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Cloud manufacturing as a sustainable process manufacturing route

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ABSTRACT

Cloud Manufacturing (CM) is a service oriented business model to share manufacturing capabilities and resources on a cloud platform. Manufacturing is under pressure to achieve cost and environmental impact reductions, as manufacturing becomes more integrated and complex. Cloud manufacturing offers a solution, as it is capable of making intelligent decisions to provide the most sustainable and robust manufacturing route available. Although CM research has progressed, a consensus is still lacking on the concepts within CM as well as applications and scope beyond discrete manufacturing.

The aim of this paper is to demonstrate how CM offers a more sustainable manufacturing future to the industry as a whole, before focusing specifically on the application to process manufacturing (e.g. food, pharmaceuticals and chemicals). This paper details the definitions, characteristics, architectures and previous case studies on CM. From this, the fundamental aspects of the CM concept are identified, along with an analysis of how the concept has progressed. A new, comprehensive CM definition is formulated by combining key concepts drawn from previous definitions and emphasizes CM potential for sustainable manufacturing.

Four key methods of how CM increases sustainability are identified: (1) collaborative design; (2) greater automation; (3) improved process resilience and (4) enhanced waste reduction, reuse and recovery. The first two key methods are common to both discrete and process manufacturing, however key methods (3) and (4) are more process manufacturing specific and application of CM for these has yet to be fully realised. Examples of how CM's characteristics may be utilised to solve various process manufacturing problems are presented to demonstrate the applications of CM to process manufacturing. Waste is an important consideration in manufacturing, with strong sustainability implications. The current focus has been on using CM for waste minimisation; however, process manufacturing offers waste as a resource (valorisation opportunities from diversifying co-products, reuse, recycle and energy recovery). Exploring CM's potential to characterise and evaluate alternative process routes for the valorisation of process manufacturing waste is considered for the first time. The specific limitations preventing CM adoption by process manufacturers are discussed. Finally, CM's place in the future of manufacturing is explored, including how it will interact with, and complement other emerging manufacturing technologies to deliver a circular economy and personalised products.

1. Introduction

Today's manufacturing sector includes a broad range of industries, from food and drink, pharmaceutical, automobile and aerospace, to computer and electronic product manufacturing. Manufacturing is a vital sector in society, irrespective of being a high or low-income economy. In previous decades the manufacturing sectors of the USA, Japan, the UK, France and Italy have lost global market shares due to pressure from China. The exception being Germany, which has instead increased exports to China and Asia [1]. This is in part due to Germany's Government support of the application of manufacturing technology. Since the 2008 recession, policymakers in the West have focused on rebalancing the economy away from the service sector towards manufacturing [2]. Manufacturing in the USA and the UK account for 12% and 10% of the country's gross domestic product (GDP) respectively [3]. Whereas, in Germany the manufacturing sector accounts for 23% of GDP [3]. This led to the German economy making a faster recovery. It is not only Western economies that are facing new manufacturing chal-

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lenges. The recent trend has been for manufacturers to move to low-income economies to benefit from cheaper production costs. However, China's manufacturing growth is slowing due to the rapid increase in the cost of human resources, materials and energy [3]. Governments are facing the further challenge of developing policies which support manufacturing, while maintaining their commitment made in Paris to lower carbon emissions [4]. There are also additional drivers such as the EU Waste Framework, which promotes the waste hierarchy with financial incentives to minimise and/or reuse wastes [5]. The circular economy has emerged as an alternative economic model that supports growth, while minimising environmental impacts from production and consumption. The Waste and Resources Action Program charity offers a clear definition of the circular model: "A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life." [6]. To create a sustainable manufacturing future, new manufacturing models need to be explored that support this circular approach.

Various advanced manufacturing models have been proposed to achieve this [7–10]. A concurrent concept across these models is the idea of an increase in collaboration, automation, and knowledge and data sharing throughout the supply chain. As a result, the manufacturing process benefits from an increase in flexibility, resource efficiency, and customisation. Recently a new manufacturing paradigm called Cloud Manufacturing (CM) has emerged, which serves to act as a platform to deliver this vision [11]. Underlying the CM model is the concept of sharing manufacturing capabilities and resources on a cloud platform capable of making intelligent decisions to provide the most sustainable and robust manufacturing route available. Limitations in largely computer processing power, data collection and analytics, and security solutions have hindered the deployment of previous advanced manufacturing models. Cloud manufacturing however, has the advantage of utilising new technologies such as cloud computing, big data, and the Industrial Internet of Things (IIoT, the industrial focus of the Internet of Things), enabling CM to overcome many of these previous limitations. Cloud manufacturing also has the potential to be a key component in the future manufacturing landscape. It complements emerging manufacturing processes, such as Additive Manufacturing (AM), to deliver consumer customised products via sustainable processes. Where AM utilises 3D design data to build up a component in layers by depositing material, it is more commonly known as 3D printing [12].

Several projects have investigated research themes and applications of CM. In 2009, China launched the National High-Tech Research and Development Programme to promote research related to CM [13]. Two of the earliest and most cited papers on CM came from China. Tao et al. established and illustrated the basic ideas of CM including architecture, definition, characteristics and benefits [14]. Xu analysed how cloud computing is changing manufacturing and defined the difference between cloud computing alongside manufacturing and CM [15]. Under the European Seventh Framework Programme, the project ManuCloud was established. The ManuCloud project objective was to investigate and develop a cloud-based infrastructure to provide better support for on-demand manufacturing supply chains in the photovoltaic, organic lighting and automotive sectors [16]. There are now companies emerging which offer cloud-based services for manufacturing. For example, Plex Systems has developed the Plex Manufacturing Cloud, which is a software as a service (SaaS) enterprise resource planner (ERP) that manages the manufacturing process [17]. The software is designed to provide managers and engineers with real time access to production data. However, the full implications of CM have yet to be fully realised in industry. Industry 4.0 was first coined in Germany and refers to the digitisation of the manufacturing sector driven by huge increases in data volumes, computational power and increasing manufacturing plant connectivity [18]. Cloud manufacturing has potential to work within Industry 4.0 to exploit an on-demand access to a shared collection of manufacturing resources to form temporary, reconfigurable supply chains with enhanced efficiency, reduced production costs, and optimal resource allocation.

This paper shall aim to explain how CM may offer a route to sustainable process manufacturing. To achieve this effectively, this paper will address five key questions:

1 What is CM, its key characteristics and what are the proposed frameworks and architectures for implementing CM?
2 How does CM offer a route to future sustainable manufacturing?
3 How does process manufacturing vary from discrete manufacturing?
4 What are the opportunities for CM to benefit process manufacturing?
5 What limitations specific to process manufacturing currently prevent the widespread adoption of CM, and what future research is necessary to overcome these limitations?

2. Cloud manufacturing

2.1. Cloud manufacturing definition

Cloud manufacturing's first definition emerged in 2010 [11]. However, since that publication CM has generated considerable research interest and there now exists a variety of definitions. Unfortunately, there has yet to be an agreed common definition. Even the nomenclature and abbreviations can vary from author to author. A selection of some of the first CM definitions to emerge are detailed in Table 1, these definitions have since been commonly cited in recent publications on CM [19–25].

Each of these definitions prioritises different aspects of CM; for example, service oriented manufacturing, product development, resource allocation or customer centric manufacturing. The chosen aspect normally reflects the possible application of CM that was being demonstrated and was therefore highlighted in the authors' definition. Despite the differences in these definitions, all contain common elements such as, network manufacturing, ubiquitous access, multi-tenancy, virtualisation, big data, everything-as-a-service, scalability, and resource pooling. These can be used to help define the fundamental principles and characteristics of CM, which in turn give thought to how it can be utilised to achieve a sustainable manufacturing route.

To draw out the main themes, these definitions have been entered into a word cloud generator [30], the result of which is presented in Fig. 1. The word cloud highlights the following concepts: service oriented, on-demand, network, intelligent, access, knowledge based, shared pool, rapid, scalability, advance and virtualised. This paper proposes a comprehensive CM definition combining the highlighted concepts from all these definitions and emphasising CM potential for sustainable manufacturing.

> "Cloud manufacturing is a service oriented manufacturing model that virtualises manufacturing resources and capabilities into on-demand services accessed through the manufacturing cloud. This transforms manufacturing supply lines to become temporary, and provide greater flexibility and scalability resulting in increased resilience and sustainability throughout the manufacturing process. Cloud manufacturing is a multi-tenant, intelligent, knowledge based platform that can provide sustainable solutions throughout the product and process life cycle via