table 1 shows a summary of different topics that have been cover in CM and not only limited to it. There we can also see how the once the study was introduced there was interest in developing architecture, platforms, application, frameworks and other research areas were identified based on the growth and more gaps were identified.

Figure 4 shows data that was collected from the Scopus database. For the study, the authors customised the searching settings to be aligned with the study. The study evaluated the number of publications in CM from 2010 to 2021 focusing on the journal papers.

The results show significant progress in CM, as the publication in 2010 was 145 and increase to 5,307 journal papers in 2021. Observing Figure 4, it can clearly be seen the trend and appetite on CM study. It shows that the concepts was introduce in 2010 because

the publications were just 145, then from 2011–2013 there an increase on publications with 86%, then from 2014–2016 the percentage of publication dropped with 22%, which shows that new gaps were identified inside and outside CM, furthermore, from 2017–2019 there was an increase of the research output on CM with 1% and finally we were able to see an increase from 2020 – current year at 12%.

**Figure 3** Developments in CM (see online version for colours)

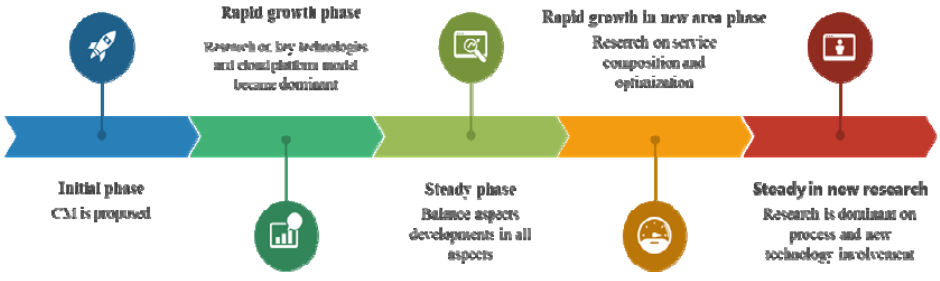
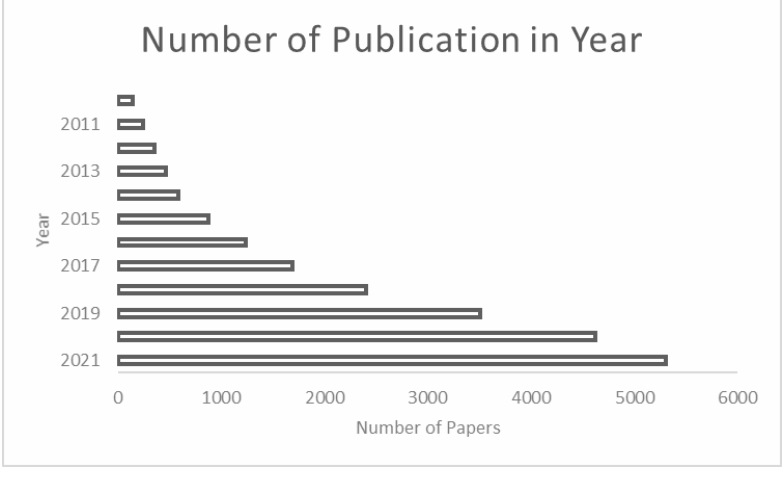



**Figure 4** Number of publication in year




When the analysis was made based on publications of affiliated countries in Figure 5, the results demonstrated that China is the leading country in the publication of the CM journal papers, followed by the USA, then India in the third place. In contrast earlier in the year Germany was in the third-place accord to Scopus database, this demonstrates the changes and evolvement around the CM in academia. The origins of publication were limited to only ten countries and the first nine countries are the leading countries in publication. In contrary, South Africa's publication is not even visible as seen in Figure 5. This illustrates that the origin of CM opportunities in South Africa presents a gap with relations to publication on CM.

**Table 1** Different studies in CM

| *Author* | *Classification* | *Purpose* | *Year* |
|---|---|---|---|
| Zhang et al. (2010a) | Architecture | Flexible management of resource service composition, with modules for function, monitoring and coordination. | 2010 |
| Li et al. (2010, 2011) | Architecture | Five layers (physical, virtualised resource, service (core middleware), application and user layers. | 2010 and 2011 |
| Tao et al. (2011) | Architecture | 10 layers (Resource, Perception, Resource virtualisation, cloud service, application, portal, enterprise cooperation, knowledge, cloud security and wider internet layers). | 2011 |
| Zhou et al. (2011) | Model | Manufacturing resource-sharing | 2011 |
| Zhou et al. (2011) | Application | Networked modelling and simulation platform, COSIM-CSP. Service scheduling, resource-sharing and collaboration simulation, collaborative design of virtual products, etc. | 2011 |
| Ning et al. (2011) | Architecture | Six layers (physical, resource-oriented interface, virtual resource, core services, service-oriented interface and application layers). | 2011 |
| Xu (2012) | Platform | Distributed interoperable manufacturing platform (DIMP). Integrative CAX environment. Integrates software suites based on the requests and tasks from users. | 2012 |
| Zhang et al. (2012a) | Platform | Multi-user oriented, service-based, commercial-available CMfg (CM) platform. | 2012 |
| Jiang et al. (2012) | Platform | Integrated service platform based on CAgent. | 2012 |
| Ding et al. (2012) | Platform | Collaborative manufacturing resource-sharing based on cloud services. | 2012 |
| Rauschecker and Stohr (2012) | Application | MaaS infrastructure with service description structure in a case for manufacturing of façade elements (ManuCloud). | 2012 |
| Wang and Xu (2013a, 2013b) | Architecture | Interoperable cloud-based manufacturing system (ICMS), three layers (user cloud/ application layer, smart cloud manager/virtual service layer, and | 2013 |
| Huang et al. (2013) | Manufacturing technology | Cloud manufacturing service platform for small and medium-sized enterprises' | 2013 |
| Tao et al. (2014) | Architecture | Five-layer architecture for intelligent perception and access of CM resources based on IoT. | 2014 |
| Ferreira et al. (2014) | Framework | A cloud-based web platform to support dashboard integrating communicational services, to enhance applications' interoperability | 2014 |
| Tao et al. (2014) | Framework | Frameworks for perception and access of hard, computational and intelligent manufacturing resources. | 2014 |
| Adetunla (2015) | Software | Developing manufacturing execution software as a service for small and medium size enterprise | 2015 |

**Table 1** Different studies in CM (continued)

| *Author* | *Classification* | *Purpose* | *Year* |
|---|---|---|---|
| Guo et al. (2015) | Cloud manufacturing | Agent-based manufacturing service discovery method for cloud manufacturing' | 2015 |
| Caggiano et al. (2016) | Machining | Cloud manufacturing framework for smart monitoring of machining | 2016 |
| Esposito et al. (2016) | Cloud computing | Cloud manufacturing: security, privacy, and forensic concerns', IEEE Cloud Computing | 2016 |
| Shamsuzzoha et al. (2016) | Virtual collaboration | Implementation of cloud-based manufacturing environment to facilitate virtual collaboration between industries', facilities | 2016 |
| Kassim et al. (2017) | Manufacturing process | An overview of cloud implementation in the manufacturing process life cycle | 2017 |
| Ren et al. (2017) | Cloud manufacturing | Cloud manufacturing: key characteristics and applications | 2017 |
| Wang et al. (2017) | Cloud-based process | Manufacturing system on the cloud: a case study on cloud-based process planning | 2017 |
| Hassanzadeh et al. (2018) | Cloud manufacturing | Cloud manufacturing: from a concept to a way for being lean | 2018 |
| Ellwein et al. (2019) | Cloud manufacturing | An automated literature review | 2019 |
| Liu et al. (2019a) | Cloud manufacturing | Cloud manufacturing: key issues and future perspectives' | 2019a |
| Liu et al. (2019b) | Cloud manufacturing | Scheduling in cloud manufacturing: state-of-the-art and research challenges | 2019b |
| Chang (2020) | Information systems | Presenting cloud business performance for manufacturing organisations | 2020 |
| Mourad et al. (2020) | Cloud manufacturing | Assessment of interoperability in cloud manufacturing | 2020 |
| Nurrahman et al. (2020) | Information systems | Designing information system for student practicum assessment in the laboratory | 2020 |
| Wan et al. (2020) | Cloud manufacturing | Cloud manufacturing in China: a review | 2020 |
| Yang et al. (2020a) | Software | Software-defined cloud manufacturing with edge computing for industry 4.0' | 2020a |
| Yang et al. (2020b) | Architecture | Big data-driven edge-cloud collaboration architecture for cloud manufacturing: a software-defined perspective' | 2020b |
| Zhang et al. (2020) | Service composition | Service composition in cloud manufacturing: a DQN-based approach | 2020 |
| Zhao et al. (2020) | Simulation | Modelling of service agents for simulation in cloud manufacturing | 2020 |
| Lim, et al, (2021) | Architecture | A critical analysis of its development, characteristics, and future agenda to support its adoption | 2021 |
| Gaiardelli et al. (2021) | Industrial revolution | Product-service systems evolution in the era of Industry 4.0 | 2021 |

**Table 1** Different studies in CM (continued)

| *Author* | *Classification* | *Purpose* | *Year* |
|---|---|---|---|
| Liang et al. (2021) | Logistics | Logistics-involved QoS-aware service composition in cloud manufacturing with deep reinforcement learning' | 2021 |
| Liu et al. (2021) | Resource optimisation | A privacy-preserving resource-trading scheme for cloud manufacturing with edge-PLCs in IIoT | 2021 |
| Lou et al. (2021) | Agent-based modelling and simulating | Cooperation emergence of manufacturing services in cloud manufacturing with agent-based modelling and simulating | 2021 |
| Wang et al. (2021) | Scheduling | Multi-user-oriented manufacturing service scheduling with an improved NSGA-II approach in the cloud manufacturing system | 2021 |
| Wu et al. (2021) | Logistics | Integrated cross-supplier order and logistic scheduling in cloud manufacturing | 2021 |
| Yuan et al. (2021) | Scheduling | Dynamic service resources scheduling method in a cloud manufacturing environment | 2021 |
| Zhang and Fan (2021) | Collaboration | Recommending collaborations with newly emerged services for composition creation in cloud manufacturing | 2021 |

**Figure 5** Origins of publication in CM (see online version for colours)

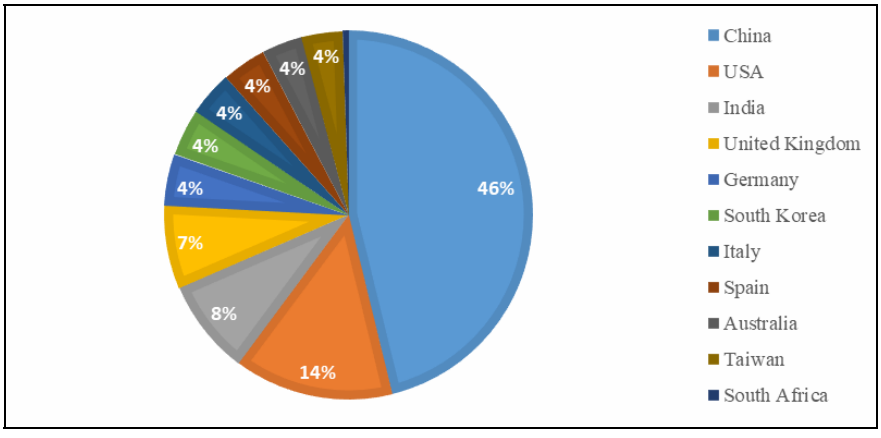
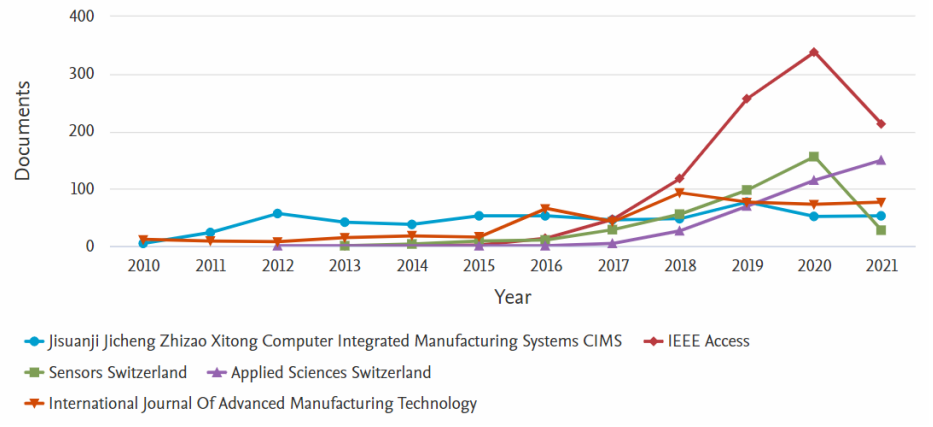



Figure 6 shows the journal publications of CM as shown below. *IEEE Access* is leading with 27% on publication of journal papers in the engineering area, followed by *Jisuanji Jicheng Zhizao Xitong Computer Integrated Manufacturing Systems CIMS* with 15% and *International Journal of Advanced Manufacturing Technology* in third place at 14%. This was an analysis based on the 11 years of research of CM by means of the Scopus database which also limiting us in only selecting ten journal publication. The results show the top nine publications and illustrate the *IJIMS* has 34 publications around CM meaning there more opportunities to publish and develop CM. Furthermore, the results show more prospects and innovations around CM and that there are more digital solutions in all areas of industry as we evolve technologically.

**Figure 6** Journal Publications of (see online version for colours)




## 5 Conclusions

Cloud manufacturing is a manufacturing model that is derived from the concept of radical manufacturing concepts, i.e., (NM, MGrid, AM, VM and VE) and that was enabled by the key technologies and drivers of cloud computing which integrated technology and convert the traditional manufacturing industry to the serviced-oriented manufacturing system. This paper aims at analysing the trends and developments that have been achieved with the concept of cloud manufacturing over the past 11 years. In order to ascertain the trends and developments with the concept of cloud manufacturing to the current state, we start by introducing a few concepts relevant to cloud manufacturing, cloud computing and advanced manufacturing concepts especially the ones that significant to the development of cloud manufacturing. The author utilised the Elsevier Scopus database, to identify the transition from 2010 of just being a concept to 2021 of being a manufacturing execution system. This paper summarised the radical manufacturing idea and key technologies, presented the methodology that presents the approached that was adopted for the study, and discussed and analysed the data that was collected from Elsevier Scopus database which showed us the significant growth in cloud manufacturing. Base on Figure 3, we were able to identify that in 2010 CM research areas were based on concept and key technologies investigating the operational model, framework and architecture, likewise from 2011 to 2013 we were able to recognise the growth in the research area and the number of publications increased with 88% from what is was compared in 2010.In the same way in 2014 to 2016 more technologies were explored and employed in CM as a result we were able to find that CM is no longer a concept but is an implemented manufacturing system as a solution as research area arise around scheduling problem and service optimisation algorithm. Furthermore in 2017 to 2019, the author acknowledged that research area in CM grows with 84% from 2010. In the future we will investigate on how we can alter these technologies and make them be a perfect fit in the Africa content, basically to customise them to solve the issues that are face in Africa as most of the work is around cloud computing adoption compared to cloud manufacturing. Additionally, we can make use of simulation game or simulation

software to make the environment best fitting to the conditions of the African content by benchmarking what it has been done around the world.

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