PHD

# Interoperability Assessment in Cloud Manufacturing

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# Interoperability Assessment in Cloud Manufacturing

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# Abstract

Cloud manufacturing is defined as a resource sharing paradigm that provides on-demand access to a pool of manufacturing resources and capabilities aimed at utilising geographically dispersed manufacturing resources in a service-oriented manner. These services are deployed via the Industrial Internet of Things (IIoT) and its underlying IT infrastructure, architecture models, as well as data and information exchange protocols and standards. In this context, interoperability has been identified to be a key enabler for implementing such vertically or horizontally integrated cyber-physical systems for production engineering. Adopting an interoperability framework for cloud manufacturing systems enables an efficient deployment of manufacturing resources and capabilities across the production engineering life cycle.

The overarching aim of this research is to investigate interoperability in the context of cloud manufacturing to identify the key parameters that determine whether or not a change-over from cloud manufacturing that deploys traditional g and m codes to interoperable cloud manufacturing is financially viable for a given scenario of service providers and manufacturing orders in a cloud manufacturing set up. The interoperable framework described in this thesis entitled, Cloud Manufacturing Resource Sharing (C-MARS) enables error-free and non-ambiguous information transfer between the various components and layers of a typical cloud manufacturing system. C-MARS is based on the STEP-NC (ISO 14649) standard for product data exchange. The Interoperable framework captures the key operational steps and processes of both cloud-based manufacturing processes and thus forms a basis for further investigating the behaviour and significance of parameters in response to a given production scenario.

Building on this, an activity-based deployment model (C-MARS-ABM) is proposed to simulate and further compare interoperable and non-interoperable cloud manufacturing scenarios for production parts of different complexity, varying production numbers, and manufacturing service composition setups typical to SMEs of varying sizes. The results of this research confirm that interoperable cloud manufacturing systems cannot be considered a one-size-fits-all option. Rather, its applicability depends on a number of driving parameters that need to be analysed and interpreted to determine whether or not it provides a financially viable alternative to cloud manufacturing without an overarching interoperability framework.

Dedicated to my parents, Ahlam & Hassan

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# List of Abbreviations

| | |
|---|---|
| **CAD** | Computer-Aided Design |
| **CAM** | Computer-Aided Manufacturing |
| **CAx** | Computer-Aided System |
| **CIM** | Computer Integrated Manufacturing |
| **C-MARS** | Cloud Manufacturing Resources Sharing |
| **C-MARS-ABM** | Interoperable Cloud Manufacturing Activity Based Model |
| **Cmfg** | Cloud Manufacturing |
| **CNC** | Computer Numerically Controlled |
| **ERP** | Enterprise Resource Planning |
| **Haas** | Hardware-as-a-Service |
| **IaaS** | Infrastructure-as-a-Service |
| **IIoT** | Industrial Internet of Things |
| **IoT** | Internet of Things |
| **IP3AC** | Integrated Platform for Process Planning and Control |

| | |
|---|---|
| **NC** | Numerically Controlled |
| **NC-MARS-ABM** | Non-Interoperable Cloud Manufacturing Activity Based Model |
| **OOP** | Object Oriented Programming |
| **OOT** | Object Oriented Technology |
| **PaaS** | Platform-as-a-Service |
| **SaaS** | Software-as-Service |
| **SMEs** | Small and Medium sized Enterprises |
| **STEP** | Standard for the Exchange of Product Model Data |
| **UML** | Unified Modelling Language |
| **WSDL** | Web Services Description Language |
| **XaaS** | Everything-as-a-Service |
| **XML** | Extensible Mark-up Language |

# Nomenclature

| **Symbol** | **Definition** | **Unit** |
|---|---|---|
| $A_o$ | Assignment Indicator | 0 or 1 |
| $A_C$ | Assignment of SMEs | 0 or 1 |
| $C_t$ | Clamping decision time required | minutes |
| $E_x$ | Number of CAD/CAM enterprise experts | |
| $E_p$ | Number of employees in the whole enterprise | |
| $Ex_a$ | Number of CAD/CAM experts assigned | |
| $M_a$ | Total number of machine-tools assigned | |
| $M_{ds}$ | Number of machine tools assigned per order | |
| $M_d$ | Number of enterprise deployed machine tools | |
| $M_{ta}$ | Machining time available | minutes |
| $M_{da}$ | Number of machine tools assigned | |
| $M_{tr}$ | Machining time required | minutes/part |
| $O_r$ | Number of order required | |

| | | |
|---|---|---|
| $O_p$ | Number of operators in enterprise shop-floor | |
| $P_tr$ | Process planning time required by C-MARS | minutes |
| $Q_r$ | Quantity per order | parts |
| $R_p$ | Required number of parts | |
| $S_f$ | Number of enterprise operating shifts | |
| $Tp_r$ | Number of tool-paths required by C-MARS | |
| $U_m$ | Utilisation of the machining time | |
| $Z_c$ | Total cost value of the interoperable deployment approach | £ |
| $Z_nc$ | Total cost value of the non-interoperable deployment approach | £ |

# Chapter 1

# Introduction

Decentralisation and resource sharing are key drivers for success in today's globalised economy, as small and medium size enterprises strive to overcome the aggressive competency due to sharing of resources and assets all over the world. This market change has lead to the introduction of the distributed manufacturing with the aim of sharing geographically dispersed manufacturing resources and capabilities. The move away from manufacturing service provision on the basis of installed machines at a given site towards almost freely configurable requirements-based service provision is paving the way for an ongoing transition from traditional onsite manufacturing to cloud manufacturing.

The manufacturing industry is gradually moving to view resources as a set of services that can be used on an ad-hoc basis (Ren et al., 2014; Xu, 2012; Tao et al., 2011; Gao et al., 2009). As services require more information compared to the traditional view of dedicated manufacturing resources (Tao et al., 2011) , informatisation of manufacturing is emerging as a strategic step for realising this new paradigm (Lv, 2012). In order to bring this change about, recent advances in Information and Communication Technologies (ICT), including the Internet-of-Things and Cloud Computing are being deployed. This informatisation is an enhancement and collaborative approach aimed at expanding the competitiveness of small and medium size manufacturing enterprises known as SMEs (Ren et al., 2015).

As a result of this enhancement, SMEs gain the ability to provide manufacturing services and accommodate larger and more complex jobs, which allows them to take steps towards globalisation of economy, resources and further rapid development of advanced manufacturing, information, computer and management technologies (Valilai and Houshmand, 2013) .The resulting environment allows for various application services to be provided, e.g. Collaborative design services allowing different users of different platforms to share product design information, digital manufacturing services that leverage different manufacturing resources from different domains and B2B e-Commerce that enriches the online business transactions among a cloud-based manufacturing enterprises.

The initial movement in this direction was triggered by the introduction of grid computing technology, which refers to a pool of computing devices connected in a network allowing sharing of resources such as data storage and processing power in a community-like environment. Once adopted, this paradigm became known as "Manufacturing Grid" and is widely understood as a means of enabling and offering remote access to distributed manufacturing resources via the Internet and the application of grid technologies, to support applications such as product design and sharing, integration, scheduling of manufacturing resources (Fan et al., 2004). However, many challenging issues limited the approach from practical implementation: lack of protocols, standards and criteria and commercial operation models as well as interfacing issues between physical manufacturing resources and software applications (Tao et al., 2011).

Subsequently, cloud Manufacturing was introduced as a new service-oriented manufacturing paradigm. which is defined as a resource sharing paradigm that provides on-demand access to a pool of manufacturing resources and capabilities aimed at utilising geographically dispersed manufacturing resources in a service-oriented manner. It utilises cloud computing technology along with the Internet-of- Things and state-of-the-art manufacturing technologies to integrate manufacturing resources and capabilities to offer on-demand, reliable and affordable manufacturing services for the entire manufacturing product life cycle (Zhang et al., 2012). Through the intelligent integration of manufacturing resources and capabilities, a shared pool of resources is created via a cloud manufacturing framework, promoting cloud users to acquire manufacturing tasks as a service (Ren et al., 2015). The integration of the deployed manufacturing resources and capabilities is achieved through virtualisation, as resources are enabled for sharing and accessed as cloud services (Liu et al., 2011a).

Ren et al. (2014) point out that the cloud within the manufacturing environment would thus enable : (i) delivering standardised manufacturing services over the Internet, discharging cloud users to obtain, develop, maintain, and manage hardware and software manufacturing resources; (ii) promoting virtualisation and a shared pool of resources to enhance the utilisation of manufacturing resource usage; (iii) scalability, promoting cloud manufacturing users to dynamically control production capacity, based on users demand; (iv) cost metering, "the pay-as-you-go" scheme which is utility based cost metering that assign costs based on user/provider resource consumption; (v) on-demand self-service approach that promotes users to have ubiquitous access and natural human computer interaction to manufacturing resources.

The cloud manufacturing approach strives to overcome the drawbacks of former approaches of networked manufacturing: absence of stable manufacturing resource transactions on a large-scale manufacturing operations (Xu, 2012), insufficient middleware interfaces or APIs to deploy heterogeneous manufacturing resources for network representation (He and Xu, 2012), and lack of flexibility and agility between the manufacturing enterprise and the shop-floor (Wu et al., 2014b; Panetto and Molina, 2008).

The emerging cloud paradigm has a prominent effect on manufacturing (Ren et al., 2015; Wu et al., 2013b; Xu, 2012), the move from hardware bound systems to requirements based service provision is one of the main issues for enabling the transition to cloud manufacturing, as recent research efforts have summarised the main challenges for cloud manufacturing as follows:

1. Unclear principles for the protection of the end user investment. The new business model that comes with cloud manufacturing requires fresh perspectives on protection of rights.
2. Difficulty in communication and interaction between departments within the enterprise and among the stakeholders within the supply chain. due to the use of different systems with different focuses.
3. Limited collaboration and interaction between business partners within cloud manufacturing.
4. Absence of a readily available implementation framework for cloud manufacturing services. Each company has to implement this as a new system.
5. Difficulty in the deployment of physical resources, such as machines, monitors and facilities. This is due to un-preparedness of a large portion of resources for the required connectivity.

A networked manufacturing service provision system should allow various stakeholders to access the necessary manufacturing information according to their requirements, enabling integration of heterogeneous manufacturing resources along the product life cycle. Accordingly, a large amount of data exchange will be required to realise cloud manufacturing.

Interoperability is identified as one of the essential requirements for enabling cloud manufacturing (He and Xu, 2014; Vincent Wang and Xu, 2013). Researchers, have identified that having a framework of open standards and application protocols to enable easy migration and integration of manufacturing applications and data between different cloud service providers is critical for cloud manufacturing (Xu, 2012). To date, interoperability has not been implemented at a sufficient level to allow for commercial cloud manufacturing. There still is a lack of standardized methodologies of information exchange between different cloud users (Xu, 2012). This standardisation can be carried out at different conceptual levels.

This research attempts to identify the key process parameters for selecting the level of interoperability in cloud manufacturing processes via a generic and costing-based operation and deployment model. The model is used to simulate cloud-based manufacturing scenarios at two levels of interoperability for parts of different complexity, varying production numbers, and service composition set-ups typical to SMEs of varying sizes. This methodical approach will promote cloud stakeholders and architectures of having a rigorous and clear assessment for the appropriate industrial standard to be adopted within cloud manufacturing activities.

The following chapter will present the overall scope of the research, followed by chapter 3 which reviews the state-of-the-art in cloud manufacturing. Chapter 4 illustrates the proposed interoperable framework for cloud manufacturing and explores the various prospectives of the framework. The realisation of the proposed framework is discussed in chapter 5. The design of experiments and analysis of results are explained in chapter 6 and chapter 7, followed by an explicit discussion of the research conducted in chapter 8. Finally the conclusions and potential future of the proposed work is outlined in chapter 9. The overview of the thesis structure is depicted in figure 1-1.

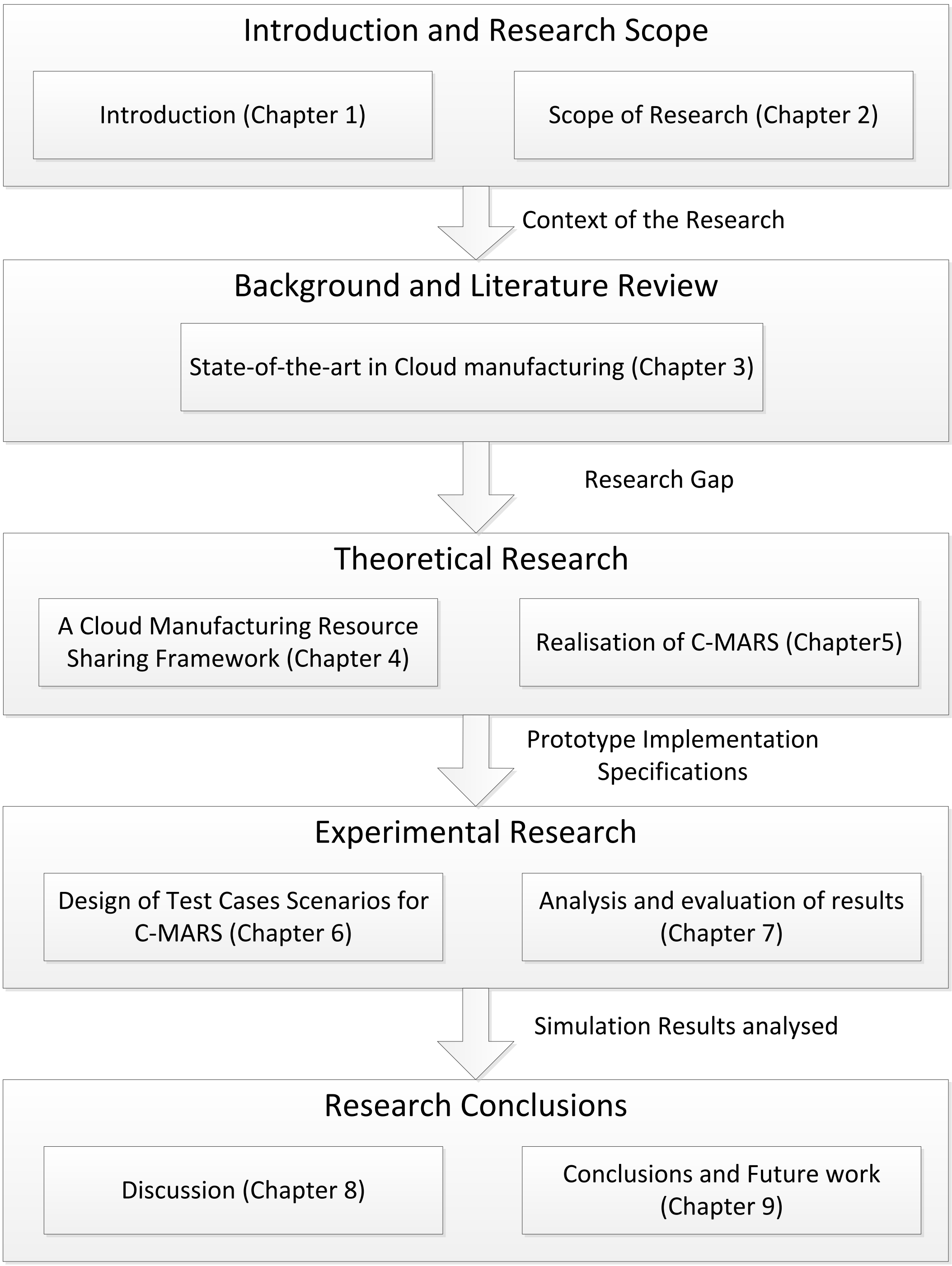

Figure 1-1: Structure of Thesis Chapters

# Chapter 2

# The scope of research

## 2.1 Introduction

This chapter unpacks the research aim to derive supporting objectives and boundaries of the research. In subsequent sections, the boundaries of cloud manufacturing system are defined and the scope of research clarified to identify the author's perspective on the application of interoperable cloud manufacturing systems within a distributed manufacturing environment.

## 2.2 Aim

Previous research has shown that cloud manufacturing system requires costly preparations and investment for increasing interoperability in a manufacturing resources and capabilities across the product life-cycle. The aim of this research is to investigate interoperability for cloud manufacturing environment to identify the key parameters that determine whether or not deployment of an interoperability platform is financially viable for a given manufacturing scenario.

## 2.3 Objectives

The following objectives have been identified to track the progress of the research and ensure that the aim is achieved:

(I) Identification of existing research gaps in the context of interoperability in cloud manufacturing.

(II) Identification of existing interoperability techniques for the exchange of product life-cycle information in relevant ISO standards and other national and international academic research to assess their potential applicability for realisation of an interoperable framework for cloud manufacturing.

(III) Creation of a verified theoretical framework to meet the requirements for an interoperable resource sharing system by combining existing methods identified in the second objective with novel approaches as required.

(IV) Realisation of activity based models for both interoperable and non-interoperable cloud manufacturing systems based on the validated framework developed in the third objective within the boundaries and scope of the research.

(V) Development of an experimental model for assessing both approaches via industrially inspired simulated cloud formations in order to contain the emerging industrial application of cloud manufacturing.

(VI) Identification and specification of the driving key parameters for determination of the appropriate deploying approach for cloud manufacturing system, outlining a rigorous decision making approach for deployment approach adoption.

## 2.4 Research method

The hypothesis of this research is that in a given cloud manufacturing framework, the specific values of select process parameters can be used to decide whether or not the deployment of a standardised interoperable cloud manufacturing framework will be cost effective. The following steps will be undertaken to test this hypothesis and achieve the aim of research.

(I) **Review of the relevant literature on cloud computing, cloud manufacturing and interoperability in manufacturing context**

  (a) Investigation and analysis of Cloud manufacturing: The state-of-the-art of cloud manufacturing will be reviewed and identified to explicitly show its impact on the manufacturing sector through resource sharing, rapid prototyping and reduced cost. Furthermore investigating the intermediate processes throughout the product life-cycle will be obtained.

  (b) Review of cloud computing with regards to costing methods and virtualisation of manufacturing resources and capabilities: This area of research will review the literature on cloud computing used in the manufacturing virtualisation process to define the tools used for virtualisation of manufacturing capabilities and manufacturing resources. Furthermore, the cloud-based strategies, costing methods and business intelligence of SMEs will be reviewed to determine the aspect of business models used by SMEs.

  (c) Review of application of interoperability in manufacturing: A systematic review of previous industrial and academic studies on manufacturing interoperability as well as ISO 10303 (STEP) and ISO 14649 (STEP-NC) will be undertaken. As a result an understanding of the current techniques and their achievements for reaching an interoperable manufacturing system will be achieved.

(II) **Selecting a cloud manufacturing approach**

In this section, a review of cloud manufacturing frameworks will be conducted and the results analysed based on functional requirements, business constraints and technology constraints, in order to adopt a suitable approach for system deployment. As the object oriented approach, explicitly UML and IDEF0 tools have been utilised to depict the adopted cloud manufacturing framework.

(III) **Designing an interoperable and non-interoperable cloud manufacturing framework(activity models)**

Based on the research gaps identified in the review of literature, and the following outcomes of research steps, a theoretical framework will be devised to address the required interoperable cloud manufacturing system. Additionally, a non-interoperable framework will be developed to form the baseline for the analysis and testing of the research hypothesis. [1]

(IV) **Development of activity-based models for both interoperable and non-interoperable cloud manufacturing system deployment approaches**

At this stage, the illustration of the order processing activities for both approaches is explored, in order to reveal a holistic overview of machining processes for executing cloud manufacturing orders. The activity models developed will be utilised further to allocate and specify the significant parameters of enabling the adequate deployment approach for cloud manufacturing systems.

(V) **Establishment (preparation) of experimental scenarios for cloud ordering process**

The formulation of the simulated experimental model will be established in this phase, as the Montecarlo simulation approach is utilised in order to represent an industrially inspired case scenarios.

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[1] non-interoperable is used as a relative term rather than an absolute one; in other words, the "non-interoperable" system is less interoperable than the other system but low-level interoperability would still exist.

(VI) **Analysis of the cloud manufacturing frameworks developed to identify key parameters for deploying approach**

In this phase various simulated industrially case scenarios will be applied on the frameworks developed followed by a sensitivity analysis of the results obtained using ANOVA technique, in order to specify the driving key parameters for determining the appropriate deploying approach for a cloud manufacturing systems.

## 2.5 Research context and boundaries

The overall methodology of the research is chosen to test the hypothesis within a positive context. The fundamental positivist assumption here is that cloud manufacturing systems behave deterministically and that it is possible to understand, predict and model their behaviour objectively. Thus, a deductive research methodology with a quantitative approach has been adopted. The deductive methodology explores a known theory, and tests for the validation of the theory under given circumstances. The approach begins with definition of the problem, followed by an analysis phase to establish the hypothesis. This is followed by synthesis, validation and conclusion (Bock, 2001).

An interoperable cloud manufacturing system will require an information exchange system for high-level integration of software tools and hardware manufacturing devices. The concern of this research is to identify an architecture for this information exchange system and discover the parameters that define the appropriate industrial scenarios for applying an interoperable cloud manufacturing framework. The boundaries of the research are defined with respect to manufacturing technologies, simulation, and integration to focus the work. These boundaries, shown in figure 2-1 are described in the following sections:

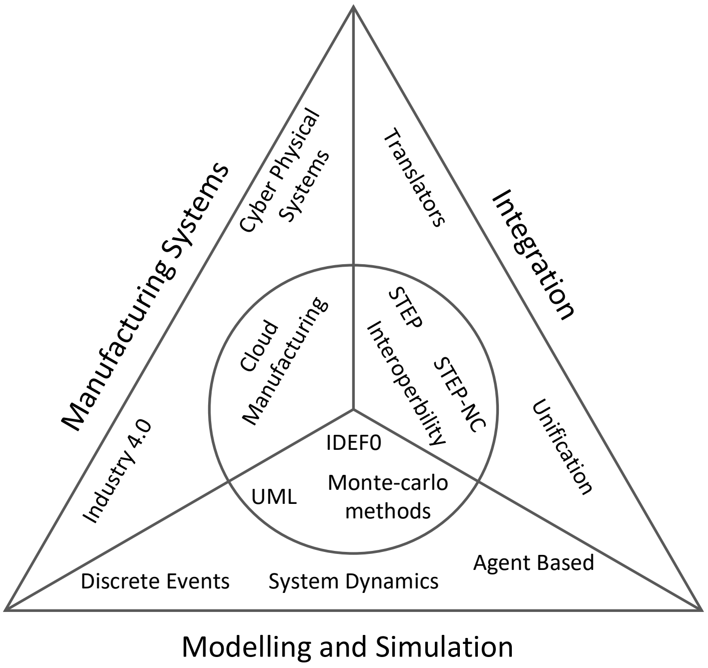


Figure 2-1: Research boundaries within context

### 2.5.1 Manufacturing systems

Emerging trends in manufacturing technology including Industry 4.0 (Zhou et al., 2016), Virtual manufacturing (Khan et al., 2011), and Cyber physical systems (Wang et al., 2015) are leading to ever closer integartion of digital and manufacturing technologies.

Cloud manufacturing has been identified as one of the enabling manufacturing technologies aimed at further advancing distributed manufacturing. It is based on application of the software as a service (SaaS) concept from cloud computing to manufacturing. It is a new paradigm that aims to share manufacturing resources (i.e. equipment, materials, software, knowledge, and skills) and manufacturing capabilities (i.e. design, production, management, and communication) on a large unified network using the Internet. This will enable access to these resources and capabilities in the form of manufacturing services, based on the user's request. It can potentially execute the manufacturing processes from design to final machined part. This research will only focus on those aspects of digital manufacturing that are relevant to cloud manufacturing, furthermore, machining of metals has been selected as the process focus of the work, although the techniques used in the research can be applied to other processes.

### 2.5.2 Integration

The scope of research involves the cloud manufacturing systems which utilises heterogeneous manufacturing resources and capabilities from design to final part. Thus integration of these components is required in order to enable manufacturing in the cloud. Mainly, interoperability was deployed as a key parameter for cloud manufacturing system deployment. As it allows different components of a system (or different systems) to communicate and/or interact between each other to facilitate shared goals. Further, the STEP (ISO 10303), explicitly STEP-NC (ISO 14649) has been elected as a communication language between the developed cloud manufacturing framework within this research. This international standard offers interoperable exchange of information among CAx, manufacturing equipments and planning systems.

### 2.5.3 Modelling and simulation

The unified modelling language (UML) has been utilised as a tool to design the interoperable cloud manufacturing system, as it provides agility and flexibility that can be further deployed in Java programming which adopts an object oriented approach that STEP-NC utilises. Cloud manufacturing paradigm is still in the juvenile phase and not yet fully implemented nor adopted on a world wide scale (Siderska and Jadaan, 2018; Adamson et al., 2015). Hence, Monte-Carlo simulation was utilised for representing the various ordering scenarios and different sizes of SMEs deployed in the cloud, via generating feasible sets of machining orders along with elected numbers of deployed SMEs.

# Chapter 3

# State-of-the-art in Cloud Manufacturing

## 3.1 Introduction

The objective of this chapter is to review the state-of-the-art of cloud manufacturing along with its related approaches and enabling key technologies. Techniques used for cloud manufacturing design are investigated, followed by a review of cloud manufacturing service management aspects. Furthermore, a systematic review of manufacturing interoperability is provided. This is then used to identify the research gaps.

## 3.2 Cloud computing: A history and background

### 3.2.1 Overview and background

As the core technology of the cloud manufacturing paradigm, a brief overview of the cloud computing concept is investigated. Cloud computing is defined as "a computing model, in which resources (e.g., CPU and storage) are provided as general utilities that can be leased and released by users through the Internet in an on-demand fashion" Zhang et al. (2010b). It was firstly introduced in 1999, for delivering enterprise applications through the usage of the Internet by a website interface (Aref, 2009).

Cloud computing is the result of evolution of the peer computing technologies developed. There are thus relative technologies with which cloud computing shares certain aspects with, as Zhang et al. (2010b) explained: (a) Grid Computing: that operates distributed resources in order to execute requested tasks. (b) Utility Computing: which offers on-demand resource availability along with "pay-as-you-go" pricing. (c) Virtualisation: that transfers resource's physical features into virtualised features. (d) Autonomic Computing: its a self management computing technique that enables computer systems to overcome management complexity.

Accordingly, these related technologies provide cloud computing with some essential characteristics as (Chabrow, 2011); (a) on-demand self-service: gaining independent access to computing services without human interaction with each service provider; (b) broad network access: which is providing cloud capabilities over the network and accessing it through standard mechanisms that promotes usage by different client platforms (e.g. mobile phones, tablets, laptops and workstations); (c) resource pooling: the service provider's resources are pooled together using multiple-tenant model and are dynamically assigned and reassigned according to service user demands; (d) rapid elasticity: cloud capabilities can be scaled easily inward and outward depending on demands, thus, providing a continuous service in any quantity at any time and (e) measured service: cloud systems utilise the metering capability approach to control and optimise computing resources automatically, based on the type of service required.

This enables enhancement of the cloud capabilities to offer services such as (Kremian, 2014); storage and scalability, backup and disaster recovery, mobility, Cost efficiency and Enable IT innovation. Various cloud computing models will be demonstrated in the next section in order to illustrate the architectures designed to offer the cloud services.

### 3.2.2 Cloud computing architecture

In this section a description of the different types of architecture models have been demonstrated to provide reference for developing a cloud manufacturing architecture. The cloud computing architecture is mainly described using four types of models: (i) layered models (Zhang et al., 2010b), (ii) business models (Bogataj and Pucihar, 2012), (iii) deployment models (Mell and Grance, 2011) and recently (iv) agent based models (Sim, 2012):

(i) A layered model describes the system in terms of interlinked layers of abstraction. The layered models used in cloud computing generally comprise four layers:
1. The hardware layer: responsible for configurations, fault tolerance, traffic management, power and cooling resource management of the cloud physical computing resources (physical servers, routers, switches, etc)
2. The infra-structure layer: which is considered to be an essential component of cloud computing, that is responsible for virtualisation of the pooled cloud computing resources through using virtualisation technologies.
3. The platform layer: consisting of operating systems and application platforms, to minimise the load of direct application deployment of virtual machine containers.

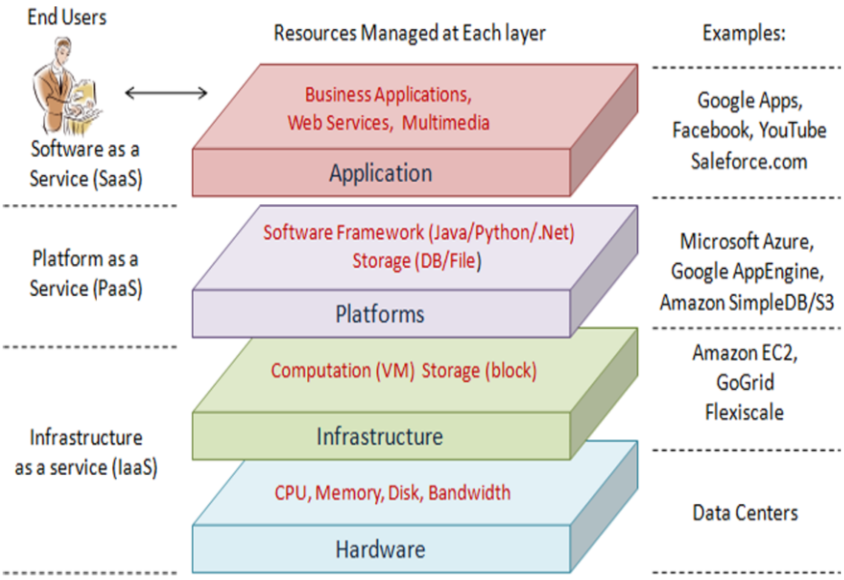


Figure 3-1: A general layered model for Cloud computing
Zhang et al. (2010b)

4. The application layer: containing the actual cloud applications that leverage the automatic-scaling feature to achieve better performance, availability and lower operating cost.

As shown in figure 3-1 the layered model explains the structure of cloud computing for supporting a wide range of application requirements while reducing management and maintenance overhead.

(ii) A Business model; is considered to be a service driven model that describes the cloud's ability to offer on-demand services for cloud users that can be grouped into three categories (NIST, 2012): (1) Infrastructure-as-service (IaaS); that enables the cloud user to gain access and control over fundamental computing resources such as: processing, storage, networks, also to deploy and run other software including operating systems and applications (2) Platform-as-a-service (PaaS) offers the service user to deploy onto cloud infrastructure applications that are acquired or created by programming languages and tools supported by cloud service provider, and (3) Software-as-a-service (SaaS) this service allows the cloud user to access and use the cloud applications through a thin client interface as a web browser.

(iii) A Deployment model (Mell and Grance, 2011) addresses the implementation of the cloud and typically divides clouds into four types; the public cloud, the private cloud, the community cloud and the hybrid cloud, these deployment models are categorised based on the service cost, and the resources scalability and level of control.

1. Public cloud: offers an open use strategy of cloud services as computing applications and storage to cloud users, thus eliminating initial capital investment and risks on infrastructure. On the contrary there is lack of fine-grained control over data, network, and security.
2. Private cloud: enables authorised users only to gain access to the cloud computing services, as it can exclusively be owned, managed and operated by specific party (organisation). In comparison with public cloud, it has the higher degree of control over cloud computing components (highly virtualised), despite it chargers for up-front capital costs.
3. Community cloud: specifies the cloud services usage to specific sectors that share the same interests (e.g., mission, security requirements, policy, and compliance considerations) within different organisations.
4. Hybrid cloud: consists of merging two or more of the cloud deployment models, in order to enable data and computing applications sharing among these models.

(iv) An Agent-based model (Sim, 2012) describes the cloud using interacting entities called agent. The interaction between the agents can follow various protocols such as cooperation, negotiation, and coordination. These are adopted to automate the activities of resource pooling and sharing in cloud computing, through building software tools and test-beds to manage the heterogeneous cloud resources by developing novel approaches for service discovery, service negotiation, and service composition.

## 3.3 Cloud manufacturing

### 3.3.1 Overview and background

Together with advances in manufacturing processes, information exchange is considered to be strategically important for development of production enterprises (Amours et al., 1999), as there is an increasing need for global sharing of technology and knowledge (Mitsuishi and Nagao, 1999). Significant efforts have thus been made in developing frameworks and systems aimed at sharing and exchanging of manufacturing information. Networked manufacturing emerged as the intial outcome of these efforts where a significant body of research generally exists in 5 main categories; agile manufacturing, virtual manufacturing, application service providers, collaborative manufacturing, and grid manufacturing.

Early examples of research into information sharing were agile manufacturing that enables the coordination and control of organisation resources (Montreuil et al., 2000), in order to meet changes of market requirements by suitable alliances, organising to manage change and uncertainty, and leverage of people and information (Gunasekaran, 1999). This was achieved by defining a framework that represents the interactions between the manufacturer, customers, suppliers and the basis of competition in the agile paradigm (Yusuf et al., 1999). Virtual manufacturing was introduced as an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control (Saadoun and Sandoval, 1999), this environment was mainly formed by the integration of various activities along with facility and product life cycle, various resources such as hardware, software, human resources, standards, and additionally the integration of real world and the virtual world (Iwata et al., 1997).

There are numerous works of research in this area: Peng et al. (2007) approached a collaborative network that composes a computer model within the manufacturing system to share usage of the latest integrated design and manufacturing facilities of SMEs by using Internet technology, namely; networked virtual manufacturing (net-VM), which consists of three main tiers as shown in figure 3-2; application, service, and database tier; that provide remote service access to users, integration of the hardware and software manufacturing resources into one system with limitation on remote operation of hardware resources, and thirdly, stores the whole of the required system data and knowledge.

Qi et al. (2010) proposed a virtual manufacturing framework composed of 3 modules to address the chaining components of product design, production and controlling processes. First, a design module that offers real time communication between customers and cooperators (manufacturers) to share design and material databases and also CAD software. Second, a production module that strengthens the confidence of the customers for the manufacture by providing on line production status through linking production components with cooperators. Thirdly, the controlling module manages the entire manufacturing process.

Customisation or the ability to modify product specification to individual customer needs is often an important element in virtual manufacturing. Offering manufacturing services demands incessant requirements to design easy-to-use, highly customizable interfaces and high-performance, scalable distributed systems that hundreds of concurrent users can access (Smith and Rupp, 2002). Su et al. (2009) introduced an application service provider (ASP) to offer a product life cycle oriented customisation service mode to assist SMEs offering significant commercial and organisational benefits including low cost entry and easy software maintenance.

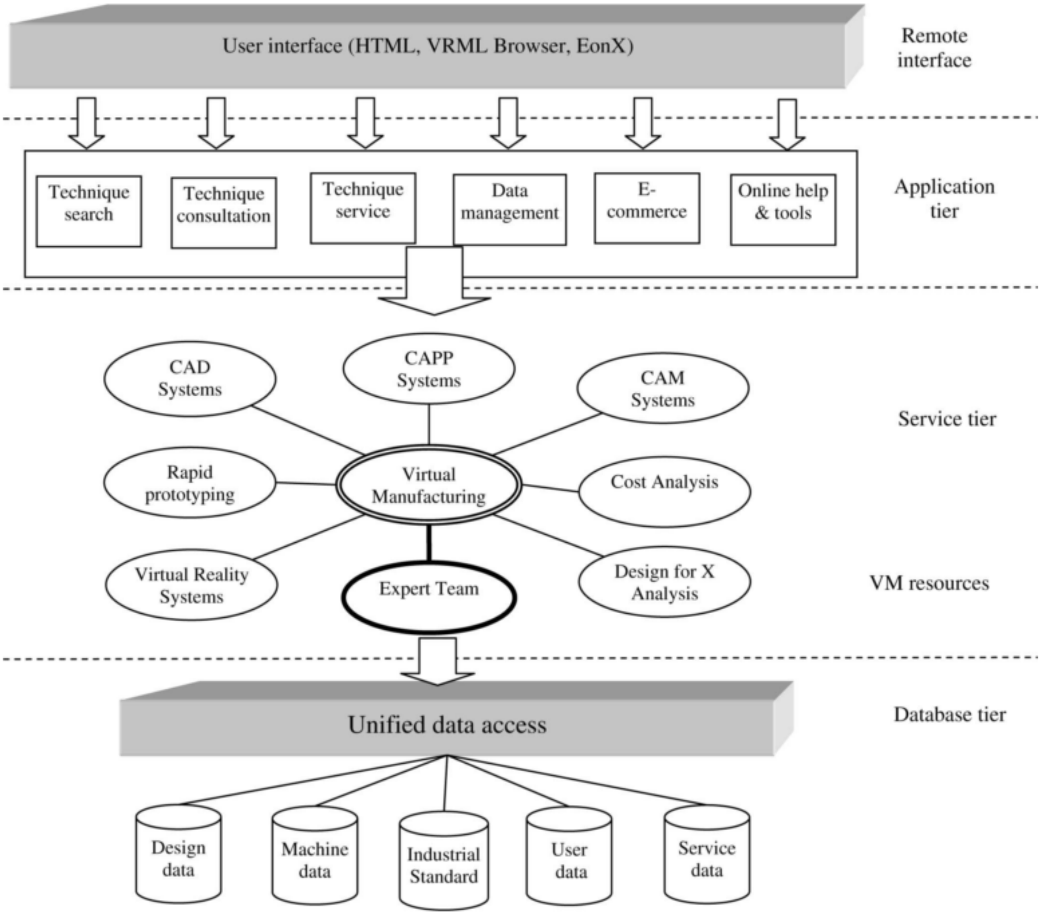


Figure 3-2: An example of a virtual manufacturing platform
Peng et al. (2007)

A manufacturing service platform can be integrated by using rule based and service oriented techniques through a virtual federated operating system (Xu et al., 2008).

Collaborative manufacturing was defined as a business paradigm where group of enterprises cooperate through their resources and abilities to perform a unified task in order to enhance the performance of the business network (Johansen et al., 2005), in other words collaborative manufacturing can be expressed as a multi-layered mode-based system that realises the manufacturing service chain and modelling (Wang, 2008). Collaborative manufacturing is created to address (a) total cost reduction, (b) shortest delivery time to the customer and (c) highest possible product quality (Firmansyah and Amer, 2013). The concept has been implemented in different fields: project planning and scheduling (C. H. Chen and Chen, 2003); collaboration in product design and development (Zhan et al., 2003); collaboration in forecasting (McCarthy and Golicic, 2002); collaboration in production systems (Chen et al., 2009); and collaboration in the supply chain (Danese, 2006). It has been noted that the absence of a holistic process model to maximise the benefits of the production cycle, limits the effectiveness of the collaborative manufacturing approach (Firmansyah and Amer, 2013).

The manufacturing grid were introduced to share manufacturing resources using grid technology but with more flexible features (Tao et al., 2008). This networked approach attempted to introduce an integrated supporting environment to share and integrate decentralised enterprise manufacturing resources based on grid computing and relatively advanced computer and information technology. The resources are encapsulated as services to provide a single portal for user access along with unified protocols for manufacturing resources (Fan et al., 2004). Furthermore, Tao et al. (2011) identified the limitations for practical implementation of the manufacturing grid as; (a) lack of protocols, standards, and criteria, (b) lack of commercial operation models, (c) security and reliability problems, and (d) embedded connect problems of physical manufacturing facilities.

Cloud manufacturing has emerged as a new paradigm that enhances manufacturing resources and capabilities sharing of the entire product life cycle between manufacturing structures and enterprise systems (Ren et al., 2014), Figure 3-3 illustrates the evolution of former networked manufacturing technologies leading to the introduction of cloud manufacturing.

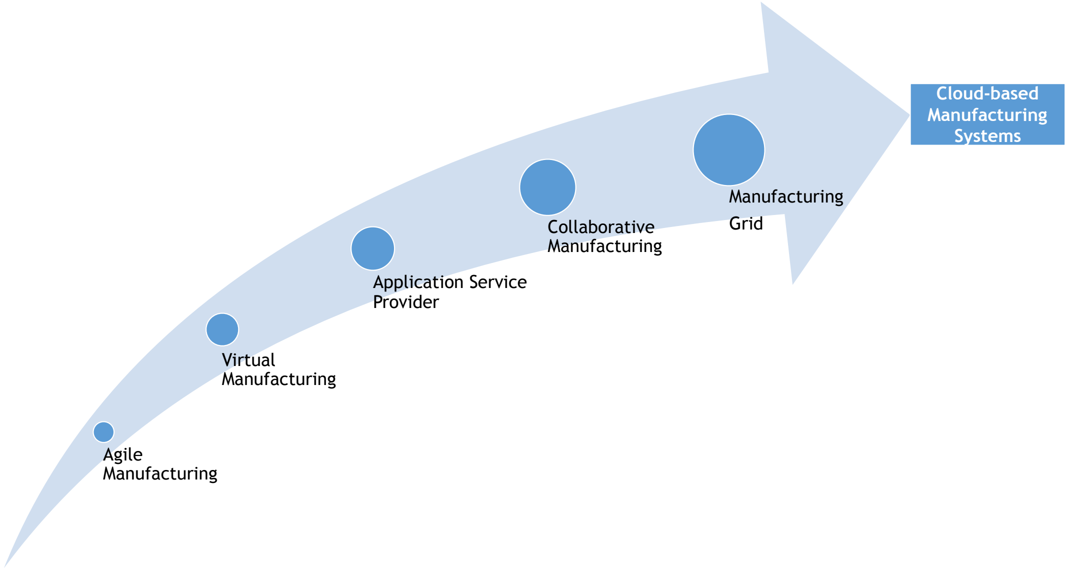


Figure 3-3: Evolution of manufacturing information sharing systems

As stated in the previous section, cloud manufacturing is the result of adoption of cloud computing by manufacturing enterprises to share resources and capabilities in order to enhance their respond to market requirements and increase cost effectiveness (Ren et al., 2015). Through this adoption, cloud manufacturing aims to address the limitations of preceding manufacturing technologies which lack the requirements needed for modern manufacturing enterprises (Chituc and Restivo, 2009). An integral element of cloud manufacturing is the "pay-as-you-go" service management across its levels, provides on-demand self-service, and adapts dynamically to demand changes (Ren et al., 2014).

These features can enhance cloud manufacturing to support the product life-cycle development by involving networks and decentralised information sharing, that will help SMEs to save money and increase their efficiency (Wu et al., 2014a). Furthermore, cloud manufacturing can promote ubiquitous access to product design information, thus enhancing collaborative design techniques, it can also enhance resource sharing, rapid production of prototypes and reduce costs. Distributed manufacturing can be developed as a result, and on the marketing and service sector, cloud manufacturing can reduce time-to-market, improve service, and enhance user experience, advantageously impacts customer co-creation area (Wu et al., 2013a).

Wu et al. (2015b) conducted a cost benefit anaylsis study of cloud manufacturing. The study explored key factors of the cost breakdown for implementing the cloud based manufacturing approach in contrast with the traditional centralised design and manufacturing. The study used cloud computing pricing plans and the pay-as-you-go price structure compared to provision of the same services on different levels (i.e. IaaS, Paas, SaaS) as the analogy. This led to good insights into the feasibility of cost reductions for adopting cloud manufacturing by SMEs over the traditional manufacturing in specific manufacturing situations. Adamson et al. (2013) , in their study, discovered that the cloud based paradigm for manufacturing is not always a feasible solution for enterprises, mainly due to insufficient assessment and lack of skills for its implementation.

Another strategic study (Wu et al., 2013a) on the impact of cloud manufacturing adoption is shown in Figure 3-4. The study showed three sectors that could be affected by cloud manufacturing on long and short terms: (i) the engineering and design sector; (ii) the manufacturing sector; and, (iii) the marketing and service sector. Explicitly, In the short term; cloud manufacturing can offer ubiquitous access to design information, improve efficiency, adequate computing resources for the engineering and design sector, thus producing a collaborative design approach in the long

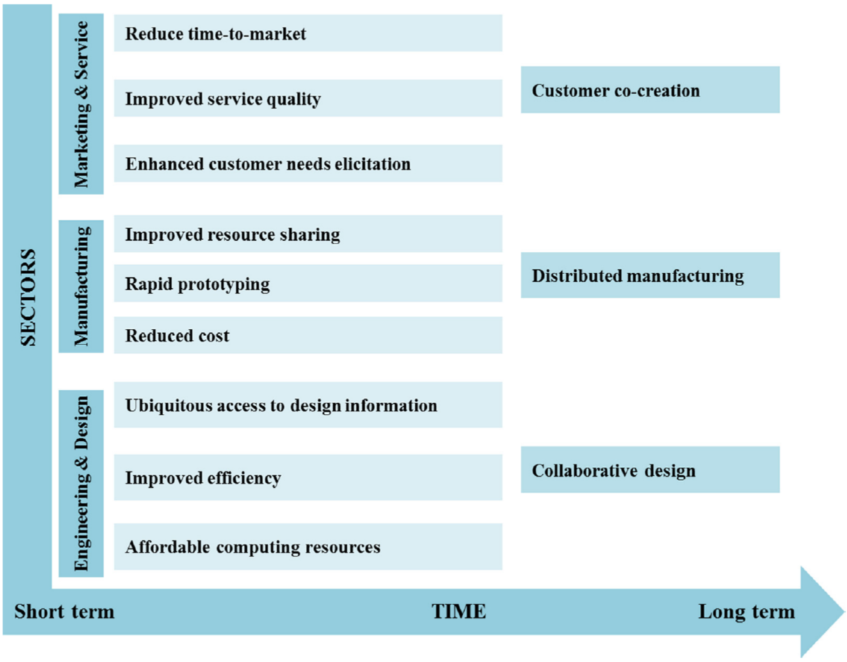


Figure 3-4: Potenial impact of cloud manufacturing across sectors
Wu et al. (2013a)

term. In the manufacturing sector, cloud manufacturing environment can potentially improve resource sharing, rapid prototyping, and reduction in costs, hence improving distributed manufacturing in the long term. As for the marketing and service sector, time to market can be reduced, service quality can be improved, and customer needs elicitation can potentially be enhanced. Consequently, cloud manufacturing can possibly provide a customer co-creation environment.

Throughout these insights, cloud manufacturing would thus play a significant role in the development and execution of product lifecycle processes, as in cloud manufacturing; product life cycle activities and functions can be supported by virtualised manufacturing resources and the manufacturing capabilities layer allocated within the cloud manufacturing system (Liu et al., 2011a). Thus, this can freely allow SMEs to access these services, delegating the manufacturing enterprises (service provider) to carry out all activities (processes) involved in the entire life cycle of the product, and to focus only on their core business and services (Tao et al., 2011). Various approaches tried to address the resource virtualisation problem in cloud manufacturing, which is considered as one of the key enablers of manufacturing resource sharing; Liu et al. (2011a) proposed an algorithm to prioritise virtualised resources according to manufacturing capabilities throughout two phases; normalisation of manufacturing resources followed by encapsulation of resource functional features into the manufacturing cloud services.

In addition, efforts addressing cloud manufacturing challenges from different aspects as, Jiang et al. (2012) introduced a cloud manufacturing system based on cloud-agent technology to realise resource sharing and collaboration for service integration. Tao et al. (2011) applied a ten layered architecture of cloud manufacturing system to enhance resource utilisation and to enhance service-oriented manufacturing technology. Despite the tremendous efforts made by interested collaborators, cloud manufacturing still attractive in the development phase (Adamson et al., 2017; He and Xu, 2014).

### 3.3.2 Related distributed manufacturing approaches

This section catalogues the recent approaches that have been proposed for sharing of manufacturing resources and capabilities on different scales; horizontally and vertically. These approaches utilise the same enabling technologies as Internet of Things (IoT), cyber physical systems, information technology (IT) , cloud computing, and service management. Related approaches that fall within the distributed manufacturing environment are mainly noted as: Industry 4.0, crowd manufacturing (Koussouris, 2013), and cloud based design and manufacturing (CBDM) (Wu et al., 2015a).

### (i) Industry 4.0

Indutry 4.0 (sometimes known with the German spelling Industrie 4.0) was introduced in 2011 to take advantage of modern digital technologies and connectivity to revolutionise manufacturing (Koussouris, 2013). The cyber physical system was introduced as the enabling technology for Industry 4.0, as it offers the digital representation of the heterogeneous manufacturing resources and capabilities (Shafiq et al., 2015).

Additionally, it provides dynamic real-time tracking of manufacturing processes through the utilisation of the Internet and information technology (Monostori et al., 2016). Thus, cyber physical manufacturing systems enhance the collaboration among various stakeholders in the manufacturing industry of numerous manufacturing processes as design, implementation, modeling, and maintenance (Lasi et al., 2014). The adoption of cyber physical production systems (CPPS) will provide a holistic overview and control over the entire manufacturing life cycle that involves human operators, machine-tools, manufacturing networks, product design, leading to manufacturing cost reduction and improvements in quality (Lasi et al., 2014).

Clearly, as Industry 4.0 involves massive knowledge and information sharing and data exchange among various interacting manufacturing components, seamless and flexible integration and communication is a necessity (Lasi et al., 2014). Interoperability is thus identified to be one of the key factors for industry 4.0 (Lu, 2017). Interoperability can exist on four different levels Ruggaber (2006): (1) organisational level which involves the overall standards and communication languages between cyber physical systems and industry 4.0; (2) application level that identifies protocols and principles of standards, models, and domains; (3) technical level which involves the technical development tools, information technology systems and software applications; and (4) the interoperable semantics among the industry 4.0 components.

A framework for interoperability in industry 4.0 is proposed by Lu (2017) in figure 3-5.

The four levels of interoperability are mapped on the overall principles that presents the main components of Industry 4.0.

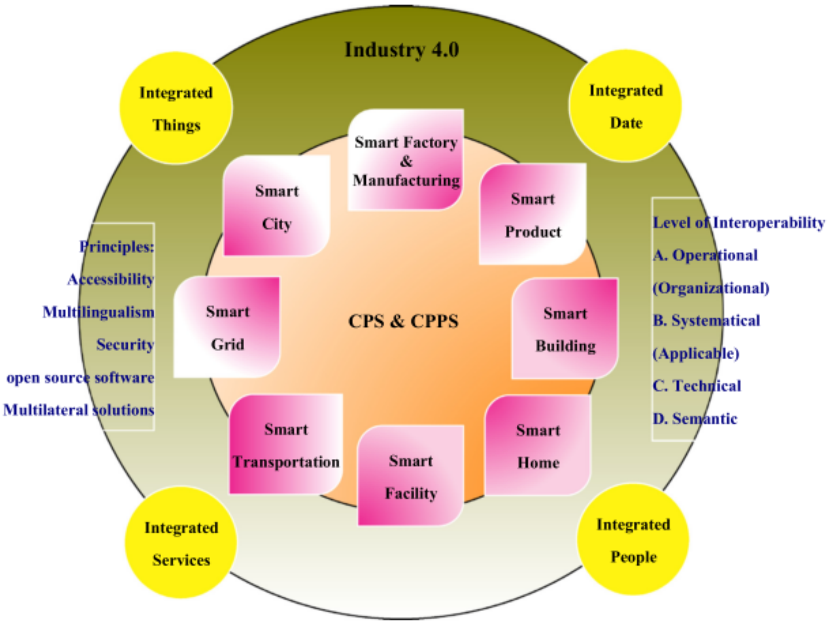


Figure 3-5: A framework of interoperability in Industry 4.0
Lu (2017)

Currently, poor data security and lack of standards and protocols among Industry 4.0 components is considered to be one of its major challenges (Schröder, 2017; Ruggaber, 2006).

### (ii) Cloud Based and Design Manufacturing

Cloud based design and manufacturing (CBDM) aims to leverage cloud computing features as on demand services, multi-tenancy, virtualisation and rapid scalability of manufacturing resources and capabilities to offer manufacturing services on different scales as Infrastructure-as-a-Service (IaaS), Platform-as-a- Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a- Service (SaaS) (Wu et al., 2014a).

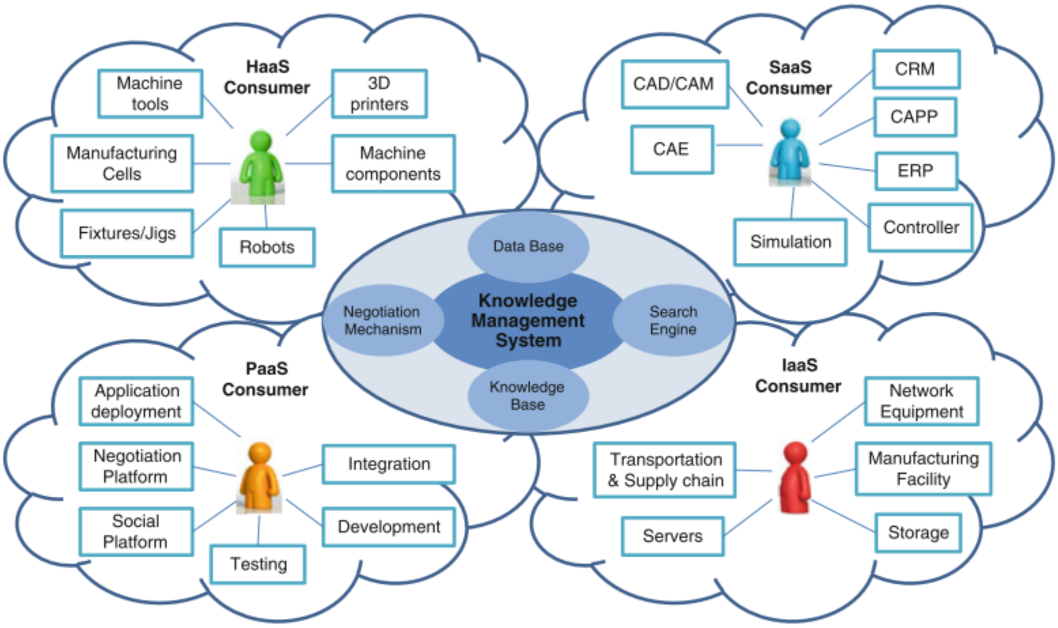


Figure 3-6: Service levels of CBDM
(Wu et al., 2013c)

Figure 3-6 shows the categorised levels of manufacturing services potentially offered by the CBDM; as the machine-tools along with the compulsory hardware equipments offered as Hardware-as-a-Service (HaaS), the Platform-as-a-Service (PaaS) is concerned with manufacturing tasks as negotiation, integration and testing. The CAx chain along with related manufacturing software offered as Software-as-a- Service (SaaS). As for the manufacturing facilities (i.e.shop-floor), transportation and supply chain, networking equipments are offered as IaaS. Finally, a knowledge management system is associated with the 4 levels of services in order to enable the cloud features stated earlier.

In addition, Wu et al. (2015a) identified 8 main key requirements for enabling CBDM; (1) utilising social media to connect various stakeholders of cloud users as it deploys crowdsourciong processes in matching service users with service providers; (2) elastic and cloud based storage of heterogeneous 3D geometric data to enhance collaboration among cloud users; (3) handling and analysis of Big data; (4) leveraging multiple access to software applications (i.e. CAD/CAM software) simultaneously at the same time "multi-tenancy"; (5) real-time data capturing of heterogeneous manufacturing resources and capabilities through the utilisation of Internet-of-things (IoT); (6) offering everything as a service (XaaS) through the deployment of service oriented model with the CBDM; (7) Rigorous search engine to enable cloud users for acquiring various manufacturing queries; and (8) on-line quoting engines for enhancing cloud business processes.

Similarly, as the latter drawbacks of Industry 4.0, one of the significant challenges for enabling CBDM is concerned with data confidentiality, integrity, and availability which is noted as "Cybersecurity" (Wu et al., 2016), although the CBDM main focus is on cloud-based manufacturing software applications (CAx) (Thames and Schaefer, 2016) and additive manufacturing (Wu et al., 2015a).

### 3.3.3 Cloud manufacturing architectures

Various models are used to describe the architecture of cloud manufacturing. A multi-layered architecture with modular approach is commonly used to model cloud manufacturing (He and Xu, 2014), where each layer is assigned with a specific role to accomplish the required functions. In this section, a various cloud manufacturing architectures, are described in order to embrace the similarities and contrast between them and further to be a baseline for the development of this research.

Ding et al. (2012) proposed a three layered compact architecture that further decomposed into more specific layers as shown in figure 3-7. This consists of (a) a cloud service provider layer that is divided into manufacturing resource layer, virtual interface layer, and virtual resource layer to collect and virtualise hardware and software manufacturing resources on three subsequent layers, (b) cloud service center layer which support the system with the available services and functions by publication, retrieval, aggregation and scheduling, and (c) a cloud service demander layer that handles the interface between the system and different cloud users.

Moreover, Jiang et al. (2012) introduced a five layered structure demonstrated in figure 3-8 with the following layers: (a)basement layer (b)access layer (c)functional layer (d)portal layer (e) application layer, supported by cloud-agent technology within the functional layer to control and coordinate the various service transactions within the cloud manufacturing system. The basement layer encapsulates CAx tools and physical resources that allow the cloud to function. The access layer creates a low-level data sharing platform for these systems. The function layer organises the functions achievable by the systems in lower levels into cloud services. The portal layer provides an interface between the available services and the users. The application layer connects the cloud to the existing business processes in the enterprise. Followed by Vincent Wang and Xu (2013) proposing to incorporate the intelligent-agent technology within the smart cloud manager layer to analyse, optimise and control the cloud manufacturing service interactions between the user layer and the manufacturing capability layer within the cloud manufacturing architecture.

Lv (2012) analysed a four layered architecture based on multi-view model that integrates different views (function view, resource view, information view and process view), with each view depicting different aspect of the cloud manufacturing architecture. This can be achieved initially through defining of various system views (He and Xu, 2014). The function view lists the various tasks that a system can perform and comprises interlinked activities. The resource view enumerates the resources required to perform activities. The information view focuses on the data that is required for the activities and the process view captures the sequence of the activities.

Further, Škulj et al. (2015) proposed a decentralised perspective for a cloud manufacturing architecture (CMdna) shown in figure 3-9. This identified the concept of

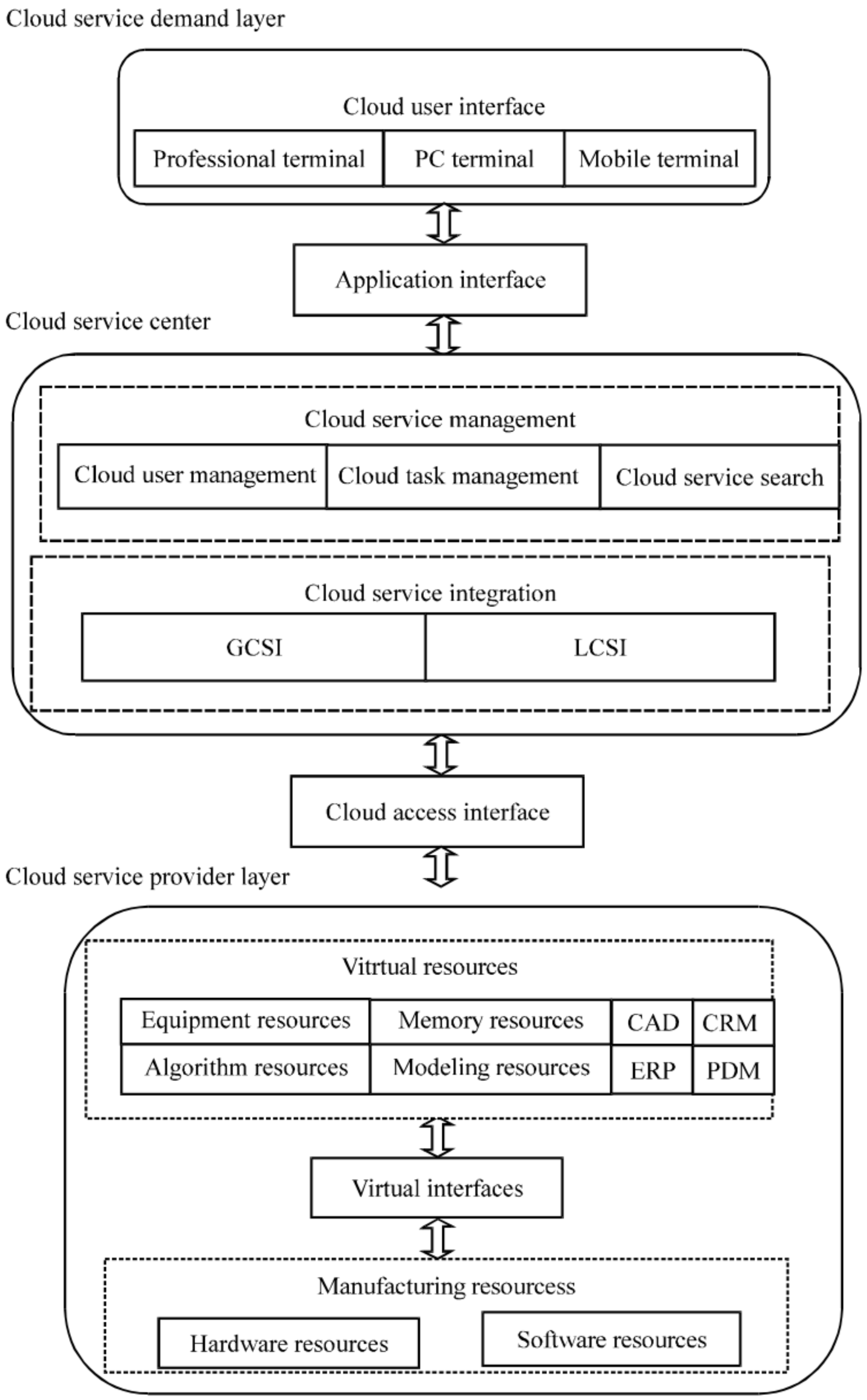


Figure 3-7: A compact architecture for Cloud manufacturing (Ding et al., 2012)

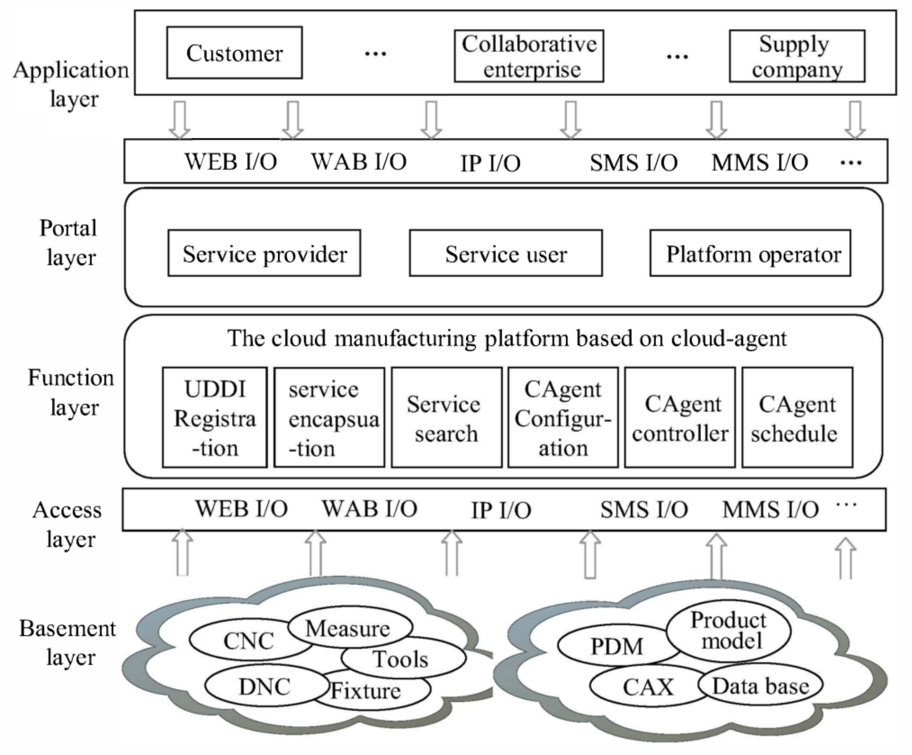


Figure 3-8: Five layered architecture for Cloud manufacturing (Jiang et al., 2012)

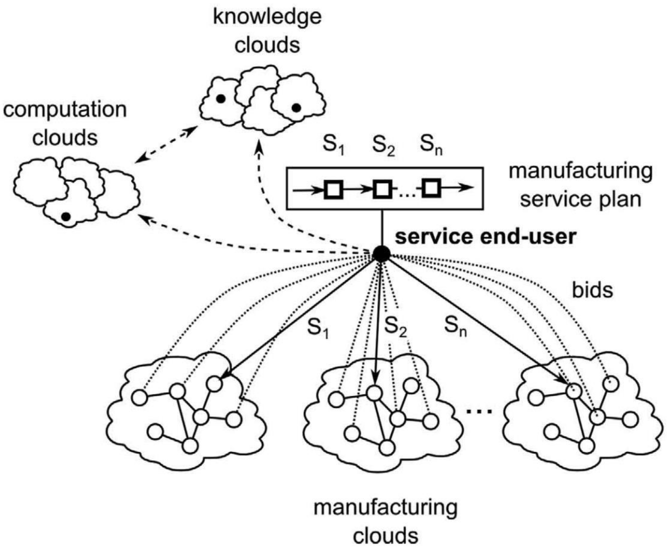


Figure 3-9: A Decentralised architecture for cloud manufacturing (Škulj et al., 2015)

a cloud manager component (layer) with the aim of creating a flexible connection between cloud service providers and service users through the utilisation of an autonomous work system (AWS) that acts as numerous manufacturing clouds which vary depending on the requirements of both service users and service providers. Such an architecture would allow several clouds to bid for each stage of the required work to make the process as cheap as possible for the end user.

Guo (2016) suggested a design method for cloud manufacturing (CMAS) through analysing and aggregating the system into 6 different perspectives. These are defined as: A Business Model (BM) that represents the business to business strategy of the cloud that covers four different modes of interactions among cloud different individuals; System Structure (SS), that describes the core layers of the cloud as physical and virtual layers of the architecture, Production Life Cycle (PLC) that is concerned with the product attributes such as planing design and demand analysis, manufacturing state space (MSS) covering the manufacturing information view that represents the overall manufacturing activities of the cloud, manufacturing industry granularity (MIG) that analyse the different manufacturing product ranges, and finally, Manufacturing Service Area (MSA) which resembles the geographical location of hardware manufacturing resources.

Recently, Liu et al. (2017) introduced four layered conceptual model shown in figure 3-10 which integrates cyber physical systems with cloud manufacturing paradigms utilising the internet for direct operation of machine tools from cloud manufacturing. The resource layer comprises the hardware that perform the manufacturing tasks. This is connected through standards such as MT-connect on TCP/IP to communicate with the resource virtualisation layer that encapsulates the manufacturing capabilities in homogeneous sets of web services. The core cloud manager layer manages communication and metering of requirements expressed by the upper "Application layer" as executed by the layers below. The use of REST for communication between

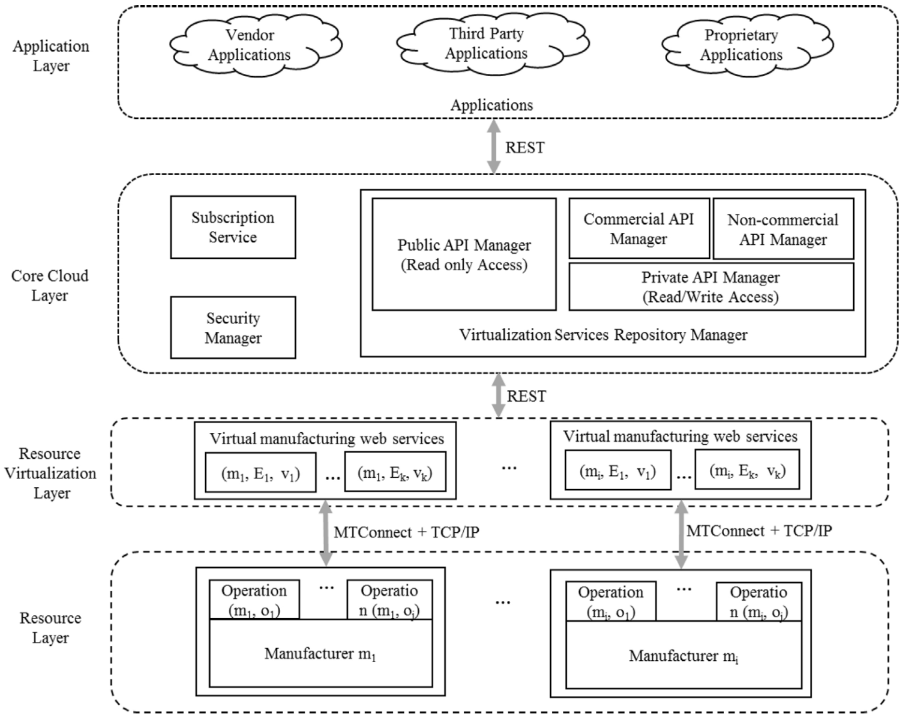


Figure 3-10: Four layered architecture
(Liu et al., 2017)

the top three layers implies that each layer considers the service of the layers below as deterministic and stateless. This is in clear contrast to traditional manufacturing architectures where the state of the manufacturing equipment is closely monitored and expensive (in terms of expertise, information and communications) processes are put into place to close the loop.

Wang (2013) introduced the IEC 61499 function blocks as a component for cloud manufacturing systems to enable real time monitoring of machine availability, thus enrich the process planning with adaptive decision making based on real-time process monitoring and dynamic resource scheduling. The function blocks along with the machining features are defined as the key enablers for information transfer across the various system modules from design to machining. Explicitly, the two tier system architecture involves a dynamic scheduling function that is allocated between a high-

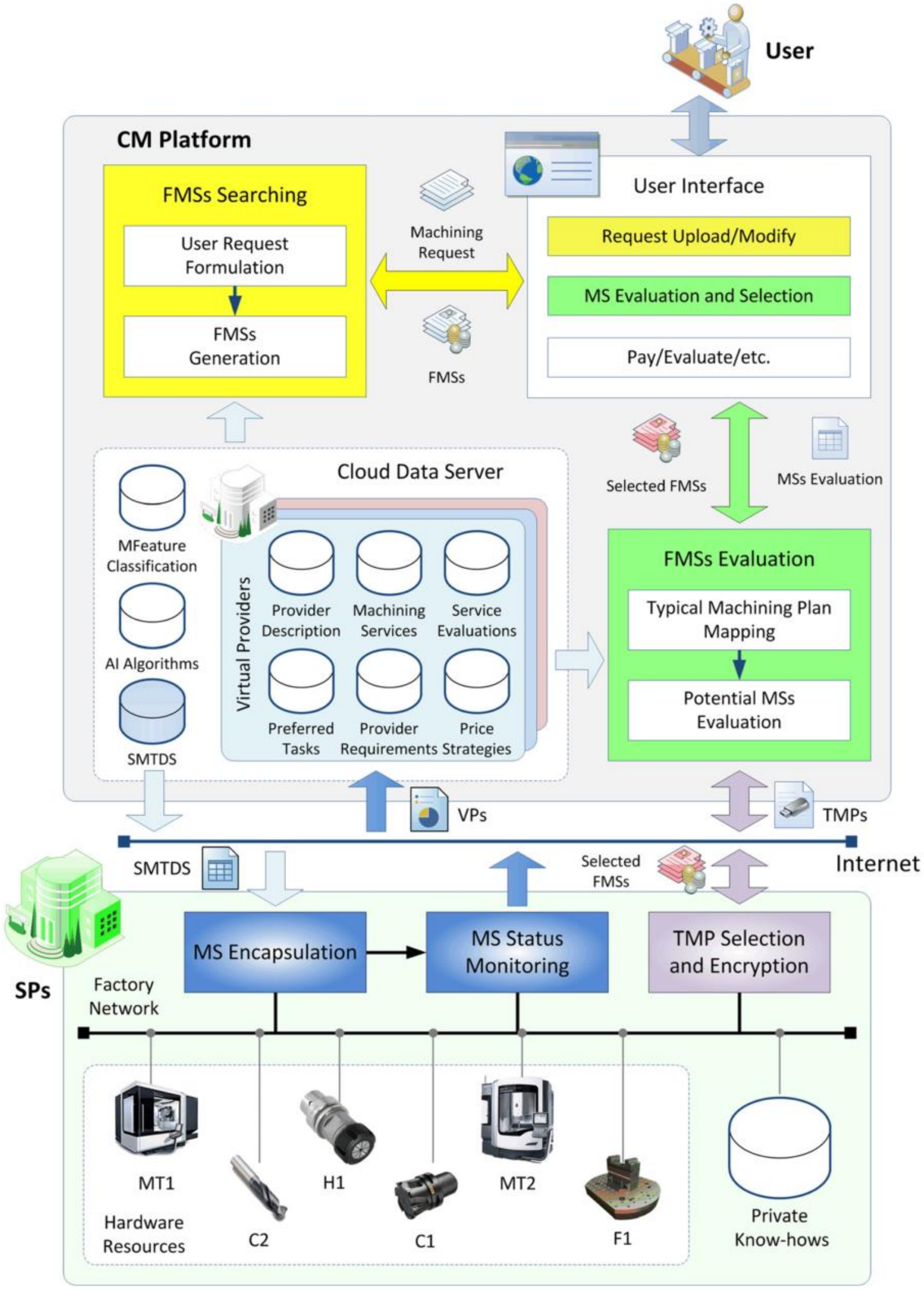


Figure 3-11: Cloud manufacturing architecture for complex parts (Liu et al., 2015)

level module ( in advance planning) that is responsible for initial setup planning and machining features and low-level module (at runtime) that handles detailed operation procedures of the machining operations such as tool-path strategy, cutting attributes, etc. Thus this establishes a enable distributed decision making process across the system.

An alternative aspect for developing a cloud manufacturing architecture that is based on the product or part characteristics is shown in figure 3-11 (Liu et al., 2015). This work proposed a novel cloud manufacturing architecture for machining aviation complex parts. The architecture aims to overcome the barrier of acquisition of preparatory knowledge of service providers during the machining process by defining standardized machining task description strategies (SMTDS) for each service provider. As the machining knowledge is kept at the provider's side and only the encapsulated machining ability of parts (MSs) are being shared on the cloud platform. Similarly, the same strategy is used for matching the service user with service provider.

Other cloud manufacturing architectures have been designed for specific industries such as the architecture developed by Qiu et al. (2016) for polymer industries, as illustrated in figure 3-12. The architecture is derived through the modification of the layer components to suite the characteristics of polymer industry in comparison to discrete and continuous manufacturing industries. These include notions of production capacity, environmental impacts, and manufacture features. As the model is mainly based on the cloud computing (CC) and big data techniques that includes a service composition optimal-selection algorithm (SCOS) for searching and identifying data stored in the cloud as processes, production data, and environmental. Additionally, it includes advanced process control (APC) within the model which is a customer and application oriented (CAO) to control the successful achievement of customer demands, allocation of production capability and optimise financial benefits.

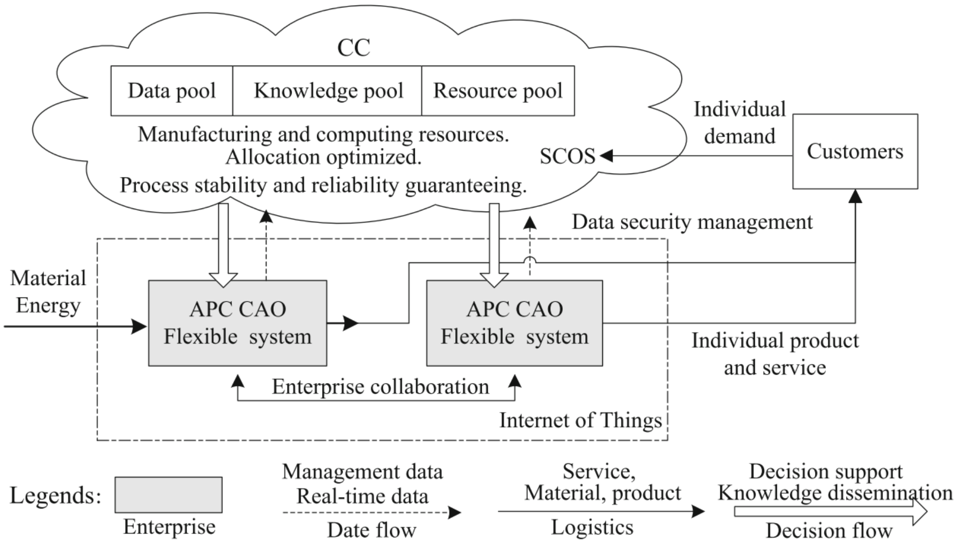


Figure 3-12: Cloud manufacturing architecture for polymers industry
(Qiu et al., 2016)

Based on the proposed architectures for cloud manufacturing and considering the similarities of the proposed models, a general architecture can be used to summarise the typical configuration of the cloud manufacturing systems propsed in existing research. Figure 3-13 shows this typical layered structure of cloud manufacturing systems and provides examples of components in each layer. The application layer encompasses cloud enabled applications such as new product development where the initial order for part production is issued. The application interface layer which is the topmost layer of the cloud manufacturing middle-ware, manages the order received from the application layer and coordinates with the core service layer to match the part requirements with virtual resource capabilities. The core service layer then passes the order to the virtual machine tool on the virtual resource layer that corresponds to one or several cloud enabled physical machine tools. The order which is now translated into executable instructions on the physical machines is executed and the produced parts are delivered to the user who initiated the order.

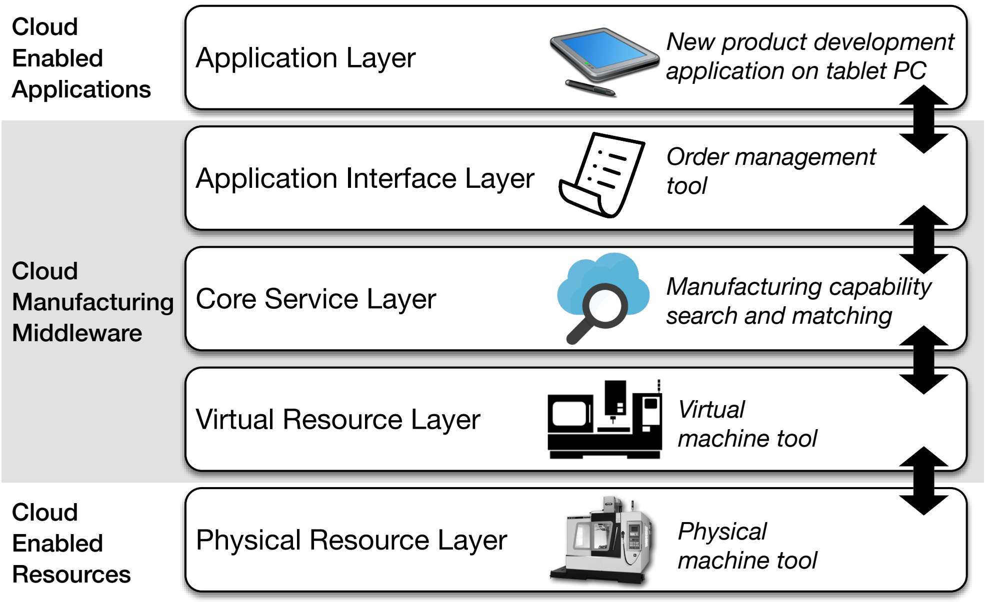


Figure 3-13: Generic cloud manufacturing architecture with examples for each layer

Table 3.1 documents the mapping of existing cloud manufacturing architectures to the generic model in figure 3-13.

Table 3.1: Architecture components summary

| **Architecture References** | **Component or Layer** | **Generic layer (function)** |
|---|---|---|
| (Ding et al., 2012) | Cloud service demander layer | Application Layer (provides user interface) |
| (Jiang et al., 2012) | Application layer | |
| (Lv, 2012) | Cmfg application layer | |
| (Guo, 2016) | Application layer | |
| (Liu et al., 2017) | Application layer | |
| (Liu et al., 2015) | User interface | |
| (Liu and Li, 2015) | Application layer | |
| (Ding et al., 2012) | Cloud service center layer | Application Interface Layer (connecting user applications and cloud services) |
| (Jiang et al., 2012) | Portal layer | |
| (Lv, 2012) | Cmfg application layer | |
| (Guo, 2016) | Cloud platform portal layer | |
| (Liu et al., 2017) | Core cloud Layer | |
| (Liu et al., 2015) | Feasible machining services evaluation | |
| (Liu and Li, 2015) | Global service layer | |
| (Ding et al., 2012) | Cloud service center Layer | Core Service Layer (matching order requirements and capabilities provided by the layer below) |
| (Jiang et al., 2012) | Function layer | |
| (Lv, 2012) | Cmfg core service layer | |
| (Guo, 2016) | Application business operational layer | |
| (Liu et al., 2017) | Core cloud layer | |
| (Liu et al., 2015) | Feasible machining services searching | |
| (Liu and Li, 2015) | Global service layer | |
| (Ding et al., 2012) | Cloud service provider layer | Virtual Resource Layer (encapsulation of heterogeneous resources as homogeneous services) |
| (Jiang et al., 2012) | access layer | |
| (Lv, 2012) | Cmfg virtual resource layer | |
| (Guo, 2016) | Cloud platform management | |
| (Liu et al., 2017) | Resource virtualisation layer | |
| (Liu et al., 2015) | Machining service encapsulation | |
| (Liu and Li, 2015) | Virtual layer | |
| (Ding et al., 2012) | Cloud service provider layer | Physical Resource layer (physical manufacturing devices with interfaces to allow information exchange with the cloud) |
| (Jiang et al., 2012) | Basement layer | |
| (Lv, 2012) | Cmfg physical resource layer | |
| (Guo, 2016) | Interface layer | |
| (Liu et al., 2017) | Resource layer | |
| (Liu et al., 2015) | Hardware resources | |
| (Liu and Li, 2015) | Resource layer | |

### 3.3.4 Cloud manufacturing service management

The management of services within cloud manufacturing is considered to be a critical issue, as it requires effective coordination between the manufacturing resources and manufacturing capabilities to execute on-demand services through the cloud (He and Xu, 2014). Resources can interact depending on the business needs or requirements whether it is collaborative between enterprises i.e.public cloud or within the enterprise i.e.private cloud (Zhang et al., 2012). There are numerous hardware and software resources in an enterprise (Liu et al., 2011a), therefore complex manufacturing processes may require integration among several resource services in a scheduled sequence (Tao et al., 2010). This leads to challenge of guaranteeing service levels in the cloud.

In order to ensure service performance of cloud manufacturing, various methods have been proposed. Wang and Liu (2012) developed a system based on an ontology of virtualised manufacturing resources. Liu et al. (2011b) used a multi-agent system to implement manufacturing resource sharing within three different cloud manufacturing models to suit different sized enterprises (small, medium, and large).

Similarly Jiang et al. (2012) introduced agent technology to reflect capabilities and behaviour in manufacturing resources, thus integrating its services within cloud manufacturing. Tao et al. (2013) addressed the uncertainty issue in the service composition with optimum selection (SCOS) of manufacturing resources by applying an intelligent algorithm (FC-PACO-RM) within the cloud manufacturing system.

Specifically, service management in cloud manufacturing focuses on the following six aspects He and Xu (2014):

1. Service publishing, request and discovery: Cheng et al. (2012) analysed the interacting service parties of cloud manufacturing provider, operator and consumer, also there are several frameworks which addressed the resource service

match and search mechanism namely: Wang and Liu (2012) and Tao et al. (2009).

2. Resource allocation and service scheduling: this refers to an algorithm implementation outlined by Lee et al. (2011) who proposed an architecture to achieve high performance and fairness of resource allocation and service scheduling within the cloud.

3. Quality of service (QoS) management: Xu et al. (2012) discussed and applied the quality of service concept for manufacturing networks through the deployment of of a novel optimisation algorithm within a framework to fulfil the various performance requirements of manufacturing networks.

4. Service composition: this is a more comprehensive definition of manufacturing resource services, when multiple manufacturing resources are combined (Xu, 2013). Zhang et al. (2010a) designed an architecture to address the flexible management of resource services composition through the analysis of its life-cycle and classification of flexibility. Formerly, Liu et al. (2013) introduced a multi-composition for each task" approach through a"MTO-MCSCO" (multi-task oriented manufacturing cloud services composition and optimisation) model to enhance customer satisfaction in cloud manufacturing.

5. Security, trust and reliability management: this addresses the enhancement of the cloud manufacturing trustworthy, by the application of authentication and authorisation mechanisms on the cloud manufacturing services (He and Xu, 2014).

6. Service execution evaluation: this is described by Cheng et al. (2012) who specified various operations of the cloud manufacturing service transactions. Furthermore, they identified the key problems to comprehensively realise cloud manufacturing services.

Thus far, several studies have investigated the quality and composition of services within a cloud manufacturing framework. Lin et al. (2015) introduced a knowledge based system (OICS) for selecting adequate machinery and cutting tools for cloud services. This was composed of three main components: the user interface component; the manufacturing cloud services, that provides machine tool functions; and lastly, the virtual machine tool for simulating and evaluating machining and cutting tasks. The proposed system provides the optimal number of machine tools for the acquired system based on the designed ontology data of the system, and thus aims for improving the quality of the cloud manufacturing services.

Additionally, Lu and Xu (2017) explored a service composition approach for cloud manufacturing in order to develop an integrated networked environment enabling the optimal allocation of resources based on given criteria. The accurate mapping of customised manufacturing requirements (services) with the distributed cloud manufacturing resources occurs through a web based system that is composed of 3 main stages; verification of manufacturing requests, construction of knowledge based queries of adequate manufacturing resources, and assessment of the manufacturing resources with the elected service plans in terms of the quantitative criteria of cost and time.

## 3.4 Interoperability in Manufacturing

Since the first introduction of the Interoperability issue by the Department of Defence in 1965, it has been the interest of researchers in various fields, to results in numerous definitions for interoperability (Ford et al., 2007). Interoperability as defined in the manufacturing arena is the ability of two or more systems or components to exchange information and to use the information that has been exchanged (September, 1990). ISO 16100-1:2009 defines interoperability as the ability to share and exchange information using common syntax and semantics to meet an application-specific functional relationship across a common interface. Noticeably, there is no specific definition for the term due to differing expectations that are constantly changing (Figay et al., 2012).

Newman et al. (2008) identified that "Implementation of interoperability has an enormous impact on all manufacturing sectors": it can (a) enhance collaborative manufacturing among large manufacturing companies, globally; (b) Eliminate redundant re-planning of fixturing, tooling, and tool path for manufacturing components; and, (c) Provide flexibility of production at the shop-floor level, for the SMEs.

Many researchers have considered the issues related to interoperability in manufacturing: Euzenat (2001) classified interoperability requirements into 5 different levels: (a) grouping system representation into characters (encoding); (b) segmenting it in words (lexical); (c) structuring a representation of a system into complete sentences (syntactic); (d) constructing a suggested meaning of the system representation (semantic); and lastly, (e) studying the communicative behaviour of the system representation (semiotic). Alternatively, Ray and Jones (2006) determined three possible approaches for addressing interoperability: "point-to-point customised solution" which is achieved by pairing systems with a specific solution; vertical integration where a single manufacturing resource vendor offer solutions for the entire supply-chain; and, adopting open, neutral standards such as; ISO14649 and ISO10303.

### 3.4.1 Interoperability of CAx chain

Since the first commercial introduction of Numerical Control (NC) machine in 1955 Tsuji (2003), there has been significant developments in the NC/CNC technology. Today's CNC machines are more sophisticated than ever, with 5 axis and multiple processes, making CNC programming extremely complex (Zhang et al., 2011a). The pace of innovation has affected the CAx chain gradually resulting in a plethora of languages and standards (Nassehi, 2007). The corresponding CAx chain consists of a number of computing tools responsible for the digital representation of the part geometry (CAD) and software tools for process planning and generating G and M Code (CAM) and post-processors. Due to the problems of individual automation solutions being adopted by the manufacturers, a holistic and systematic integration between manufacturing collaborators (enterprises) is required (Nagalingam and Lin, 2008). This is compounded by the emerging trend for manufacturing enterprises to collaborate in order to meet the demands of the increasingly volatile and fragmented market (Rodríguez Monroy and Vilana Arto, 2010). Consequently, there is a need for seamless data exchange among different parties to achieve the acquired tasks (goals) (Zhang et al., 2011a).

STEP-NC (ISO14649) is a relatively new data format for manufacturing control, and is part of the ISO 10103 Standard for the Exchange of Product Model Information (STEP) suite (Hardwick et al., 2012). The purpose of this data model is to overcome the lack of process planning information in ISO 6983 files (G and M codes) (Rosso et al., 2004), by offering a comprehensive and interoperable product and process data seamless flow among CAM systems and machine-tool controllers, (Xu et al., 2011; Yusof and Case, 2008). Figure 3-14 illustrates the process chain of both standards the G-code and the STEP-NC manufacturing data chain (Rauch et al., 2009). Following the introduction of 10303 and implementation methods such as the use of function blocks by Xu et al. (2006), for enabling interoperability across the CAx chain, the STEP-NC standard has been used to represent the data flow among the CAD/CAM.

A considerable amount of literature has been published on the Interoperability of CAx chain, as these studies commonly use STEP-NC to address interoperable integration of CAx chain (Zhang et al., 2014; Hardwick et al., 2012; Zhang et al., 2011b; Xu et al., 2006). Since, CAx results in large exchange of information the interoperability issue

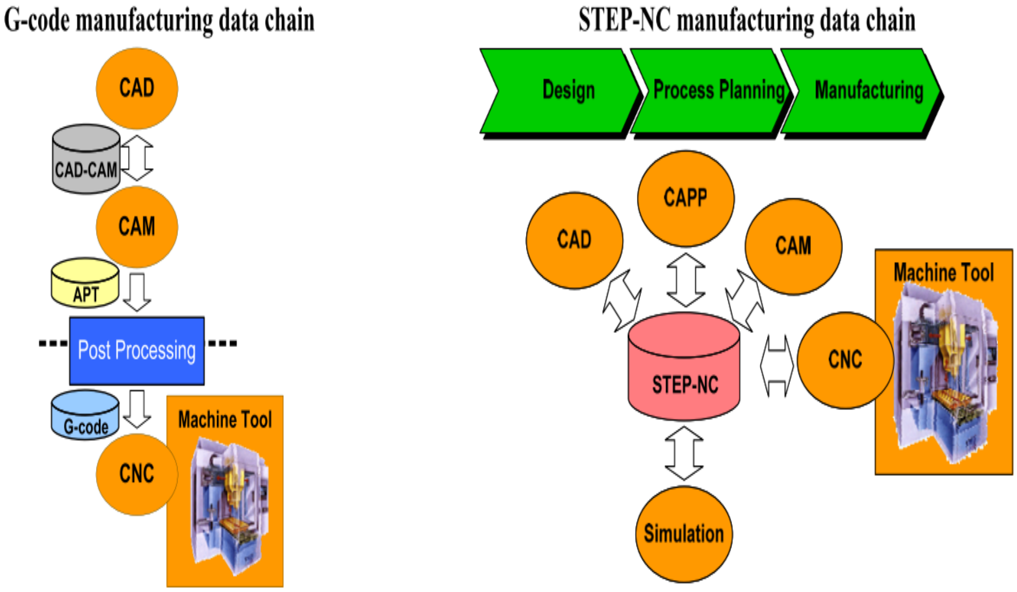


Figure 3-14: Data process chain comparison
Rauch et al. (2009)

has arisen in order to help integrate the chain effectively without any errors. Newman and Nassehi (2007) Provided a vision for a universal manufacturing platform (UMP) that enables seamless information transfer between various CAx systems by using STEP-NC, the platform consists of three main components: the intercommunication bus, the manufacturing data warehouse and the manufacturing knowledge-base, as shown in figure 3-15.

The platform achieves interoperability by abstraction of resources, encoding relevant knowledge in a standardised manner and communication infrastructure to transfer data from one application to another. This framework enables interoperability among CAx resources by increasing information availability and semantic homogenisation during the CAx manufacturing process. (Newman and Nassehi, 2007)

Rauch et al. (2009) provided an enhanced vision of this to address interoperability requirements and enhance manufacturing efficiency, by enabling STEP-NC files

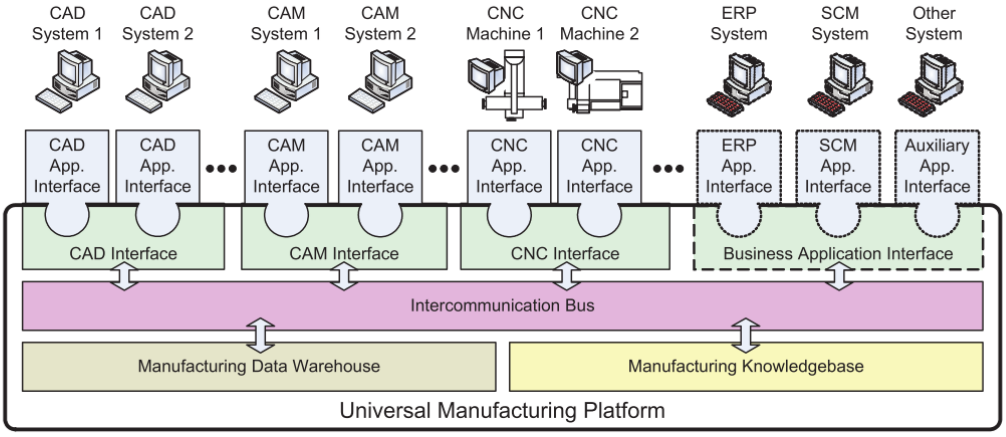
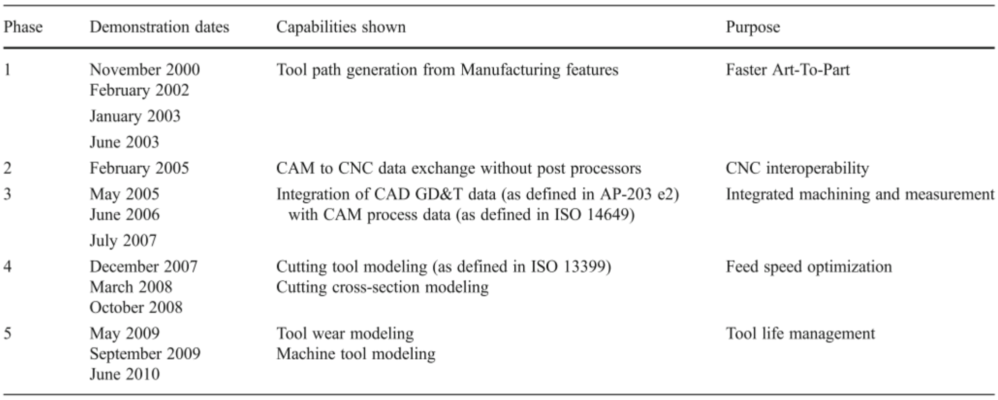


Figure 3-15: Universal manufacturing platform architecture
Newman and Nassehi (2007)

to have direct control over machine tools via a platform namely SPAIM. This was achieved through realisation of data portability between heterogeneous proprietary formats (IIMP),

Mokhtar and Houshmand (2010) illustrated utilisation of the STEP standard extensively using STEP-NC in CAx chain integration. Furthermore, they proposed a systematic roadmap using Axiomatic Design methodology to address interoperability via the implementation of the Universal Manufacturing Platform (UMP) proposed formerly by Newman and Nassehi (2007). Zhang et al. (2011c) proposed an interface to realise interoperability between CNC machine and CAx systems through a STEP-NC compliant data structure, it comprehended the process plan from G and M code part programmes and translated them to into a generic STEP-NC compliant representation. Wang and Xu (2011) utilised the STEP-NC data model and service-oriented-architecture(SOA) to develop a platform notated as Distributed Interoperable Manufacturing Platform (DIMP), for seamless data exchange between CAx systems. Additionally, they demonstrated the interoperation difficulties of systems in CAx chain.

Furthermore, Hardwick et al. (2013) clarified the importance of extending and applying STEP-NC industrially, in a Sequential 5 phase approach as shown in table 3.2. Emphasizing the interoperable needs of manufacturing information. As well, introducing future STEP-demonstrations in modifying tool paths to meet acquired tolerances. Mokhtar and Valilai (2013) developed a platform (INFELT-STEP-NC), based on an integrated CAD/CAM architecture through STEP-compliant agents (feature recognition and process planning), to ascertain integration and interoperability among the CAx chain. Lastly, Lipman and Lubell (2015) identified and addressed two challenges: (i) Association of product design concepts as presented to CAx developers along with data model defined in standard (STEP), and (ii) ensuring semantic implementations of standards by software (CAx) application by modelling Product and Manufacturing Information(PMI) using STEP.



| Phase | Demonstration dates | Capabilities shown | Purpose |
|---|---|---|---|
| 1 | November 2000<br>February 2002<br>January 2003<br>June 2003 | Tool path generation from Manufacturing features | Faster Art-To-Part |
| 2 | February 2005 | CAM to CNC data exchange without post processors | CNC interoperability |
| 3 | May 2005<br>June 2006<br>July 2007 | Integration of CAD GD&T data (as defined in AP-203 e2) with CAM process data (as defined in ISO 14649) | Integrated machining and measurement |
| 4 | December 2007<br>March 2008<br>October 2008 | Cutting tool modeling (as defined in ISO 13399)<br>Cutting cross-section modeling | Feed speed optimization |
| 5 | May 2009<br>September 2009<br>June 2010 | Tool wear modeling<br>Machine tool modeling | Tool life management |

Table 3.2: Summary of STEP-NC enabled interoperable manufacturing demonstrations

Hardwick et al. (2013)

### 3.4.2 Cloud Manufacturing Interoperability

Interoperability is a critical challenge for cloud manufacturing. Wang and Xu (2013) proposed a four layered architecture for cloud manufacturing to address interoperability (ICMS) as shown in figure 3-16, consisting of a manufacturing resource layer; to abstract manufacturing capabilities into self contained modules, in order to be launched depending on user request. STEP/STEP-NC was applied to enhance the portability and longevity of the manufacturing resource data modelling, subsequently, data is backed up in the storage cloud database that is embedded within the layer. As for the Virtual Service layer; it organises the service request information into a compliant format, further, it is analysed by the broker agent to match the service request with data stored in the resource database, formerly the supervision agent handles the service approval by organising and merging related modules. the Global Service layer; promote enterprises to gain a logic control over the work-flow and processes of the service. And the Application layer that provides the interface between the cloud user and the ICMS. Followed by a Java Agent programme for evaluation, as Creo and CNC application were integrated as a Virtual Service Combination.

Li et al. (2013) provided an interoperable four phased modelling approach for a One-of-a-kind production paradigm followed-by a framework for data sharing and exchange (DES) within the cloud manufacturing system. The four phases were as follows; (1) application of four coherent sub-models: a feature based model that contains comprehensive information of the product, a customer information model, a manufacturing resource model and a manufacturing activities model. (2) the second phase is for linking the sub-models with STEP standards and application protocols namely ISO 10303 and AP203. Third, addition of self-defined entities and schemas of a customer model that is not presented within the STEP standards, hence, in the fourth phase both STEP defined and self defined models were integrated by utilising EXPRESS and EXPRESS-G languages to present the data model along with entities

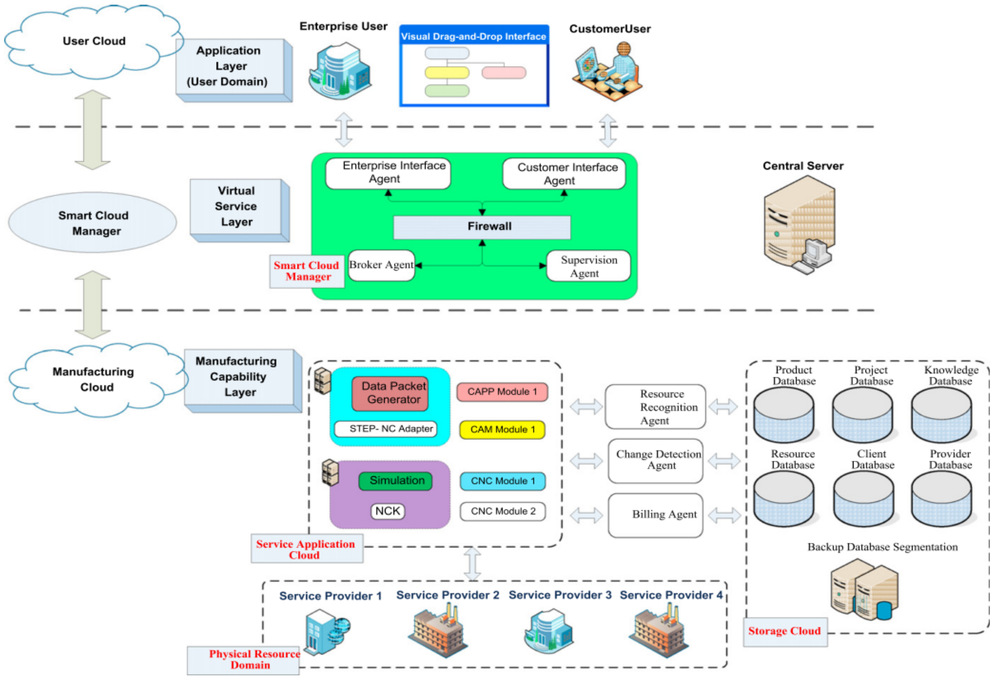


Figure 3-16: ICMS architecture
Wang and Xu (2013)

relationships. Furthermore, a framework for data sharing and exchange within the cloud manufacturing system was proposed that illustrate two different scenarios, either using STEP for CAx systems or using a standard data access interface (SDAI) for other design-related applications.

Additionally, Wang et al. (2014) addressed interoperability for manufacturing task description within the cloud manufacturing. This was achieved by applying an Ontology based framework for semantic and universal task manufacturing description (GCMT). Through utilising various approaches and technologies; documenting pre-processing technologies, domain knowledge, automatic ontology construction approaches, sub-ontology matching methods, and other relevant computer technologies. This formed a four layered model consisting of (i) General Cloud Manufacturing Task Ontology construction, (ii) General Cloud Manufacturing Task ontology semantic feature space,

(iii) cloud manufacturing task sub-ontology semantic description and (iv) applications of a cloud manufacturing task semantic model.

Lu et al. (2014) proposed interoperability through a Hybrid Manufacturing Cloud architecture that promote users to utilise different cloud modes namely, public, community, and private clouds. This gave cloud users full control over the related resource sharing authorisation, thus enhancing trustworthy and patent protection. The structure of the approached system includes the traditional layers of: Resource Layer, Virtual Resource Layer, Global Service Layer and an Application Layer. Along with a cloud management engine that deploys Semantic Web technologies to allow the bidirectional transfer among the different cloud modes, promoting users to switch between different clouds at the macro-level and to control the manufacturing resource sharing authorisation at the micro-level, for their periodic requirements. Moreover, it enables organisations to implement an integration of the three service models after a ROI (Return on Investment) analysis considers factors such as manufacturing capabilities, business strategy and security concerns.

Recently, Delaram and Valilai (2016) introduced an electronic data interchange standard (EDIX12) as a solution for realising integration and interoperability of service decomposition and service mapping mechanisms among different manufacturing clouds though the utilisation of the Internet as medium for information transfer. They also, introduced an architecture for third-party companies that tied to a pool of universally industrial standards such as STEP, STEP-NC, MANDATE and PLIB enabling integration and interoperability.

Apparently, cloud manufacturing reflects the current pinnacle of evolution of technology within the manufacturing industry, although still some work is required before large scale application (Siderska and Jadaan, 2018). Hence, based on the review of literature section, the author remarks that extensive efforts, investments and collaborations is required in order to enable and implement interoperability within cloud manufacturing systems.

## 3.5 Critique

Cloud manufacturing is a relatively new manufacturing concept that offers manufacturing production as a service; a vast amount of information is required to be exchanged in a non-ambiguous and timely manner to meet production requirements. Considering the state-of-the-art, more work is required in the areas of manufacturing information modelling (i.e.encapsulation of manufacturing resources and manufacturing capabilities information modelling), standardisation of manufacturing work-flow and the seamless integration of manufacturing information of heterogeneous and isolated manufacturing components. The research gaps identified by the author have been thus categorised as follows:

### 3.5.1 Manufacturing integration gap

Networked manufacturing has been formerly introduced as a collaborative approach for SMEs in order to enhance manufacturing resource utilisation and manufacturing cost reduction. However, deployment of manufacturing resources within a networked environment involves a lot of manual reconfiguration which limits scalability and elasticity. As Networked Manufacturing exploits middle-ware technologies for the integration of manufacturing resources, that in some instances do not comprise the corresponding interface for a related resource. Hence, integration still requires highly technical low-level programming. Networked Manufacturing thus lacks the adaptability to acquire the future and the competitive needs of manufacturing enterprises and more work is required.

### 3.5.2 Data representation gap

In the current state there is redundant data representation and description of manufacturing resources and capabilities due to proprietary semantics and data formats. Extensive efforts have been proposed to establish standardised information representation of manufacturing resources and capabilities within an integrated manufacturing system, aiming for seamless data transfer and exchange. STEP, WSDL, ontology techniques and XML have been utilised for the identification and application of standardised data models and structures for manufacturing resources and capabilities utilised through the services processing. Hence, this deployment approach can pave the way for the development of Cloud Manufacturing to realise the integration of current manufacturing information systems. Additionally, table 3.1 illustrates the cloud manufacturing architecture components developed by various authors, which clearly shows the redundant representation resembling the same role within the cloud manufacturing system, but with different description representation.

The Manufacturing enterprises are currently adopting service-orientated approaches to integrate manufacturing resources based on the cloud computing paradigm. Thus, state-of-the-art methodologies are crucially required to enhance the integration of various manufacturing resources. Additionally, there is a need for intelligent integration rather than just the current automation as it that offers autonomy in achieving manufacturing tasks. Further development is also needed in the integration of manufacturing control systems which can enhance the Cloud Manufacturing paradigm. Extensive work has been made in relation to the development of open communication standards among shop-floor connectivity to enhance machine to machine interaction (intercommunication), thus flexibility and coordination through manufacturing product life cycle has been realised.

### 3.5.3 Cloud manufacturing gap

Cloud manufacturing can have a strong impact on manufacturing, as cloud integration hardware and software resources improves manufacturing resource sharing and the product development process. Furthermore utilisation of cost via "pay-as-you-go" cloud computing approach inheritance. Further investigation is still required to identify the communication and interaction protocols of the collaboration structure that enables the merging of service providers and service users within Cloud Manufacturing system.

The most important gap identified by the author, however, is not in the constituent parts of the cloud (as many cyber physically enabled smart manufacturing components already exist), the protocols and architectures (as plenty of excellent work has been done in this area already) or the integration (as several approaches likely to succeed have been proposed by the researchers). The author believes that the main gap is in research on the required level of interoperability and integration for a manufacturing cloud. In other words, even though the technology for realising interoperability at several levels already exists, it is not clear how much of it should be implemented in a given scenario. In this work, the author has used a suite of technologies readily available to him and focused on the identified gap of creating a method of deciding the appropriate level of interoperability in a given manufacturing cloud. The technologies used by the author are :

- A tool path generator (Essink, 2016): this component compiles interoperable STEP-NC into traditional CNC executable G-code.
- Machine capability profile (Afsharizand et al., 2014): a framework for capturing machine tool specifications required for part machining and comparing these information with the deployed manufacturing resources.
- Unified manufacturing resource model (Vichare, 2009):a method for structuring

resource information

These technologies are based on the international standards STEP i.e part 203 and part 214 for geometry , AP 224 for feature recognition and STEP-NC i.e. ISO14649-201 for machine capability profile capturing. Accordingly, STEP and STEP-NC will be inspiration for the standardized concept of an interoperable cloud manufacturing systems.

# Chapter 4

# A Framework for assessing the appropriate level of interoperability in Cloud Manufacturing

## 4.1 Introduction

This chapter presents the theoretical framework of this research in the form of a typical cloud manufacturing platform, to investigate and explore cloud-resource sharing and execution of manufacturing process plans for heterogeneous-decentralised manufacturing resources. The limitations identified in the previous chapter were used to develop a set of requirements for interoperable cloud manufacturing systems that are able to deploy current and future manufacturing resources and capabilities.

## 4.2 An interoperable cloud manufacturing framework

In order to asses the value of interoperability in cloud manufacturing, a definition sufficiently flexible to incorporate both interoperable and non-interoperable scenarios is required. The concepts established in the literature in chapter 3 are combined to construct an abstract framework as the basis for analysis.

For the purpose of this research, Interoperability in cloud manufacturing is defined as: "non-ambiguous, and error free transfer of information and data between current and future cloud manufacturing components; aiming for unifying manufacturing resources and capabilities to move from a preparatory notion to open source sharing of decentralized manufacturing resources and capabilities". Additionally, considering traditional CNC machinery within the cloud manufacturing arena, interoperability is expected to facilitate the enabling of shared distributed manufacturing resources and capabilities through cloud-based connectivity. This will support the majority of SMEs stakeholders that are in capable of changing or updating their current manufacturing resources allocated in shop-floor. As the cloud manufacturing stakeholders will support service providers with the manufacturing resource interface component which will enable the machine tools to be connected to the cloud based on its technology i.e. (a) If the machine tool is fully automated, hence the machining orders is sent from the cloud is sent directly to the machine tool interface, (b) if the machine tool technology is semi-automated a NC-compiler will be installed on the machine tool by the C-MARS cloud providers. And (c) finally, if the machine tool is non-automated, the manufacturing resource interface will be a computing device allocated next to the machine tool and machining orders along with the instructions is sent to an operator for executing cloud services manually.

The interoperable framework will enable the integration of the essential components of a manufacturing system (i.e. unified manufacturing resource model, scheduler, tool-path generator, CAx systems) to realise an interoperable cloud manufacturing system, and this will provide manufacturing resources and capabilities as on-demand services on an on-demand basis through the internet of things and enable the cloud manufacturing system components to communicate and exchange data autonomously. The following figure 4-1 depicts the proposed framework, as it consists of 5 main components which collaborate (communicate) through the cloud system in order to execute manufacturing services through the cloud. These components map on the generic layers of cloud manufacturing in figure 3-13.

## 4.3 Framework Components

### 4.3.1 Machining service processing

The theoretical framework is described in this section, to explore cloud-resource systems in manufacturing and investigates the machining of associated manufacturing process plans for heterogeneous-decentralised manufacturing resources.

This model is capable of executing various manufacturing tasks by connecting (bridging) heterogeneous deployed manufacturing resources throughout the Cloud-based system. The proposed model offers the capabilities of the deployed manufacturing resources; as service for executing various process plans (manufacturing services), the execution process is completed within a framework shown in figure 4-2 this enables the deployed manufacturing resources to perform scheduled tasks (services). The functional requirements of the cloud-based model can be identified as follows:

(a) Identification of the requested task (services) as manufacturing capabilities.

(b) Assigning identified capabilities to the deployed manufacturing resources.

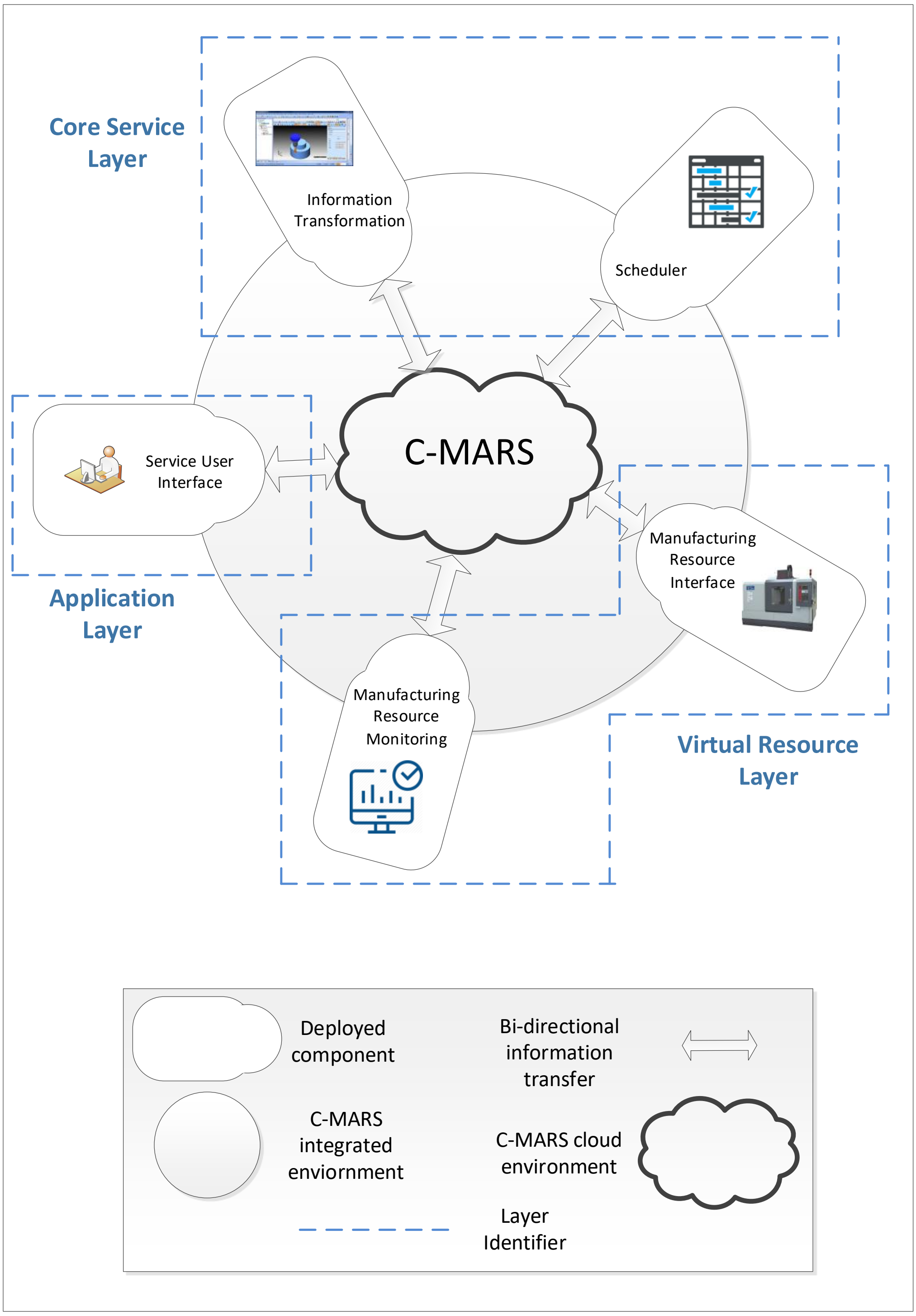


Figure 4-1: Cloud Manufacturing Framework Components

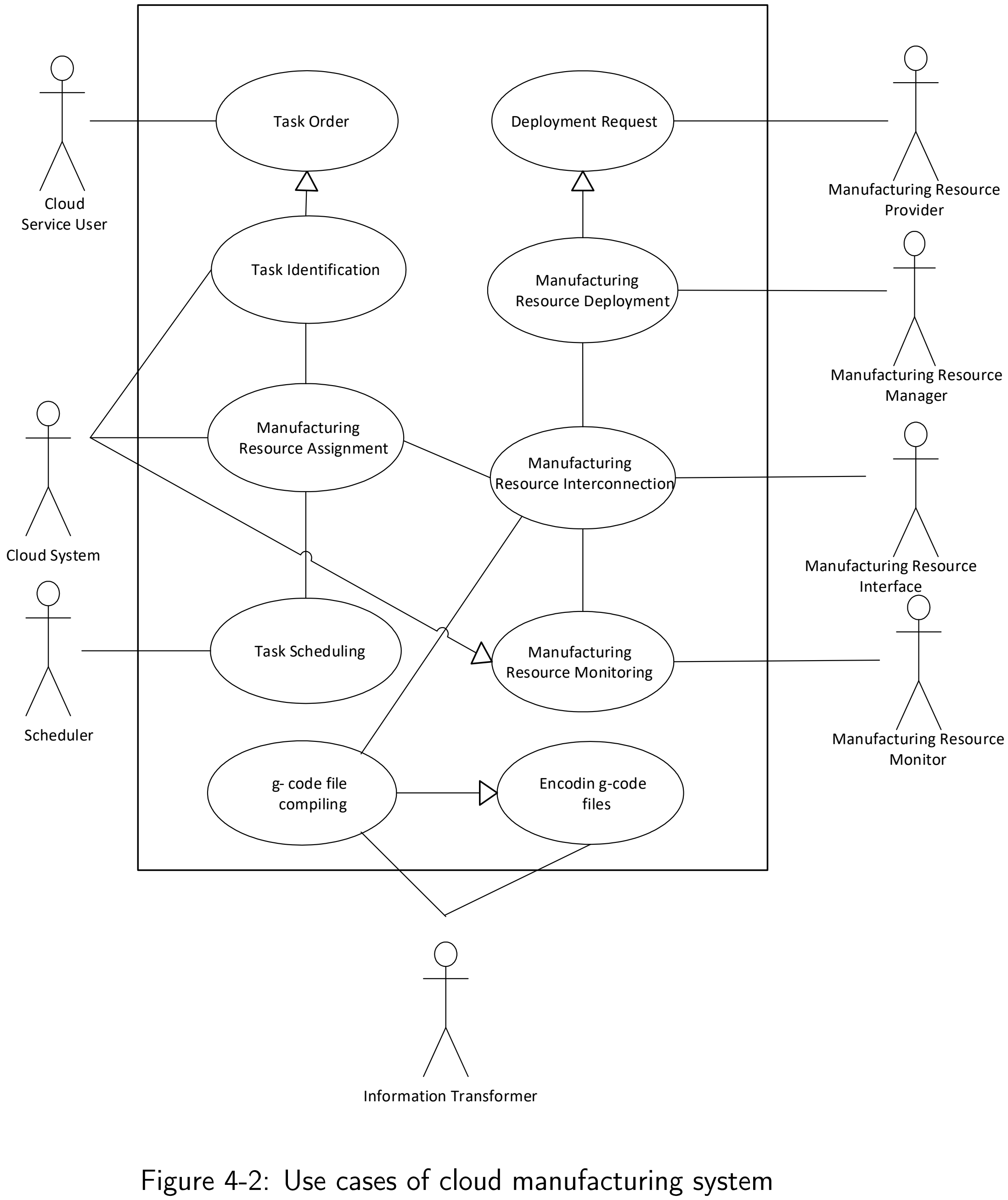


Figure 4-2: Use cases of cloud manufacturing system

(c) Scheduling an assigned task for the deployed manufacturing resources.

(d) Interconnect with various manufacturing resources via the physical manufacturing resource interface.

(e) Encoding g-code files in compliance with the deployed manufacturing resources.

(f) Compilation of heterogeneous G-code files based on the manufacturing resource proprietary.

(g) Monitoring manufacturing resource operation regarding task start and job end notification.

(h) Deployment and identification of various multifaceted manufacturing resources.

The high-level illustration of this framework and its functions are shown in figure 4-3 and 4-4 demonstrating the steps required for acquiring cloud manufacturing services. The cloud system process(s) the respective CAD file and forwards the scheduling input parameters to the scheduler. Then, the machining tasks are sent to the assigned machine tools for service execution. Explicitly, the service processing function is abstracted in three main functions; accepting service (A1), scheduling (A2), and execute service (i.e.order processing, A3). Each have specific constraints and physical aspects for mechanisms; as the accepting service function is mainly executed by the cloud system component that compares the service order with the deployed manufacturing capabilities within the cloud manufacturing sharing system (A11). This is then forwarded to the machining operation sequence along with the available machine tools (A12) for next the phase as shown in figure 4-5.

Consequently, as shown in figure 4-6 the confirmed order is scheduled by the scheduler component that sequences the assigned resources with the requested order based on the user specification criteria (A21). Furthermore, the sequence of machining operations is assigned for adequate machine tools along with scheduling criteria (A22).

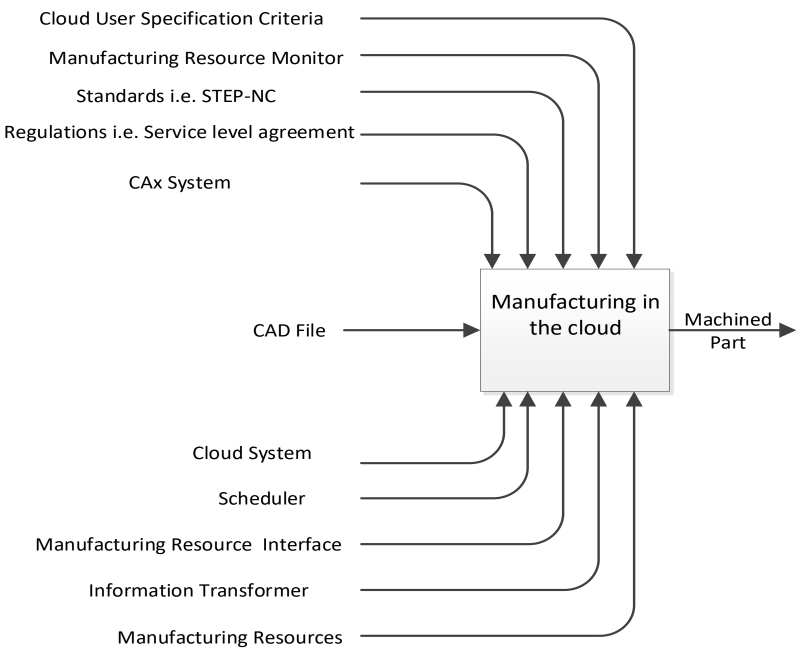


Figure 4-3: High level functional view of a cloud manufacturing system

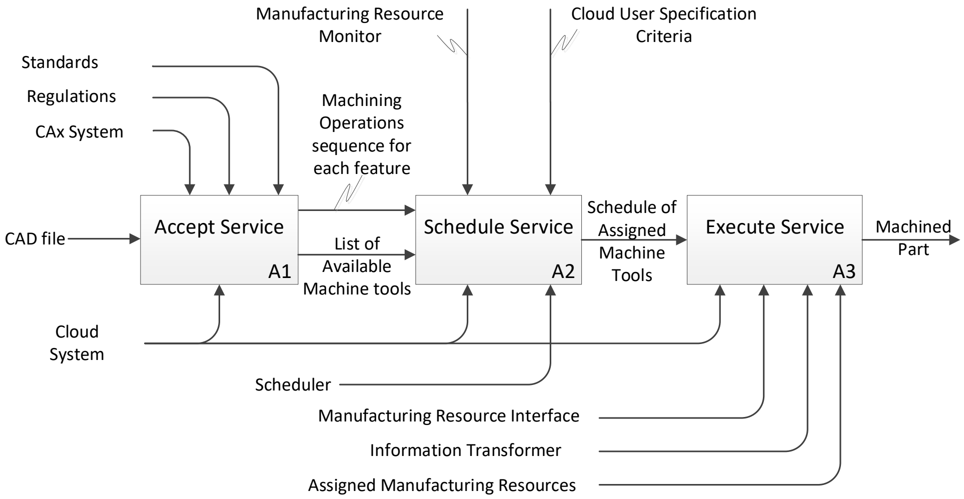


Figure 4-4: Cloud Manufacturing Service Processing

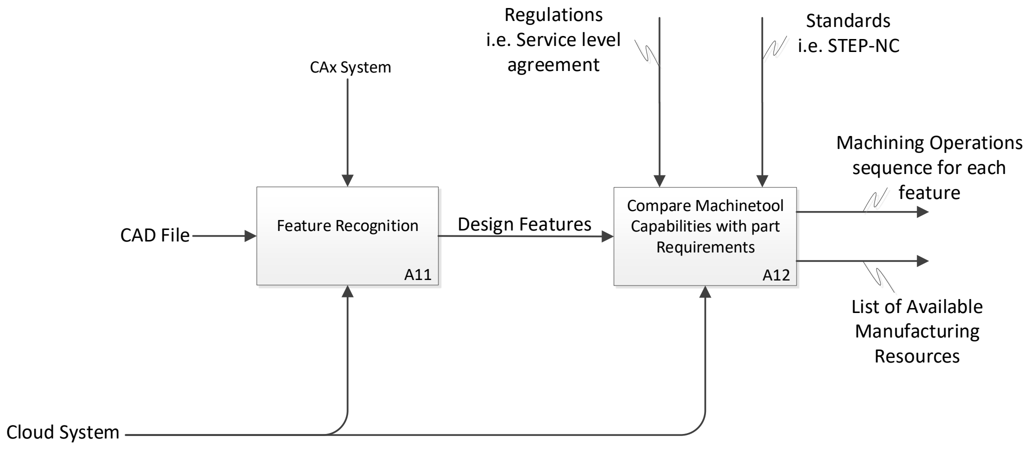


Figure 4-5: Accepting Service for cloud manufacturing system

Hence, the schedule of the assigned manufacturing resources is transfered to the service execution phase (A31). The manufacturing resource interface component receives the assigned machining order (A32) and requests the compiled NC file from the information transformer component as shown in figure 4-7. The tool path of the assigned order is generated by the tool-path generator, once received the post processor type and sequence of machining operations(A33), in order to generate the

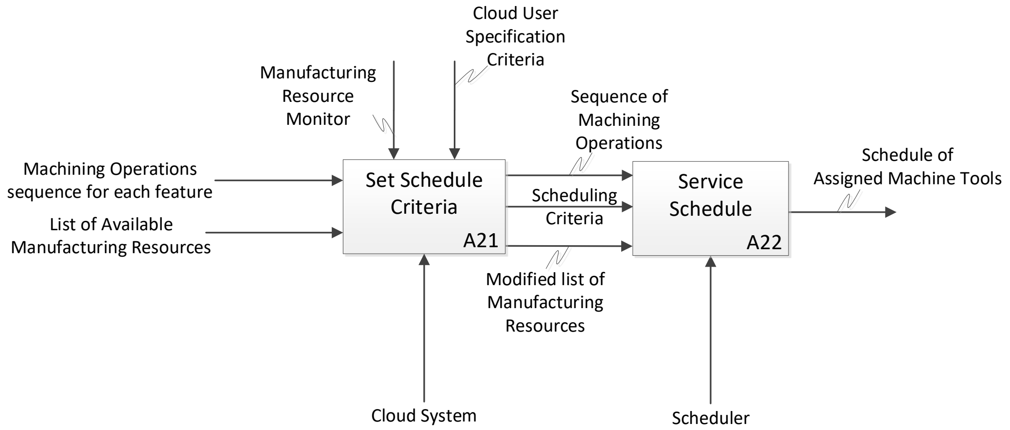


Figure 4-6: Cloud manufacturing service execution

compiled (g&m code) NC file. Henceforth, machining process is initiated by the manufacturing resource interface component to execute the machine part(A34).

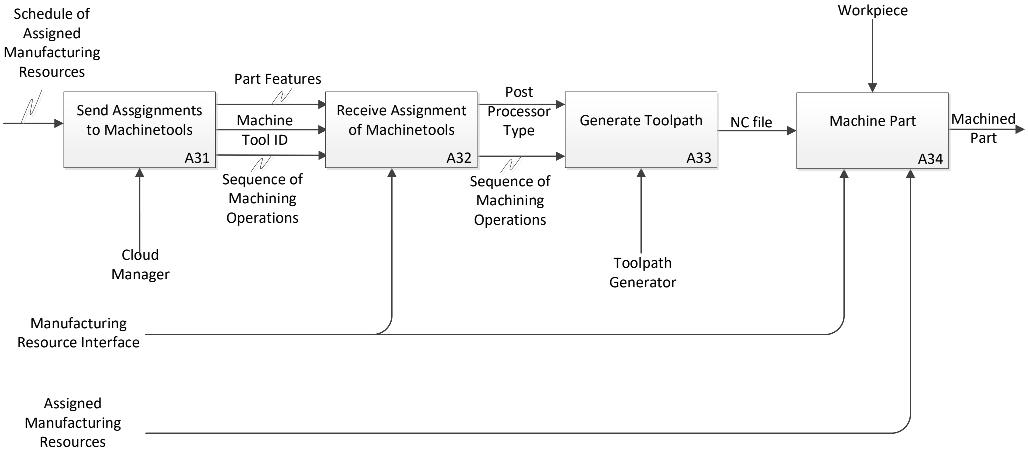


Figure 4-7: Execute Service for cloud manufacturing

### 4.3.2 Deployment of manufacturing resource

This section describes the deployment process of adding manufacturing resource to cloud manufacturing systems for service providers. As shown in figure 4-8, The manufacturing resource provider initiates a request for deploying a specific manufacturing resource (A1), consequently, the manufacturing resource manager component receives and analyses the request sent for the deployment phase (A2). Subsequently, a manufacturing resource interface (i.e.STEP-NC compiler) is installed to the recently deployed manufacturing resource hardware (i.e.machine-tool) and enrolled in the available cloud manufacturing resources (A3, A4). The deployment process will be explicitly described in the next chapter.

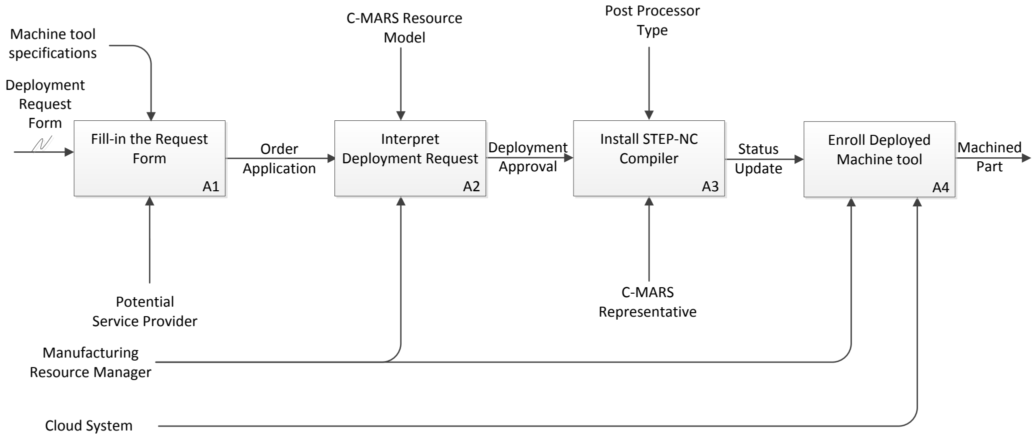


Figure 4-8: Deployment Request for cloud manufacturing

## 4.4 Cloud manufacturing structural view

In this section, the structural and functional views of the theoretical framework are specified via the uml component and class diagrams, as these tools depicts system by showing the attributes of each operations and the relationship among the cloud manufacturing components. The model structure consists of eight classes as shown in figure 4-9, each with a specific component as illustrated in figure 4-10, to perform an assigned task.

- The Service user and the manufacturing resource provider components: These are responsible for submitting a system task, by providing data input, whether for a service request (service user) or deploying a new manufacturing resource to the system (manufacture resource provider).
- The Cloud System component: This is the core component of the model for offering (acquiring) model services, It provides (a) task request for operations, (b) a list of manufacturing resources assigned to a related job request, (c) The resource capabilities of the manufacturing resources assigned (deployed), and the job order of the deployed manufacturing resources to execute the requested

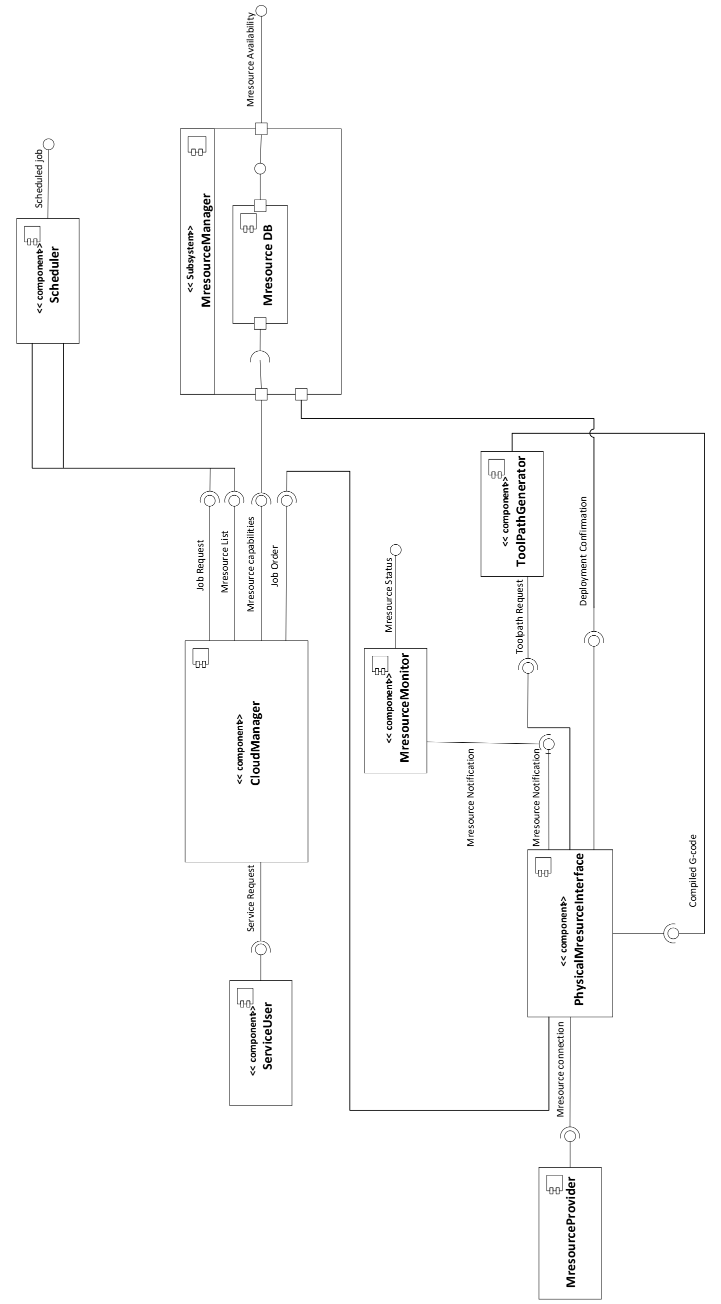


Figure 4-9: Components of cloud manufacturing system

Figure 4-10: The structure of a cloud manufacturing system

task.

- The Manufacturing resource interface component: This is the point of contact between the heterogeneous (various) manufacturing resources and the Cloud-based model for task executing and monitoring; some advanced resources allow this interconnection consistently and others may require an interface port attachment to enable their connectivity (deployment).
- The Manufacturing resource monitor component: It has responsibility for monitoring the task execution beginning and end times.
- The Manufacturing resource manager component: Manages (handle) the deployment process of the Manufacturing resource to the cloud-based; by receiving deployment requests from manufacturing resource provider component (2) and update the cloud manager component with the manufacturing resource availability.
- Scheduler component: Schedules the requested task with the manufacturing resources assigned by the cloud manager component.
- The Information transformer component: Interprets the scheduled tasks of the cloud-based model to generate compiled g-code files for the deployed manufacturing resources for task execution.

## 4.5 The sequence of events in a cloud manufacturing system

The operation of the cloud-based manufacturing system, involves a service user, cloud system, manufacturing resource manager, scheduler, manufacturing resource interface, manufacturing resource monitor, and information transformer. This system is illustrated from the point of task demand (service request) as shown in figure 4-11

Once this service request is sent to the cloud manager component, it verifies the availability of manufacturing capabilities with the resource manager component. By identifying the type of service and determining the manufacturing capabilities needed for acquiring the request task. Consequently, the manufacturing resource component replies with the notation of the resource availability. Previously, the cloud system has filtered and matched the required manufacturing capabilities to send a task scheduling request to the scheduler component for scheduling the deployed manufacturing resources with the assigned task. The service proposal is sent then to the service user component for confirmation purposes, subsequently, the cloud system forwards the confirmation to the manufacturing resource interface which corresponds to the machine-tool that is physically allocated in the shop-floor to execute the confirmed task.

Once the manufacturing resource interface receives the confirmation, it sends a tool-path request to the information transformer and the task execution process is initiated, as soon as the compiled tool path is received by the manufacturing resource interface component. Furthermore, it sends a notification of the execution status to the manufacturing resource monitor component. Thus, it allows the cloud system to be updated with the machining progress.

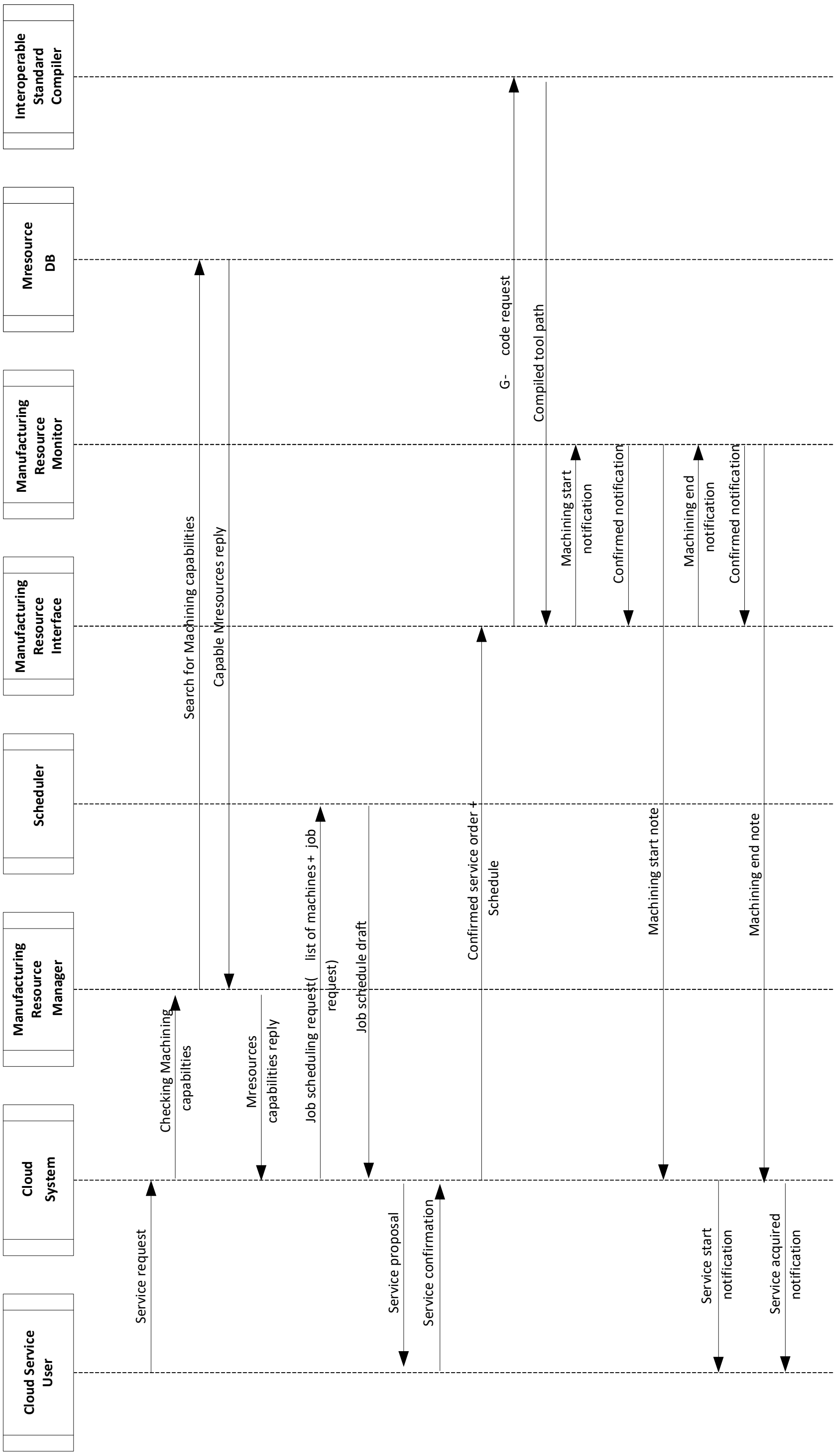


Figure 4-11: Sequential view of service request

# Chapter 5

# Implementation of a Cloud manufacturing system (C-MARS) for assessment of appropriate level of Interoperability

## 5.1 Introduction

This chapter outlines the implementation process of the interoperable cloud manufacturing framework, known as C-MARS, by means of demonstrating the flow of the machining process through a complete manufacturing cycle for prismatic parts. The interoperable cloud manufacturing framework utilises STEP-NC as an interoperable standard for executing cloud machining services. The following section explains the activity modelling developed for the system with reference to cost. Further, an overview of the case study is shown followed by the development of the C-MARS activity based model C-MARS-ABM. In order to compare the interoperable approach for cloud manufacturing, a non-interoperable cloud manufacturing activity based model (NC-MARS-ABM) has also been provided to identify the contrast between adopting both approaches for cloud manufacturing system. Finally, the quantification of the activities in reference to cost is described.

## 5.2 Case study development

The prismatic sample part in ISO 14649-11 shown in figure 5-1 has been utilised as a simple case to demonstrate the processes encapsulated in the C-MARS framework.

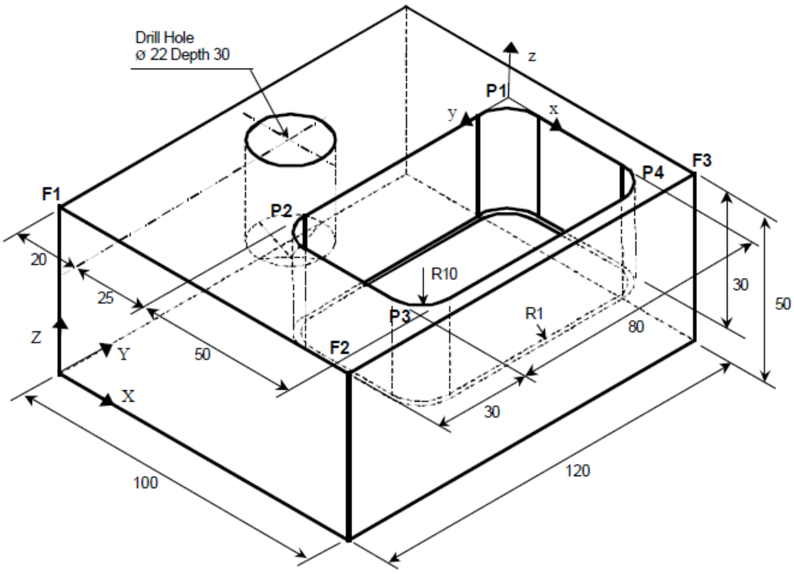


Figure 5-1: ISO14649-11 Sample Part

The machining operations identified for the STEP-NC file are as follows: (i) facing operation shown in 5-2, (ii) 2D pocket flat end milling operation for the 2D pocket and (iiI) drill hole shown in Figure 5-3 machine tool profile, machining specification, cutting tools used and machining operations, part size. The machine tool specification

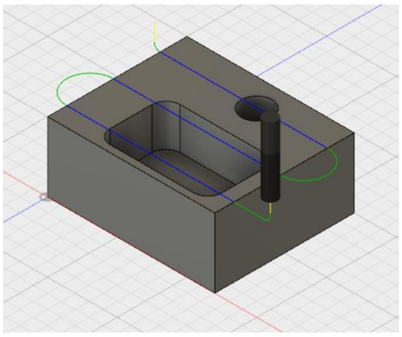


Figure 5-2: Facing Operation

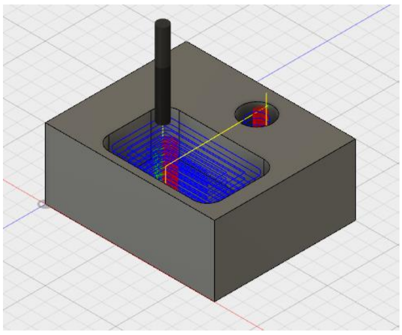


Figure 5-3: 2D pocket and hole

is: Dugard Eagle 850, 3-axis milling machine, cutting tools used are; face mill diameter 40mm and Slot drill 8mm.

## 5.3 The C-MARS of activity based model of manufacturing (C-MARS-ABM)

The business model shown in figure 5-4 illustrates the service processing request by the service user in C-MARS for manufacturing the part defined in section 5.2.

The C-MARS business operation model works by; initiating a service request (→1) by a customer for manufacturing a designed part (uploading a CAD file through a web interface in STEP format), the file is sent directly to the cloud manager (which identifies the design features,machining operations, i.e: face mill, 2D pocket, and drill hole) that consequently compares the machine capabilities available with the part requirements in the CAD file (i.e. milling and drilling operations) and requests the needed machine capabilities (→2) from the manufacturing resource manager. The manufacturing resource manager then replies to the cloud manager with a list of the available machines tools (3←) (FANUC or DMG Mori) that can machine the features of the part(based on the request of the cloud manager for the capability profile of the assigned machine tool).

Accordingly, the Cloud Manager Aggregates this information (comprehensive process sheet i.e. operations type, cutting tools used; face mill, drill and slot drill, feeds, speeds, etc) with the information sent by the Manufacturing Resource Monitor machine tools status update (idle or machining in progress or maintenance procedure) to set the scheduling criteria (i.e. delivery time, specific machine tool). The Cloud Manager then sends these sets of information (→4) to the Scheduler (machine tools type i.e, FANUC, machining operations i.e, Facing, Slot drill and drill).

The scheduler assigns the machine tools based on the criteria above and replies with assigned machine tools, machining operations and the part number (5←). The Cloud Manager then sends the schedule draft (6←) to the customer for service confirmation (→7). Based on the Scheduler assignment, the cloud manager sends the part features with the process sheet to the Physical Machine Interface of each assigned machine. This process sheet contains the related machining operations (→8).

Once the Physical Machine Interface of each of the assigned machine tools receives this information, it will send the feature manufacturing sequence and the post-processor type (→9) to the Tool-path Generator, requesting an NC file (G code) (10←) for the related machining operation.

Accordingly, the Physical Machine Interface will notify the Manufacturing Resource Monitor with the machining operation start (→11) and end (→15) time. Hence, the Cloud Manager is updated with the machine tools status (→13) and (→17), to accordingly notify the customer with machining operation start (→14) and end (→18).

The interoperable approach to cloud manufacturing has been enabled through the use of a standardised high level machining language that can describe part manufacturing requirements in a manner interpretable by a wide variety of resources. For C-MARS,

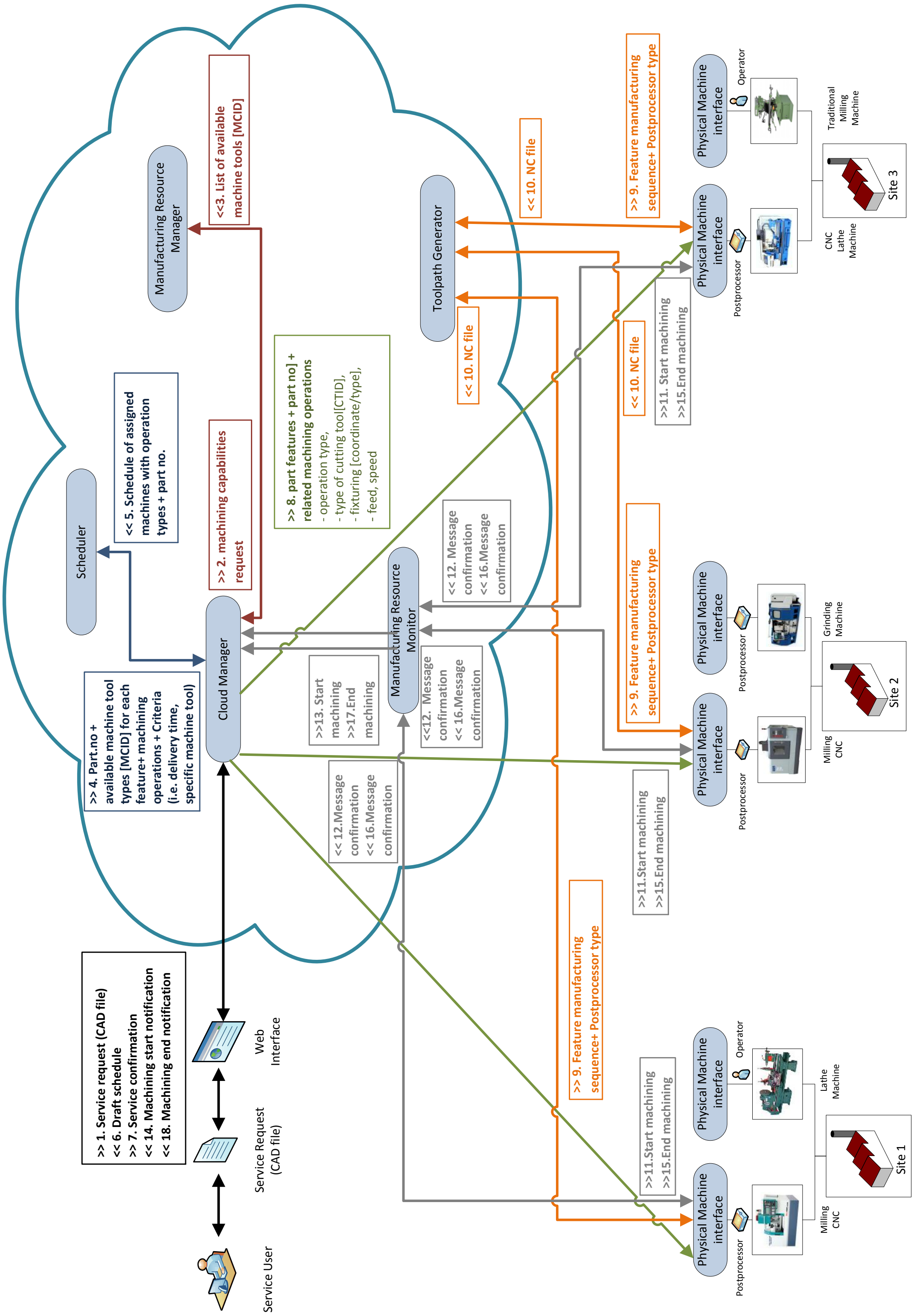


Figure 5-4: C-MARS Business model

the ISO14649 suite of standards (Hardwick et al., 2013) are used as they provide the necessary level of abstraction to describe the manufacturing requirements of prismatic parts. As shown in figure 5-5, the interoperable approach has been defined based on 23 activities assigned to four main entities namely: Process plan agent, C-MARS User, C-MARS Agent, and C-MARS Provider.

The machining process life-cycle is initiated when the design file is uploaded to the C-MARS web interface (A1.1), passed to design file interpretation (A1.2) and machining criteria identification (A1.3) by the C-MARS Agent. Hence these criteria is searched and matched with the available deployed resources (A1.5) and accordingly sent to the process plan agent for validation (A1.7). Once approved the schedule of machine tools is sent to cloud manager for final approval (A1.10), then once approved by the customer and service execution is confirmed (A1.12) It then follows the activity path from (A1.13) until the final machine part is delivered to the designated destination (A1.23). The activities explicit description illustrated in figure 5-5 are described in table 5.1 with reference to the proposed case study in section 5.2

Subsequently, the preliminary description of the activities presented figure 5-5 are shown table 5.1 will be furtherer formulated in reference to cost in chapter 6. Table As shown in table 5.2 illustrates the quantified activities of machining deploying the STEP-NC standard, depending on the activity type whether it is a machining process or machining deployment, the cost impact has been identified as variable cost for C-MARS machining process and fixed cost for Deployment process.

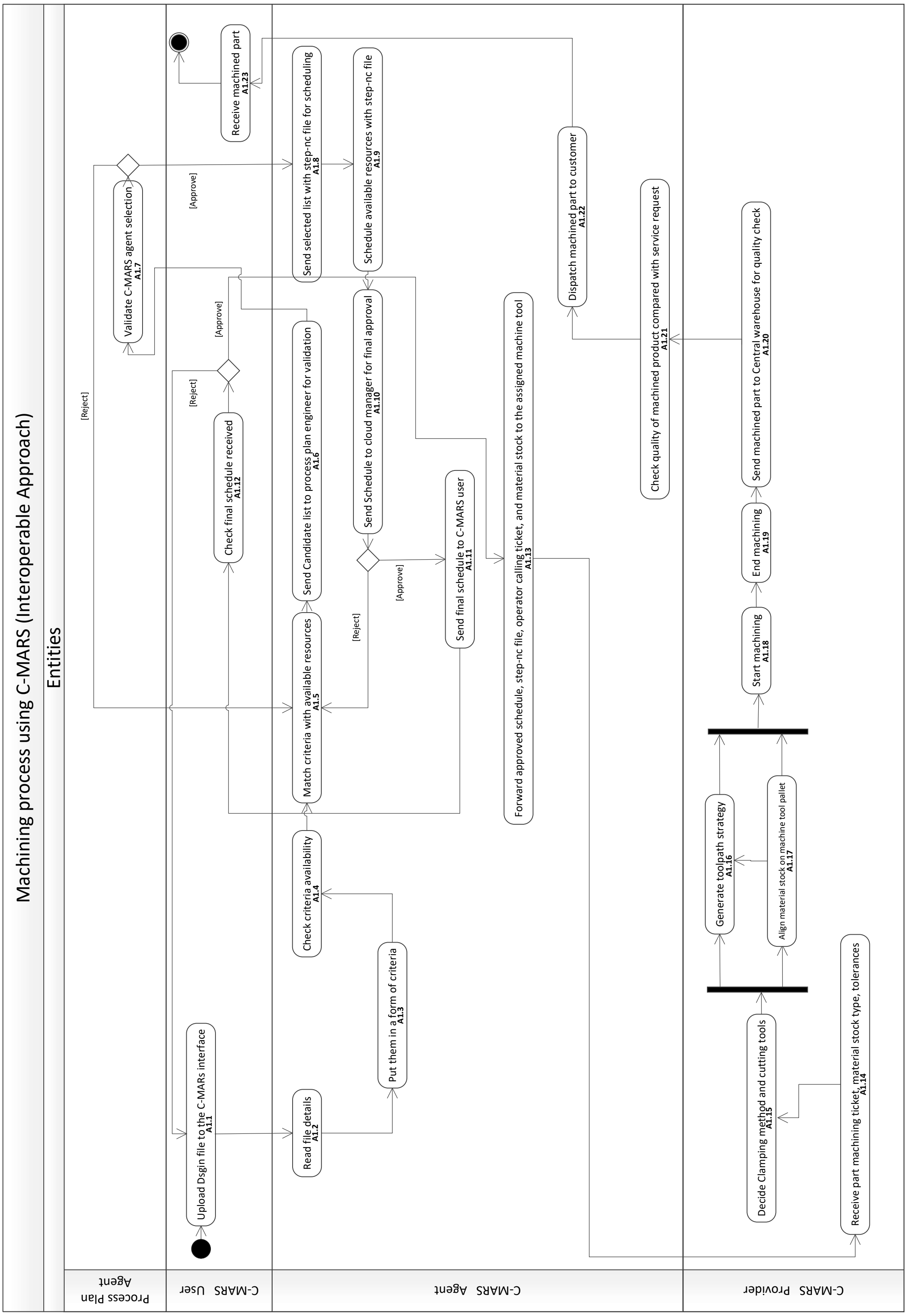


Figure 5-5: C-MARS-ABM Interoperable approach

Table 5.1: Activities description for Machining process of sample part 1 using C-MARS-ABM

| Activity Code | Activity Description |
|---|---|
| A1.1 | Upload STEP-NC file of sample1. |
| A1.2 | Read file header to identify file description, name and schema. |
| A1.3 | Import from STEP-NC file the machining parameters:<br>Workpiece, machining operations, machining axis, workholders, working space. |
| A1.4 | Check criteria availability. |
| A1.5 | If-then statement to match criteria with available resources. |
| A1.6 | Send List to process planner for validation. |
| A1.7 | Process planner approve machine tool selection. |
| A1.8 | Send file "sample 1" and selected machine tool deployment codes to scheduler. |
| A1.9 | Schedule :sample 1 on machine tool. |
| A1.10 | Schedule approved by cloud manager. |
| A1.11, A1.12 | Schedule approved by C-MARS User. |
| A1.13, A1.14 | Calling for machining ticket information:<br>Steel stock, operator, machine tool ID. |
| A1.15 | Sending clamping method, position, Cutting tools. |
| A1.16 | Generate complied tool path strategy on STEP-NC compiler. |
| A1.17 | Align material stock on machine tool pallet based on the Cartesian points given and clamping method suggested by C-MARS provider. |
| A1.18 | Start Machining based on the sequence given by toolpath strategy (update C-MARS Manager). |
| A1.19 | End machining on the expected scheduled time (update C-MARS Manager). |
| A1.20 | Release sample 1 from clamping position and dispatched through the C-MARS route vehicle. |
| A1.21 | Check the measurements and tolerances for sample 1. |
| A1.22 | After approval, pack and dispatch the sample 1 product to the C-MARS user. |
| A1.23 | Product Received by C-MARS user. |

Table 5.2: Activities for Machining process of sample part 1 using C-MARS

| Activity Type | Activity Code | Activity Description | Resources Used | Information Required |
|---|---|---|---|---|
| Machining | A1.1 | Upload STEP-NC file of sample1 | Web interface | Username, password |
| | A1.2 | Read file header to identify file description,name and schema | C-MARS STEP-NC software | File description, file name, file schema |
| | A1.3 | Import from STEP-NC file the machining parameters | C-MARS STEP-NC software | Workpiece,machining operations, machining axis, workholders, working space |
| | A1.13 | Forward approved schedule, step-nc file, | Internet connection, operator calling ticket,material stock to web interface the assigned machine tool | Machining start, expected end time, STEP-NC file, Material stock type |
| | A1.14 | Receive part machining ticket, material stock type | Internet connection, web interface, flash drive | C-MARS username, password |
| | A1.15 | Decide clamping method | C-MARS STEP-NC software | Available jigs and fixture, cartesian points |
| | A1.16 | Generate toolpath | C-MARS STEP-NC software | geometry and topology, machining working steps, manufacturing features, tolerances of these features |
| Deploying Machine tool | A2.9 | Prepare Deployment Process | C-MARS agent | Assign C-MARS operator, training date and time, physical machine interface installment |
| | A2.10 | Setup STEP-NC Writer | C-MARS agent | Machine tool postprocessor |
| | A2.12 | STEP-NC Induction Training | C-MARS Instructor | How to use C-MARS physical machine interface |

## 5.4 Development of non-interoperable activity based model (NC-MARS-ABM)

This section illustrates the activity model of the non interoperable perspective of C-MARS. The developed approach adopts a traditional post-processor allocated for the deployed CNC machine tools, hence, difference in the machining process occurs from the interoperable approach presented in section 5.3.

Alternatively, for the non-interoperable approach, Figure 5-6 illustrates 21 procedural machining activities, inspired by the traditional manufacturing CAx processes, that utilises the G&M codes for machining process. The service is initiated with submitting a service request form by the C-MARS user (B1.1). Consequently, the C-MARS agent identifies the required manufacturing resources (B1.2) that are required for the submitted service. Further, the C-MARS agent matches and allocates the available cloud-deployed resources (B1.3) for executing the machining process. The following 18 activities discuss explicitly the flow among the various C-MARS entities for acquiring the service required (B1.21).

In order to develop a rigorous assessment of the simulated case study, table 5.3 illustrate the activities description involved in the machining process of NC-MARS-ABM followed by the initial quantification of the described activities presented in table 5.4. Thus, the information demonstrated in this section will be utilised further in the development of the simulation case scenarios in section 6 .

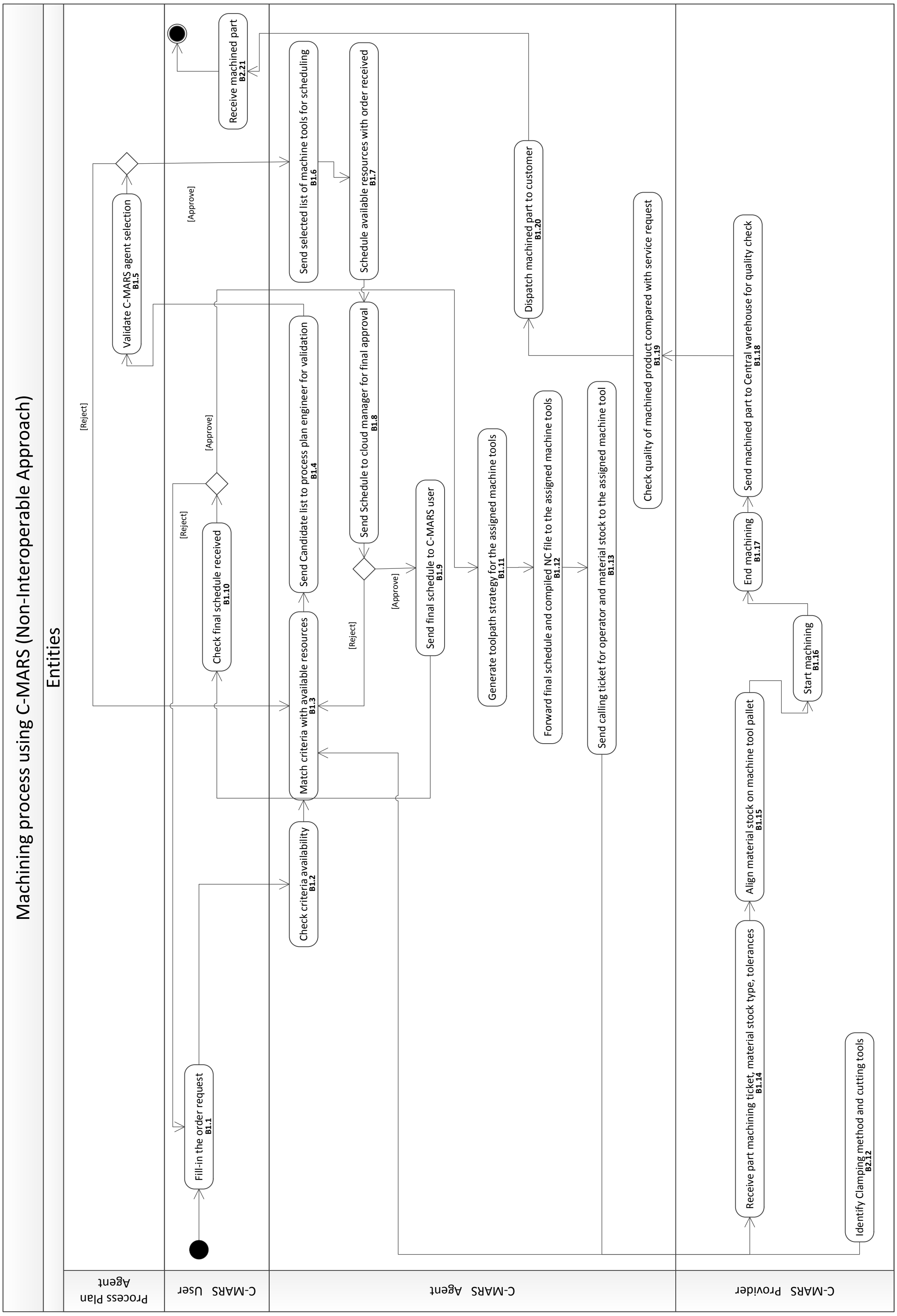


Figure 5-6: C-MARS Non-Interoperable approach

Table 5.3: Activities for Machining process of sample part 1 using NC-MARS

| **Activity Code** | **Activity Description** |
|---|---|
| B1.1 | Fill-in order request for " sample1". |
| B1.2 | Check criteria availability. |
| B1.3 | If-then statement to match criteria with available resources. |
| B1.4 | Send List to process planner for validation. |
| B1.5 | Process planner approve machine tool selection. |
| B1.6 | Send file "sample 1" and selected machine tool deployment codes to scheduler |
| B1.7 | Schedule :sample 1 on machine tool. |
| B1.8 | Schedule approved by cloud manager. |
| B1.9, B1.10 | Schedule approved by C-MARS User. |
| B1.11 | Generate toolpath strategy via postprocessor. |
| B1.12 | Forward final schedule and compiled NC file to the assigned machine tool. |
| B1.13, B1.14 | calling ticket for:stock material, Operator, assigned machine tool. |
| B1.15 | Align material stock on machine tool pallet. |
| B1.16 | Start Machining based on the sequence given by toolpath strategy (update C-MARS Manager). |
| B1.17 | End machining on the expected scheduled time (update C-MARS Manager). |
| B1.18 | Release sample 1 from clamping position and dispatched through the C-MARS route vehicle. |
| B1.19 | check the measurements and tolerances for sample 1. |
| B1.20 | After approval, pack and dispatch the sample 1 product to the C-MARS user. |
| B1.21 | Product Received by C-MARS user. |

Table 5.4: Activities for Machining process of sample part 1 using NC-MARS-ABM

| Activity Type | Activity Code | Activity Description | Resources Used | Information Required |
|---|---|---|---|---|
| Machining | B1.1 | Fill-in the order request | Web interface | list of information required for machining |
| | B1.5 | Validate C-MARS agent selection | Process planner Engineer | Information filled &deployed machine tools |
| | B1.11 | Generate toolpath for assigned machine tools | Postprocessor,toolpath generator | Part geometry,part features |
| | B1.12 | Forward final schedule,compiled NC file to assigned machine tools | Internet connection,web-interface | Machining start-end time, compiled NC-file, stock type, geometry, calling ticket for operator, machine tool ID, clamping method,verified cutting tool library |
| | B1.14 | Receive part machining ticket, material stock type | Internet connection,web-interface, usb stick | C-MARS username, password |
| Deployment machine tool | B2.3 | Inquire further detailed information for deployment | Internet connection,web-interface, C-MARS agent | Jigs and fixture used,machinetool postprocessor,maintenance health report |
| | B2.4 | Provide machinetool details,machining technology,location, working capacity, etc. | Internet connection,C-MARS provider | Jigs & fixture used, machinetool postprocessor, maintenance report |
| | B2.5 | Analyze deployment request | C-MARS agent,C-MARS Engineer | Contract agreement, barcode enrolment,adding machine tool to C-MARS |
| | B2.9 | Prepare deployment process | C-MARS agent | Assign C-MARS operator,training date & time, physicalmachine interface installment |
| | B2.11 | Training | C-MARS instructor | C-MARS physical machine interface induction |

# Chapter 6

# Design of Test Scenarios for C-MARS & NC-MARS

This chapter discusses the design of test scenarios developed for evaluating the C-MARS interoperable and non-interoperable activity models. . First, the exploration and description of the simulation scenarios are stated. Secondly, the development of case scenarios are provided. Finally the illustration and analysis of the results.

## 6.1 Introduction

The base concept of designing the test cases is to demonstrate and compare the impact of applying an interoperable vs non-interoperable deployment approach within a cloud manufacturing system. As the activity models developed for both approaches, C-MARS-ABM for the interoperable approach and NC-MARS-ABM for non-interoperable approach are utilised to demonstrate the cost reference of each activity within the developed models.

The simulated test cases represent a logical and practical application of cloud-based order processing, covering a comprehensive real case scenario of the distinctive parameters involved in the manufacturing product life cycle.

Based on each instance of an ordering scenario, the results obtained are illustrated by means of cost impacts for both interoperable and non-interoperable deployment approaches. Hence, quantifying the deployment approaches developed in reference to cost will inform the decision making as to whether or not the investment into a new interoperable solution is feasible.

## 6.2 Explanation of simulation scenarios

In order to develop a rigorous assessment of C-MARS, rational simulated scenarios are utilised to perform the order processing activities on both perspectives of deployment; interoperable and non interoperable cloud manufacturing. It is assumed that the cloud is formed by a number of small to medium enterprises (SMEs), who aim to improve their business through collaboration. Based on the activity models developed C-MARS-ABM and NC-MARS-ABM of both approaches, the Monte Carlo simulation technique has been utilised to compose feasible sets of C-MARS manufacturing clouds. Henceforth allocating the contrast of executing numerous machining orders on both activity models developed. As the Monte Carlo computational algorithms rely on probability distributions that have approximate representation of realistic approach of describing uncertainty in independent variables (Wittwer, 2004; Raychaudhuri, 2008; Du, 2015), thus meets the criteria required for C-MARS experimental representation.

The main driven parameters involved in the work approached were identified in the preliminary phase, as illustrated in table 5.2 for C-MARS-ABM and table **??** for NC-MARS-ABM. In order to reduce the computational complexity and redundancy, these activities have been refined to 11 main parameters and outlined in table 6.1, which are grouped in three main categories;

- Orders: which includes parameters that resemble the ordering attributes running within the cloud once the service has been confirmed by the service user as number of order, quantity of parts in each order, time of machining required, and time required for clamping work piece.
- Service providers: states the size of a SME and whether it is micro, macro or medium sized and the number of operators and experts within these enterprises. Additionally, the number of machine tools deployed in the cloud manufacturing framework, along with the number of working shifts per day.
- Expertise: represents the process planning required by the process planning engineers for developing the process plan for the required parts.

The reason for the refining process is neglecting the parameters that have inconsequential cost effect on the response factor obtained. As the activities that imply the Internet connection and networking as; uploading the STEP-NC file (A1.1), receive part machining ticket (A1.14) , fill-in order request (B1.1) in contrast to driven parameters for deploying machine tools within C-MARS as Preparing deployment process (A2.9), setup of STEP-NC writer/software (A2.10), Process planner approve machine tool selection(B2.5).

Each activity is thus identified explicitly and grouped in the relevant category in the form of costing formulae based on parameters such as number of orders, quantity of parts per order, complexity of process planning and post processing, the size of the SMEs, the number of the companies involved in the cloud as reported in table 6.1. The developed formulae are then used to calculate the total cloud cost based on sampling the random variables.

Table 6.1: The list of parameters used in Monte Carlo simulation of C-MARS-ABM

| Category | Parameter | Description |
|---|---|---|
| Orders | Orders | Number of orders received every day by the cloud system |
| | Quantity | The quantity of parts required in an order |
| | Time for machining | How long it takes to machine one part |
| | Clamping decision time | The amount of time it takes to design work holding |
| Service providers | Size | How many employees are there in each cloud member SME |
| | Operators | How many employees are machine operators |
| | SME members | How many SMEs are involved in the cloud |
| | Machine tools | Number of machine tools deployed in an SME |
| | Experts | The number of people who are CAM experts in the SME |
| | Shifts | The number of shifts in which the SME is active |
| Expertise | PP time | Time to process plan a manufacturing job |

## 6.3 Development of simulation model-experimental setup

This section involves the explanation and the design of the experimental case scenarios. The formulation of the enabling parameters for each category identified are demonstrated. This is followed by a generic overview of the assumed values for the given parameters. Lastly, a preliminary result of the scenarios is illustrated.

### 6.3.1 Experimental scenario development

Based on the case scenarios the experimental model was developed utilising the Montecarlo simulation technique. As the model consists of 31 enabling parameters categorised within 3 main categories; orders, C-MARS service providers, and ordering scenarios. For each individual instant of an order received by C-MARS, the mentioned parameters has to be fulfilled in order to yield the output response of deploying both C-MARS deployment approaches; interoperable (C-MARS-ABM) and non-interoperable (NC-MARS-ABM) in respect to cost value. Parameters with the related formula will be explicitly discussed in section 6.3.2.

### 6.3.2 Equations formulation

The formulation of the enabling parameters are illustrated below according to their related category within the experimental model as follows:

#### Orders

The parameters related to the orders are captured using the following equations:

$$Q_r \sim \mathcal{U}(1, 1001) \tag{6.1}$$

$$M_{tr} \sim \mathcal{U}(5, 25) \tag{6.2}$$

Where:
$Q_r$ is an integer random variable representing the quantity per order (parts)
$\mathcal{U}(\alpha, \beta)$ indicates a uniform probability distribution between $\alpha$ and $\beta$
$M_{tr}$ is a random variable representing the machining time required (minutes/part) A subset of the orders is selected for each run of the simulation is modelled using the binary variable ($A_o$)

$$A_o = \begin{cases} 1 & \text{if } R_1 > 0.65, \text{ where } R_1 \sim \mathcal{U}(0, 1) \\ 0 & \text{otherwise} \end{cases} \tag{6.3}$$

Where:

$A_o$ is Assignment (binary)

The total number of parts produced and the total machining time is thus formulated as

$$R_p = A_s Q_r \tag{6.4}$$

$$T_{Mt} = Q_r M_{tr} A_s \tag{6.5}$$

Where:

$R_p$ is required number of parts per order

$T_{Mt}$ is total machining time per order(minutes)

The time required for undertaking a decision for the clamping method for the parts to be machined on the assigned machine tool, is estimated as a function of the machining time as follows:

$$C_t = \begin{cases} 1 & \text{if } 0 < M_{tr} \leqslant 5 \\ 2 & \text{if } 5 < M_{tr} \leqslant 10 \\ 3 & \text{if } 10 < M_{tr} \leqslant 15 \\ 4 & \text{otherwise} \end{cases} \tag{6.6}$$

Where:

$C_t$ is the clamping decision time required (minutes)

### C-MARS service providers

This category concerns the parameters that represent C-MARS cloud size, as the size of the SMEs is mainly dependent on the number of employees shown in table 6.2, which is formulated in 8 equations as follows:

$$O_p = \lfloor R_2 \cdot E_p \rceil, \text{ where } R_2 \sim \mathcal{U}(0.65, 0.85) \tag{6.7}$$

Where:
$O_p$ is the number of operators in enterprise shop-floor.
$E_p$ is the number of employees in the whole enterprise.

This is based on the assumption that between 65% and 85% of the workforce in a machining SME is working on the shop-floor, considering that the shop-floor operators are a logical portion from the total number of employees working in a SME.

The number of machine tools in an SME floor is estimated based on the workforce active on the shop-floor as follows

$$M_d = \left\lfloor \frac{R_3 \cdot O_p}{S_f} \right\rceil, \text{ where } R_3 \sim \mathcal{U}(1.2, 1.4) \tag{6.8}$$

Where:
$M_d$ is the number of enterprise deployed machine tools.
$S_f$ is the number of enterprise operating shifts.
With the assumption that each operator working in a shift is responsible for between 1.2 and 1.4 CNC machines. As for the number of enterprise CAD/CAM experts,

these are based on the number of machine tools allocated within the enterprise.

$$E_x = \left\lfloor \frac{M_d}{R_4} \right\rceil \text{, where } R_4 \sim \mathcal{U}(4,8) \tag{6.9}$$

Where:

$E_x$ is the number of CAD/CAM enterprise experts.

with the assumption that for each 4 to 8 CNC machines a CAD expert could be employed.

The number of operating shifts is formulated based on the number of employees within the enterprise, which reflects the size of the SME of whether the enterprise category reference is less than 10 employees (micro) , less than 50 employees (small) or less than 250 employees (medium)

$$S_f = \begin{cases} 2 & \text{if } R_5 \cdot E_p > 8 \\ 1 & \text{otherwise} \end{cases} + \begin{cases} 1 & \text{if } R_6 \cdot E_p > 50 \\ 0 & \text{otherwise} \end{cases} \text{where } R_5, R_6 \sim \mathcal{U}(0,1) \tag{6.10}$$

With the assumption that larger SMEs are more likely to have multiple shifts. A subset of the SMEs is selected for each instance. $A_C$ represents the binary variable indicating whether an SME is selected.

$$A_C = \begin{cases} 1 & \text{if } R_7 > 0.875 \\ 0 & \text{otherwise} \end{cases} \text{where } R_7 \sim \mathcal{U}(0,1) \tag{6.11}$$

Where:

$A_C$ is Assignment of SMEs (binary)

The total machining time available ($M_{ta}$) is formulated in equation 6.12, based on 8 hours shift per day.

$$M_{ta} = 8 \times 60 \times M_d \times S_f \times A_c \tag{6.12}$$

Where:

$M_{ta}$ is the machining time available (minutes)

Consequently, equation 6.13 illustrates the total number of machine tools assigned per instance and equation 6.14 formulates the total number of CAD/CAM assigned experts per instance ($E_{xa}$).

$$M_{da} = M_d A_c \tag{6.13}$$

Where:

$M_{da}$ is the number of machine tools assigned per SME.

$$E_{xa} = E_x A_c \tag{6.14}$$

Where:

$E_{xa}$ is the number of CAD/CAM experts assigned.

### C-MARS ordering scenarios

The formulas within this category reflects the parameters that derive the cost values utilised from both interoperable (C-MARS-ABM) and non-interoperable (NC-MARS-ABM) approaches. Equation 6.15 refers to utilisation of the C-MARS machining time ($U_m$).

$$U_m = \frac{\sum_{i=1}^{n} M_{tr}}{\sum_{k=1}^{n} M_{ta}} \tag{6.15}$$

Where:

$U_m$ is the utilisation of the machining time.

$i$ is the number of orders.

$k$ is the number of SMEs.

In order to identify the process planning time required for machining the required parts equations 6.16, 6.17, and 6.18 are formulated. As equation 6.16 refers to the assigned machine tools per order ($M_{ds}$) which is derived from the utilised machine-tools that are assigned for each requested order.

$$M_{ds} = \left\lceil \frac{\sum_{k=1}^{n} M_d \cdot U_m}{\sum_{i=1}^{n} O_r} \right\rceil \tag{6.16}$$

Where:

$M_{ds}$ is the number of machine tools assigned per order.

$O_r$ is the number of orders required.

Hence, the required tool-paths ($Tp_r$) can be obtained by the product of $M_{ds}$ and $O_r$, illustrated in equation 6.17, considering different post-processor per machine tool.

$$Tp_r = M_{ds} O_r \tag{6.17}$$

Where:

$Tp_r$ is the number of tool-paths required by C-MARS. Therefore, the estimated process planning time ($P_tr$) required can be formulated in equation 6.18 as follows:

$$P_tr = 60O_r + 2Tp_r \tag{6.18}$$

Where:
$P_tr$ is the process planning time required by C-MARS (minutes). As an estimate of 60 minutes required by the assigned C-MARS process planners to develop the feature recognition and machining operations per order design, followed by 2 minutes for compiling the NC-file for machining.

In addition, the number of assigned process planners ($P_tr$) can be identified by 6.19, with the total number of machine tools assigned can be illustrated in equation 6.20

$$P_pr = \frac{P_tr}{24 \times 60} \tag{6.19}$$

$$M_a = \sum_{k=1}^{n} M_{da} \cdot U_m \tag{6.20}$$

Where:
$M_a$ is the total number of machine tools assigned.

### 6.3.3 Overview of experimental scenarios

A pool of 500 replicated runs were developed with each representing a 24 hours operating cycle. Additionally, the experimental scenarios developed comprised of 4 different perspectives of SME size that are connected with the C-MARS system. The 3 main categories of SMEs are shown in table 6.2, which represents 3 different perspectives of the experimental scenarios, additionally, a fourth perspective resembles a hybrid scenario involving the 3 categories is presented below.

Table 6.2: SME category (European Comission, 2016)

| **Company category** | **Staff headcount** |
|---|---|
| Medium-sized | $< 250$ |
| Small | $< 50$ |
| Micro | $< 10$ |

The experimental scenarios will yield an output of cost value for adopting both approaches C-MARS-ABM and NC-MARS-ABM, in order to identify the preliminary insights of the significant parameters prompting the deployment approach for cloud manufacturing system. In order to enable the formulae of the experimental model, a quantified industrially inspired assumptions were developed. Table 6.3 illustrates the cost enabling values required for enabling the costing formulas for both approaches.

Table 6.3: Industrially inspired assumptions

| **Parameter description** | **Cost value (£)** |
|---|---|
| STEP-NC deployment cost per machine-tool | 600 |
| Process planner cost hourly wage | 50 |
| Training Cost per candidate | 100 |

Hence, results can be obtained simultaneously for both interoperable and non interoperable approaches based on the costing formulas 6.21 and 6.22: Equation 6.21 shows the total cost of interoperable approach calculated based on 500 runs. This was based on considering the average of; (a) the number of experts to be trained on the C-MARS-ABM web-interface, (b) the installation of the STEP-NC writer, and (c) the clamping decision time.

$$Z_c = 100\overline{E_x} + 600\overline{M_{da}} + 50\overline{C_t} \tag{6.21}$$

Where:

$Z_c$ is the total cost value of the interoperable deployment approach (in £) .

Equation 6.22 provides the total cost of the non-interoperable deployment approach

($Z_n c$) NC-MARS-ABM, as the average process planning time required for the simulated orders has been identified as the key enabler of cost impact within this approach.

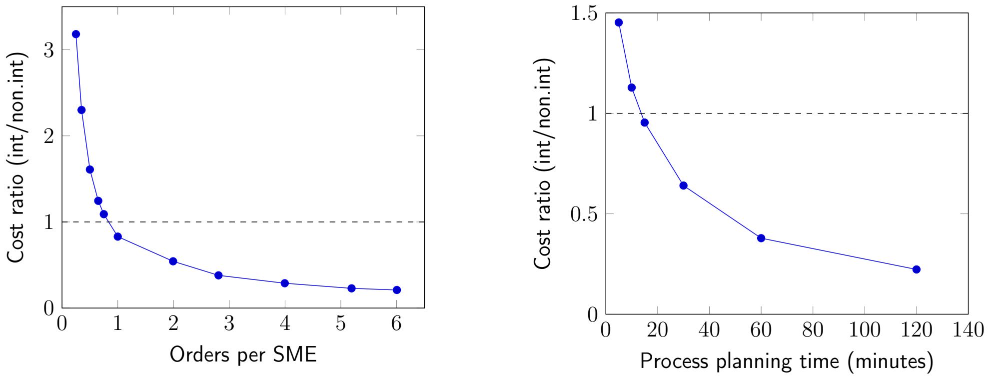
$$Z_n c = 50 \cdot \overline{P_t r} \tag{6.22}$$

Where:

$Z_n c$ is the total cost value of the non-interoperable deployment approach (£).

Therefore, based on the formulated cost equations, preliminary insights have been obtained. The preliminary results of the simulation are shown in Figure 6-1. These results confirm that Cloud Manufacturing is not a one-size-fits-all solution, and that there are indeed a number of driving parameters that need to be analysed to determine whether or not an investment in interoperable or non-interoperable cloud manufacturing may be financially beneficial and advisable given a specific scenario.

The preliminary results shows that the order size per cloud member SME and the process planning time required for each part are the two main determinants for selection of the interoperable framework over a cloud solution based on the traditional CAD/CAM/CNC chain.



(a) (b)

Figure 6-1: Preliminary analysis of simulation results

In particular, Figure 6-1(a) shows that if the cloud is producing a large number of different orders in relation to the number of SME members, the use of the interoperable framework would be cost effective. In a similar manner, Figure 6-1(b) shows that the complexity of the jobs handled by the cloud also have a major bearing on whether the additional investment required to deploy an interoperable standard such as STEP-NC would be cost effective.

For a cloud that handles very simple parts as indicated by a process planning time of less than 15 minutes per part, the traditional CAD/CAM/CNC approach or the direct use of G&M codes would be more economical than investing in the new interoperable cloud manufacturing platform. For highly complex parts, on the other hand, the investment is cost effective.

Overall, the preliminary studies indicate that for a CNC machining cloud, the variety and complexity of the parts should be significant to warrant the investment in a new interoperable manufacturing framework.

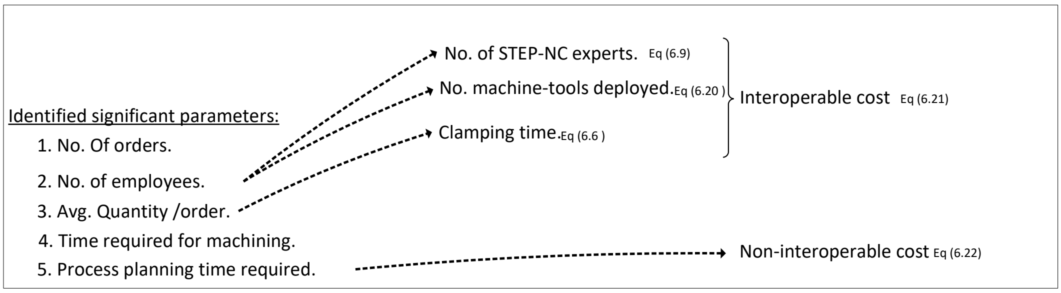


Figure 6-2: A holistic view of the experimental parameters

Clearly, the overall scenarios developed, indicates that values of parameters as Web-connection cost is inconsequential in relative to parameters as process planning time required and installation of STEP-NC writer. Hence, based on the results obtained the significant independent parameters that further studied are 6-2: (1) the number of orders, (2) average quantity per order, (3) the number of employees, (4) process planning time required, (5) time required for machining.

A comprehensive analysis will be obtained in section 7 in order to identify the significant parameters to perform a rigorous decision making process of the feasible deployment approach for cloud manufacturing system.

# Chapter 7

# Analysis and evaluation of Results

## 7.1 Introduction

This section presents the analysis of results obtained from the simulation test case scenarios in chapter 6. The full-factorial design experiment is developed to illustrate the interactions between the 5 significant parameters in respect to cost response in the form of interoperable (C-MARS-ABM) to non interoperable (NC-MARS) cost ratio. This is followed by the analysis of variance (ANOVA) which emphasises the impact of the 5 identified parameters on the response factor ratio. Finally, three different scenario levels will be discussed in order to allocate the impact of the parameters on the response factor ratio.

## 7.2 Full factorial design

A three-level $3^k$ factorial design has been utilised to model the interactions among the allocated significant parameters. The 3 levels of level 1, level 2 and level 3 in table 7.1 represent low, medium and high estimated industrial values for each parameter of the categories (orders, C-MARS size and Scenarios) and k represents the number of parameters. Hence, the number of treatments is calculated to be 243 runs ($3^5$= 243) in order to cover all the possible combination interactions among the parameters.

Table 7.1: Parameters value

| **Category** | **Variable** | **Name** | **Level 1** | **Level 2** | **Level 3** |
|---|---|---|---|---|---|
| Orders | X1 | Number of orders | 100 | 1000 | 2000 |
| | X2 | Avg. quantity/order | 50 | 500 | 1000 |
| | X3 | Time for machining (mins) | 5 | 20 | 90 |
| C-MARS size | X4 | No. of employees | 5 | 50 | 250 |
| Scenario | X5 | Process planning time (mins) | 10 | 1000 | 2000 |

The setting of these values are based upon industrial logical referencing of expected values in regards to a cloud ordering scenario per day to cover various aspects of the machining industry. As the number of orders, the average quantity per order and time required for machining resembles the ordering criteria of how many orders the cloud manufacturing systems are able to acquire. The number of employees reflects the size of SMEs deployed within the C-MARS system, whether its micro, small or medium enterprise. Lastly, the process planning time required for executing the machining order, defines the level of complexity of parts being machined beginning with simple prismatic parts (10 minutes) and ending with highly complex part features (2000 minutes).

Based on the estimated values of the parameters, a 3-level full factorial design has been developed resulting in 243 treatment combinations. Table 7.2 illustrates the first 10 scenario treatments (runs), with the consequencial runs can be found in the appendix B. The five significant parameters (X1 to X5) along with the formulated cost for relevant C-MARS-ABM and NC-MARS-ABM are provided. The ratio response reflects the interoperable to non-interoperable cost ratio.

Table 7.2: An excerpt from the full factorial matrix

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 500 | 5 | 5 | 10 | 3333.3333 | 1000 | 3.3333333 |
| 2 | 100 | 1000 | 5 | 50 | 1000 | 32666.667 | 83500 | 0.3912176 |
| 3 | 2000 | 500 | 90 | 250 | 10 | 52166.667 | 20000 | 2.6083333 |
| 4 | 1000 | 1000 | 5 | 250 | 2000 | 66666.667 | 1668333.3 | 0.03996 |
| 5 | 100 | 50 | 20 | 250 | 1000 | 71266.667 | 83500 | 0.853493 |
| 6 | 100 | 50 | 20 | 5 | 1000 | 3266.6667 | 83500 | 0.0391218 |
| 7 | 100 | 1000 | 20 | 5 | 2000 | 5833.3333 | 166833.33 | 0.034965 |
| 8 | 1000 | 50 | 90 | 5 | 2000 | 3266.6667 | 1668333.3 | 0.001958 |
| 9 | 2000 | 50 | 90 | 250 | 1000 | 57766.667 | 1670000 | 0.0345908 |
| 10 | 1000 | 500 | 20 | 5 | 2000 | 4766.6667 | 1668333.3 | 0.0028571 |

For instance in the first run, cost ratio response is $\sim$3.33 which resembles that non-interoperable (NC-MARS-ABM) is 3 times more cost efficient than the interoperable (C-MARS-ABM). On the other hand, in the second run the response ratio is $\sim$0.39 which emphasize that interoperable is much more favourable than the non-interoperable deployment approach. In addition, the response factor has been used for analysis of variance in order to identify specifically the most significant parameters that deflects the response ratio.

## 7.3 Analysis of variance

This section includes the analysis of variance for the obtained response ratio in order to determine the significant parameters associated with the change of response ratio, Thus, this will advise the feasible deployment approach for cloud manufacturing system development. The ANOVA method has been utilised in order to determine the parameters affecting the response factor ratio.

The results obtained from the full factorial design have been used for the analysis of variance to identify the impact of each parameter allocated in the previous experimental phase. The ANOVA report generated in table 7.3 illustrates the computed F-ratio and P-value of the given parameters indicates the impact proportion of each parameter and their relative interactions. An F-ratio close to 1 necessitates the ac-

Table 7.3: ANOVA report

| **Source** | **SumSq.** | **d.f.** | **Mean Sq.** | **F** | **Prob>F** | **Contribution** |
|---|---|---|---|---|---|---|
| X1 | 3154.5 | 2 | 1577.27 | 859.69 | 0 | 12.36 |
| X2 | 10.9 | 2 | 5.47 | 2.98 | 0.0547 | 0.043 |
| X3 | 9.4 | 2 | 4.69 | 2.56 | 0.0822 | 0.037 |
| X4 | 1735.4 | 2 | 867.68 | 472.93 | 0 | 6.80 |
| X5 | 4733.7 | 2 | 2366.85 | 1290.06 | 0 | 18.54 |
| X1*X2 | 9.9 | 4 | 2.48 | 1.35 | 0.2563 | 0.04 |
| X1*X3 | 14.1 | 4 | 3.53 | 1.92 | 0.1112 | 0.06 |
| X1*X4 | 2162.6 | 4 | 540.64 | 294.68 | 0 | 8.47 |
| X1*X5 | 5935.9 | 4 | 1483.96 | 808.84 | 0 | 23.25 |
| X2*X3 | 12.6 | 4 | 3.15 | 1.72 | 0.151 | 0.049 |
| X2*X4 | 6.3 | 4 | 1.58 | 0.86 | 0.4884 | 0.03 |
| X2*X5 | 21.4 | 4 | 5.36 | 2.92 | 0.0243 | 0.08 |
| X3*X4 | 7 | 4 | 1.76 | 0.96 | 0.4338 | 0.03 |
| X3*X5 | 17.9 | 4 | 4.48 | 2.44 | 0.0509 | 0.07 |
| X4*X5 | 3267.5 | 4 | 816.87 | 445.24 | 0 | 12.80 |
| X1*X2*X3 | 17.9 | 8 | 2.24 | 1.22 | 0.293 | 0.07 |
| X1*X2*X4 | 8.1 | 8 | 1.01 | 0.55 | 0.8141 | 0.03 |
| X1*X2*X5 | 19.5 | 8 | 2.44 | 1.33 | 0.2354 | 0.08 |
| X1*X3*X4 | 11.8 | 8 | 1.48 | 0.8 | 0.5996 | 0.05 |
| X1*X3*X5 | 26.8 | 8 | 3.35 | 1.82 | 0.0798 | 0.11 |
| X1*X4*X5 | 4071.8 | 8 | 508.97 | 277.42 | 0 | 15.95 |
| X2*X3*X4 | 16.3 | 8 | 2.04 | 1.11 | 0.3607 | 0.06 |
| X2*X3*X5 | 25.6 | 8 | 3.2 | 1.75 | 0.0955 | 0.10 |
| X2*X4*X5 | 14.3 | 8 | 1.79 | 0.98 | 0.458 | 0.05 |
| X3*X4*X5 | 13.2 | 8 | 1.66 | 0.9 | 0.5171 | 0.05 |
| Error | 205.5 | 112 | 1.83 | | | |
| Total | 25530.1 | 242 | | | | |

ceptance of the null hypothesis which indicates no significant difference is generated by parameters X2: average quantity per order and X3: time required for machining.

The P-value is computed based on the given two values for degree of freedom, the upper and lower degree of freedom (2,112) and the F ratio. Thus, parameters significance can be determined if the P-value is less than 0.05, i.e. X5: process planning time, X1: number of orders, and X4: number of employees.

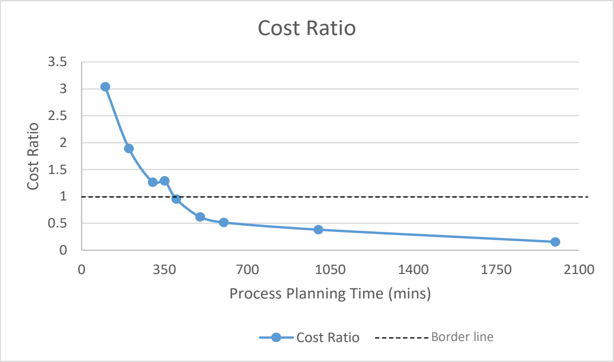
Further, the contribution percentage is calculated based on the sum of square generated in the ANOVA table in order to explicitly identify the rank of significance for each of the determined parameters; X5 (18%), X1 (12.35%) and X4 (6.79%). Finally, the obtained ANOVA results have been utilised in section 7.4 as a guideline to illustrate the impact of the identified parameters in regards to cost ratio.

## 7.4 Analysis of results

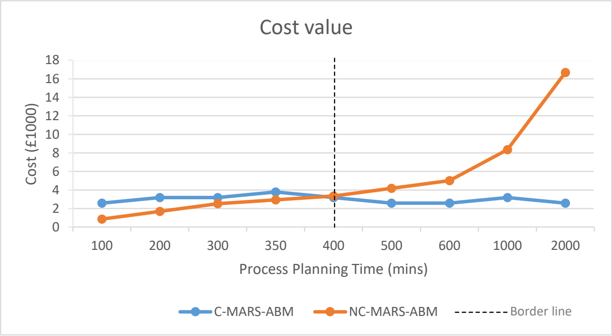
This section illustrate the effect of the identified significant parameters namely; process planning time (X5) and number of orders (X1) to the cost ratio of deployment. Based on the three-level full factorial design developed in section 7.2, three sets of scenarios have been outlined and discussed in order to assert the break-even point of interoperable to non-interoperable deployment approach.

### 7.4.1 Scenario level 1

The first explored scenario assumes the lowest level value (level 1) for the least effective parameters in table 7.1: average quantity per order (X2), time for machining (X3), and number of employees (X4). Figure 7-1 shows the successive change of the most significant parameters value obtain from ANOVA namely; number of orders in relation to the process planning time. Hence, the non-interoperable approach (NC-MARS-ABM) is more cost efficient at a very low number of orders which is approximate of 10 orders per day which responses with cost ratio >1 , at the process planning time decreases below 400 minutes per day the non-interoperable is favourable in terms of cost. The table of the scenario runs utilised is included in appendix C.1



(a) Level 1 Cost ratio



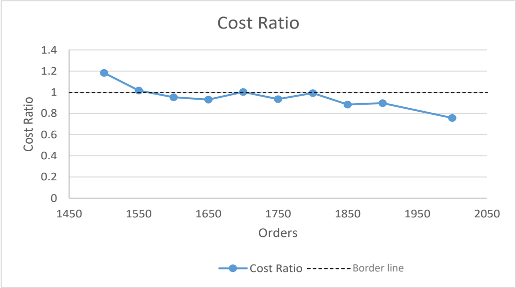
(b) Level 1 Cost value

Figure 7-1: Level1 instance

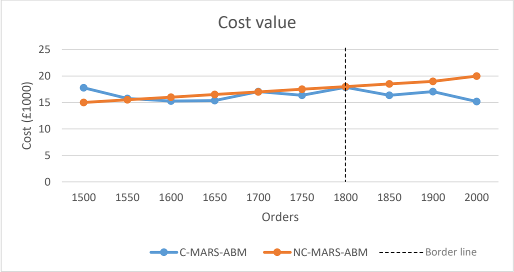
### 7.4.2 Scenario level 2

The second set of scenarios is based on the mid-level values of the least effective parameters X2, X3, and X4. The successive changes of process planning time (X5) against the number of orders (X1) illustrates that the non-interoperable approach

(NC-MARS-ABM) is more cost feasible by resulting of a cost ratio >1 at 10 minutes of process planning time and number of orders less than 1700 orders per day, as figure 7-2 shows that at Scenario run 7 ( number of orders = 1800) the C-MARS-ABM is favoured over the NC-MARS-ABM approach. The table of the scenario runs utilised are included in appendix C.2. Similarly, As shown in figure 7-3 NC-MARS-ABM is favourable when the process planning time is less then 250 minutes with 100 orders per day, as the break-even point occurs at scenario runs 4 (process planning time = 200 minutes) and 6 (process planning time=275 minute). The table of the scenario runs utilised are included in appendix C.3.

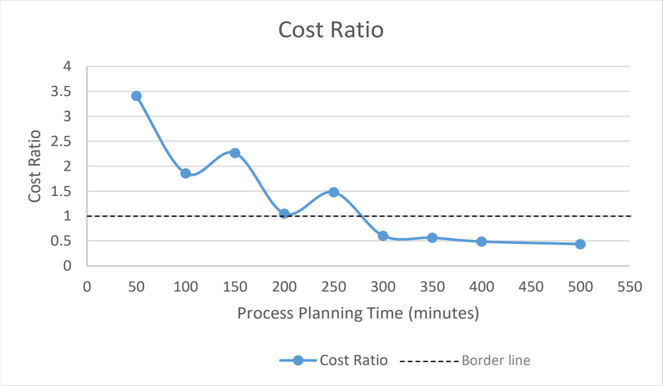


(a) Level 2 Cost ratio

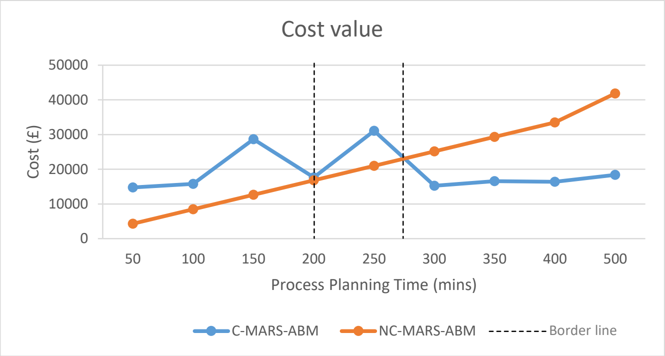


(b) Level 2 Cost value

Figure 7-2: Level 2 number of orders instance



(a) Level 2 Cost ratio



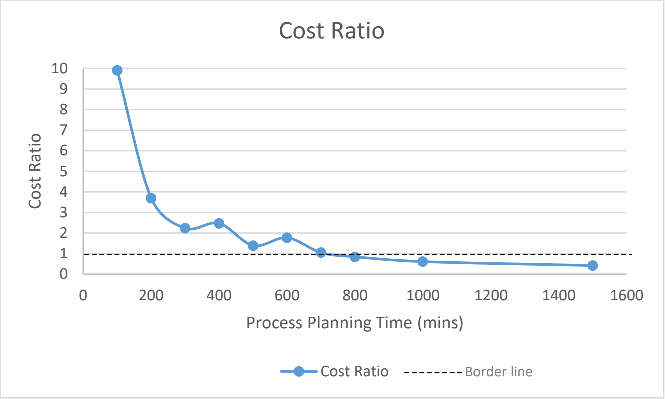
(b) Level 2 Cost value

Figure 7-3: Level 2 process planning time instance

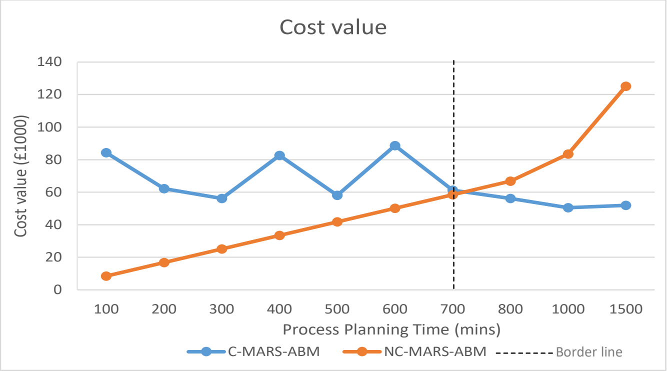
### 7.4.3 Scenario level 3

Finally, this considers the non-interoperable instances of the high level values of the least effective parameters. It can be seen that the NC-MARS-ABM would be more cost feasible in four different instances:

(1) Process planning time below 700 minutes and number of orders around 100 orders per day, which deflects at scenario run 7, as shown in figure 7-4. The table of the scenario runs utilised are included in appendix C.4.



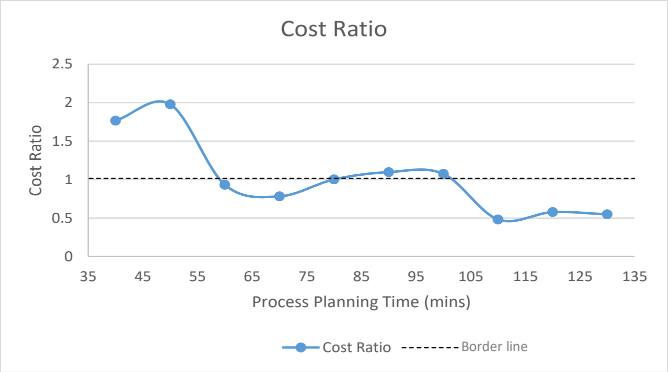
(a) Level 3 Cost ratio



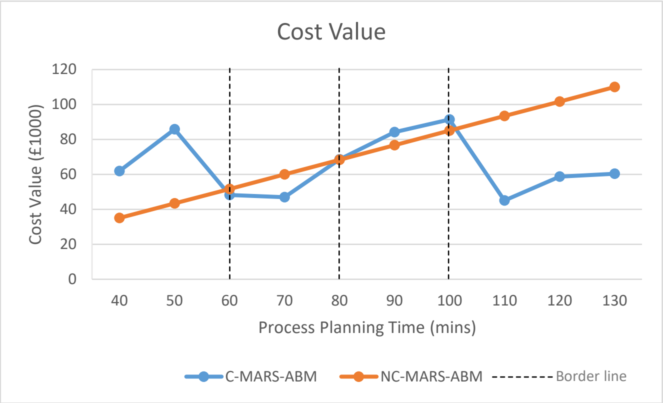
(b) Level 3 Cost value

Figure 7-4: Level 3 instance view 1

(2) Process planning time below 100 minutes and orders are around 1000, As shown in figure 7-5, there are multiple break-even points occurring at scenario runs 3 (process planning time = 60 minutes) and 5 (process planning time = 80 minutes), which stabilize at scenario run 7 (process planning time= 100 minutes) and favour the interoperable approach C-MARS-ABM. The table of the scenario runs utilised are included in appendix C.5.



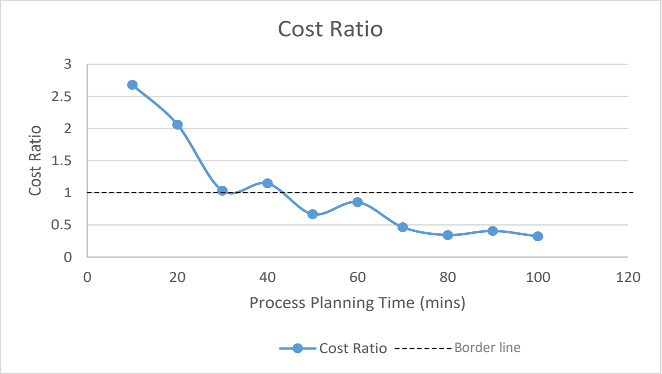
(a) Level 3 Cost ratio



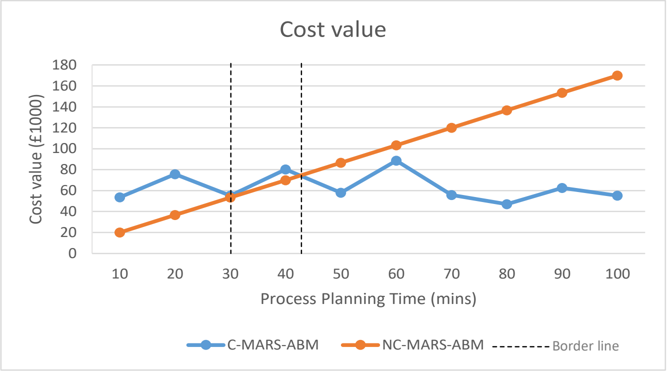
(b) Level 3 Cost value

Figure 7-5: Level 3 instance view 2

(3) Process planning time below 50 minutes compared to 2000 orders per day, As shown in figure 7-6 which defines the turning points from non-interoperable to interoperable approach at scenario runs between 3 and 5. The table of the scenario runs utilised are included in appendix C.6.



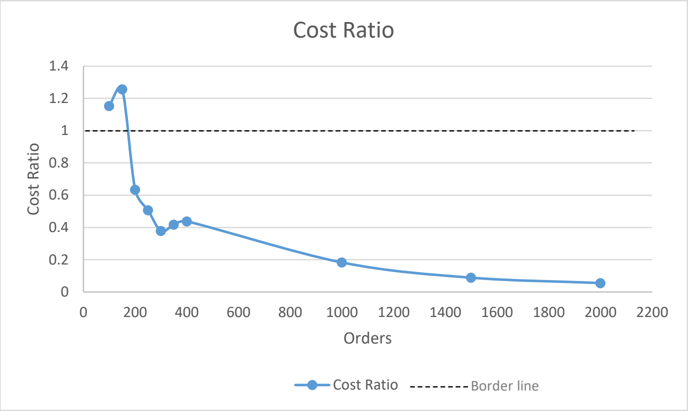
(a) Level 3 Cost ratio



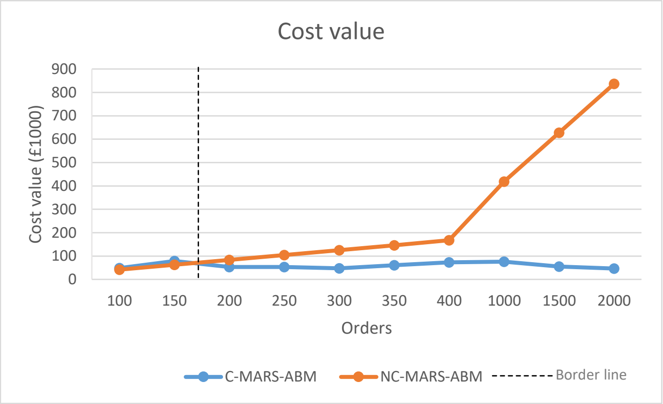
(b) Level 3 Cost value

Figure 7-6: Level 3 instance view 3

(4) Finally, when the process planning time is 500 minutes and orders are below 170 per day, the non-interoperable (NC-MARS-ABM)is more feasible in respect to cost, as figure 7-7 shows the break-even point occurrence is between scenario runs 2 and 3. The table of the scenario runs utilised are included in appendix C.7.



(a) Level 3 Cost ratio



(b) Level 3 Cost value

Figure 7-7: Level 3 instance view 4

### 7.4.4 Results overview

The results of the correlational analysis of applying different industrial scenarios between the identified significant parameters X1 and X5 and the three level scenario runs of the least effective parameters X2, X3, and X4 indicate that at certain instances the non-interoperable approach is more feasible to be deployed rather than the interoperable approach. Thus, proves the hypothesis of research which states that interoperable cloud manufacturing systems cannot be considered a one-size-fits-all option, as the non-interoperable cloud manufacturing system that utilises the traditional NC codes for machining is more feasible at specific occurrences in respect to cost. Thus using equations 6.21 and 6.22, the interoperable to non interoperable cost ratio $C_r$ shown below can be used a response factor for indicating the feasible deployment approach.

$$C_r = \frac{Z_c}{Z_n c} \tag{7.1}$$

Where:
$C_r$ is the cost ratio of deployment approaches.

Explicitly, where $C_r$ is significantly above 1, a non-interoperable approach for cloud manufacturing such as the one modelled in NC-MARS-ABM is better and where $C_r$ is significantly below 1, an interoperable approach such as the one modelled in C-MARS-ABM is more feasible.

# Chapter 8

# Discussion

## 8.1 Introduction

The investigation reported in the thesis led to a number of interesting observations related to the scope and context of the research. These are reported in the following sections to position the findings of the research.

## 8.2 State-of-the-art in Cloud manufacturing

The review of the literature on the state-of-the-art- in cloud manufacturing paradigm identified in chapter 3, illustrated the extensive efforts that have been achieved in order to integrate heterogeneous manufacturing resources and capabilities to develop a collaborative environment for manufacturing enterprises. It should be noted that the majority of these efforts are not harmonized in the context of unified manufacturing integrated system that could be seamlessly deployed for the approaching technologies as cloud manufacturing. Although, the literature showed particular strengths in the interoperable integration of CAx chain systems, shop-floor connectivity, and additionally, the unified information representation of manufacturing resources.

Additionally, the full integration of the legacy systems is not possible as the former proposed networked manufacturing systems has some significant limitations as; lack of protocols and standards, lack of operation models (i.e. management mechanisms for coordination of large data), and lack of flexibility in integration of manufacturing resources (He and Xu, 2014). Hence, former networked manufacturing systems lack the adaptability to acquire the future and the competitive needs of manufacturing enterprises. However, these legacy manufacturing systems yielded many applications that can be deployed/adopted within the cloud manufacturing system (i.e. scheduling, tool-path generators and process planning optimization, product design, resource optimal allocation, and resource service composition).

Hence, through the utilisation of the cloud computing technologies and the various manufacturing applications of the legacy systems; the cloud manufacturing paradigm potentially will be able to achieve the aim of management of decentralised and distributed manufacturing resources and capabilities to offer them as a service. This implies there is a challenge of integrate the essential components of a manufacturing system (i.e. unified manufacturing resource model, scheduler, tool-path generator, CAx systems) to realise interoperable cloud manufacturing system. Thus providing manufacturing resources and capabilities as services on an on-demand basis through the utilising of the Internet and enabling the cloud manufacturing system components to communicate and exchange data autonomously.

Henceforth, further efforts and collaboration is required for enabling a standardized cloud manufacturing system that can acquire manufacturing services seamlessly with error free transfer of information among its various components. One of the main reasons that is delaying the implementation of manufacturing cloud based systems, is data security and integrity among various stakeholders. This requires academic research and industrial expertise to overcome these challenges via high-level abstraction of manufacturing resources and their capabilities. Although interoperability has been identified to be one of the main key enablers for rigorous application of cloud manufacturing that can acquire various manufacturing services overall the product life cycle.

Additionally, the review of literature revealed and emphasized the cost impact of deploying the cloud-based paradigm and how it benefits manufacturing enterprises (Wu et al., 2015b). It also emphasized the necessity of a rigorous assessment before adopting cloud manufacturing systems in order to evaluate the feasibility of the paradigm application on SMEs. As it is inevitably required to assess the adoption approach (strategy) of a cloud based manufacturing system in order to avoid the flop of gaining the major benefits of cloud systems (Adamson et al., 2013). The research hypothesis was inspired by the aspect of assessment for the feasible deployment approach of cloud manufacturing, as a lot of redundant effort can be avoided and a rigorous evaluation of the potential impact of the cloud deployment approach can be found (identified).

## 8.3 The Cloud Manufacturing Resource sharing Framework

### 8.3.1 Theoretical framework of C-MARS

The theoretical framework proposed in chapter 4 identified and specified the requirements to realise interoperable resource sharing system for cloud manufacturing. The aim of this framework was applying open standards for non-ambiguous virtual representation and interoperability enhancement of various manufacturing resources and capabilities to be integrated within a specified framework. On the other hand, the existing architectures, models, and algorithms in relation to cloud manufacturing are insufficient for a large-scale evaluation environment, thus averting the development of the commercial applications of cloud manufacturing.

This research has taken a step in the direction of identifying interoperability as a key enabler for cloud manufacturing application, through a framework for realisation of a interoperability across heterogeneous computer aided manufacturing systems. By the deployment of various information technologies as Internet-of-Things, cloud computing, service oriented architectures to integrate state-of-the-art techniques of manufacturing resource standardisation and servitisation.

Heterogeneous manufacturing resources can thus be integrated along the product life cycle. The vision of the framework approach is through development of the cloud manager component, the cloud manufacturing resource sharing system (C-MARS) framework will be able to execute various part design features autonomously on numerous deployed manufacturing resources. Furthermore, allowing seamless added-on capabilities of manufacturing resources to be deployed within the cloud system. This can be achieved through identifying the functions of the cloud manager component with the required communication and interaction with the compulsory components for enabling C-MARS as envisioned below:

- The cloud manager component and the service request interface. Which involves the investigating of the Interoperable CAx platform to enable the cloud manager component to recognize features of different CAD file formats.
- The cloud manager component and the manufacturing resource manager. Which involves the investigation of the state-of-the-art in knowledge based process planning, to enable the cloud manager component to match the part requirements (CAD file) with the machine capabilities. Furthermore, it utilises the work done to represent the resource model "unified manufacturing resource model" in order to realise the manufacturing resource manager component.

- The cloud manager component and the scheduling systems, involve investigating job shop scheduling i.e. backward scheduling. (for the scheduler component)
- The physical machine interface component and the tool path generator component. Which involves the investigating of the toolpath algorithms (i.e. Evolutionary algorithms for generation and optimization of tool paths) for the toolpath generator component.
- Manufacturing information standards; STEP i.e. part 203 and part 214 for geometry and AP 224 for feature recognition and STEP-NC (i.e. ISO14649 -201 for machine capability profile), XML (for data storage and exchange on the web).

Consequently, development of a interoperable cloud manufacturing framework that is able to identify the major machine tool types (i.e.manufacturing resources), their controller type and capabilities (i.e. table size, number of axis, maximum tool size, etc.) is required. This ensures that only parts which are manufacturable being allocated to the available resources and additionally, can accept new models of manufacturing resources autonomously (Independent resource model that is only defined by available resources).

Furthermore an investigation is still required to identify the communication and interaction protocols of the collaboration structure that merge service providers and service users within cloud manufacturing systems. As the current literature lacks adequate studies regarding the improvement of cloud manufacturing architecture, collaboration techniques, and resource sharing. Consequently, the development of state-of-the-art models, algorithms and techniques is a necessity in order to extend traditional manufacturing industries to be adopted within the cloud environment. Additionally, virtual and physical experimentation is needed to develop good practices for validation, in order to enhance the integrity of cloud manufacturing by developing rational cloud manufacturing models.

Currently there are redundant data representation and descriptions of manufacturing resources and capabilities due to proprietary semantics and data formats. Many extensive efforts were proposed to establish standardised information representation of manufacturing resources and capabilities within an integrated manufacturing system. This aimed at seamless data transfer and exchange. Formats such as STEP, WSDL, ontology techniques and XML are deployed for the identification and application of standardised data models and structures for manufacturing resources and capabilities utilised through the product life cycle processes.

Hence, this deployment approach can pave the way for the development of cloud manufacturing to realise the integration of the current manufacturing information systems. The manufacturing enterprises are currently adopting service orientated approaches to integrate manufacturing resources based on the cloud computing paradigm, thus, state-of-the-art methodologies are crucially required to enhance the integration of various manufacturing resources. Additionally, there is a need for intelligent integration rather than just the current automation. Further development in the integration of manufacturing control systems can also enhance the cloud manufacturing paradigm. Extensive work has been undertaken in relation to the development of open communication standards for shop-floor connectivity to enhance machine to machine interaction (intercommunication), to increase flexibility and coordination through the manufacturing product life cycle (Essink, 2016; Safaieh et al., 2013; Zhang et al., 2011b; Vichare, 2009; Nassehi, 2007)

Therefore, the outlined approach embraces the integration of traditional and non-CNC traditional manufacturing components, thus facilitating the adoption of the cloud manufacturing paradigm by current manufacturing enterprises (SMEs). This service oriented system should potentially allow various stakeholders to access the necessary manufacturing information according to their requirements and priorities. Additionally, enhance the expediency of the cloud manufacturing environment.

### 8.3.2 Modelling of C-MARS

In order to validate the proposed C-MARS framework , a business model followed by an activity model C-MARS-ABM were developed. The STEP-NC ISO example 1 was used to demonstrate the flow of information for machining services in a manufacturing cloud. As described in chapter 5, each activity was described and allocated with a specific code and matched with the process planning required for machining the prismatic part selected.

### 8.3.3 Design of experiment for C-MARS evaluation

To evaluate the realised C-MARS-ABM model, an alternative activity model NC-MARS-ABM was developed (utilising the traditional G & M codes for acquiring machining services through C-MARS). Hence, the simulated scenarios is created based on three main domains: orders, service providers, and expertise, each of which contains the necessary parameters to reflect the practical application of the created scenarios. Each of the identified parameters were formulated, followed by illustration of a preliminarily run using Monte-carlo simulation through the generation of random numbers within a logical and acceptable range reflecting each parameter shown in section 6.3.2 Henceforth, according to the results obtained the highly impact parameters were elected for further analysis showed in chapter 7 and the other parameters were considered inconsequential in respect to cost according to their impact value (Wu et al., 2015b).

## 8.4 Evaluation of C-MARS

To analyse and identify the significant parameters that imply the feasible deployment approach for a cloud manufacturing system, a full factorial design was applied on both activity models C-MARS-ABM and NC-MARS-ABM to cover the possible interactions among the significant parameters allocated. As each parameter is given 3 different levels of logical values to resemble different modes of ordering scenarios.

Based on the results obtained, the analysis of variance (ANOVA) method was used to pinpoint the high impact parameters that affect the variance of the response factor.

The analysis of the conducted scenarios is illustrated based on the 3 levels parameter values of the full factorial design in order to support the hypothesis of research.

## 8.5 Advantages of C-MARS framework

The C-MARS framework was created using a limited number of assumptions and although STEP-NC was used as the standard for achieving interoperability, C-MARS can adopt any other similar standard that represents the generation of NC code could be used from CAD features. The underlying assumptions is that such a standard would need existing machines to be adopted, operators to be trained and translators to convert current code to this standard.

## 8.6 Limitations of C-MARS framework

Whilst the author took reasonable care to perform the analysis in as robust a manner as possible within the constraints of the PhD, a number of limitations that could have possible effects on the results in practice have been identified:

1. Validation of C-MARS models on real case scenarios is not possible as there are no practical implementations of the cloud manufacturing systems for CNC machining at a large scale.
2. The activity models developed did not include service composition and cyber security aspects and as C-MARS focuses exclusively on the subtractive machining activities.
3. The developed simulation scenarios assumed the continuous availability of the deployed machine tools and did not consider machine failures or quality issues and part defects.
4. Geographical location of machine tools was not put into account in regards to assigning a specific machine tool based on location.
5. The Design of experiments in assessing the C-MARS-ABM did not consider the unit cost of machine tools.
6. The tool life contributing to cost and quality was not included in the assessment cost criteria.
7. Changes/degradation in machine capability was not considered in the monitoring of machining process, only the start and end of the machining service.
8. Operator skill level was not considered in the research scope, as the hourly wage was fixed for all C-MARS operators.

9. The C-MARS-ABM approach did not take account of the Productivity versus company culture within cloud manufacturing
10. The material handling cost was not considered in the assessment criteria, as the movement, protection, storage and control of parts machined by C-MARS were considered similar in both approaches (C-MARS-ABM and NC-MARS-ABM)
11. Trust in companies meeting deadlines/due dates was not covered within C-MARS framework, as this issue concerns the quality of service i(QoS) in cloud manufacturing.
12. Logistical issues and locations of end users was not illustrated in both activity models C-MARS-ABM and NC-MARs-ABM.

# Chapter 9

# Conclusions and Future Work

## 9.1 Contribution to knowledge

The main contribution of this thesis to knowledge is a methodical approach for identifying the key driven parameters for assessing the interoperability level to be deployed within cloud manufacturing.

## 9.2 Conclusions

Based on the research conducted throughout this project, the following main conclusions can be drawn from the results obtained:

- The implementation of cloud manufacturing systems in industry is hampered by a lack of formal models, methods and unified standards for the representation, seamless integration and interoperability of distributed manufacturing resources across an enterprise (vertical integration) and beyond (horizontal integration).
- Interoperability between manufacturing resources in cloud manufacturing sys-

tems can be facilitated through a theoretical framework (C-MARS) and the adoption of STEP-NC as a standardized communication language.

- The object-oriented modelling approach embedded in the C-MARS interoperability framework is applicable to both state-of-the-art and legacy manufacturing systems.

- There is a need for a methodical approach and guiding tool aimed at helping SMEs to understand and assess whether or not processing orders through a cloud manufacturing network will be advantageous over traditional on-site manufacturing.
- The activity model C-MARS-ABM represents the main activities required to implement interoperability in cloud manufacturing. It provides a new method for comparison of interoperable and non-interoperable manufacturing order processing by identifying the key drivers or parameters that impact the decision making process.
- The research conducted has confirmed that under certain circumstances the investment in an interoperable cloud manufacturing framework is beneficial over traditional manufacturing. Specifically, in the case where the number or manufacturing orders to be processed are large in relation to the number of SMEs. In addition, the complexity of the parts to be manufacturing strongly impacts whether or not interoperable cloud manufacturing will be more beneficial.
- For parts of modest complexity based on their process planning time, the non interoperable cloud manufacturing (i.e.NC-MARS-ABM) is likely to be economically more feasible than interoperable cloud manufacturing (i.e.C-MARS-ABM) approach. For parts of high complexity the investment in a interoperable cloud manufacturing framework is economically viable.

- The research approach can be utilised as a decision making tool for deployment of industrial standards within cloud manufacturing systems having the same implementation requirements of deployment as STEP-NC.

## 9.3 Future work

During the course of this research a number of opportunities for taking the work further have been identified:

- C-MARS framework can be implemented as a web service and used to create a manufacturing cloud. Users interfaces need to be developed and then C-MARS-ABM can be used as the blueprint for software development.
- Further breakdown of the activities presented in C-MARS-ABM would allow the development of comprehensive activity-based costing for cloud manufacturing which could be used to create a business case for large scale deployment of a cloud manufacturing system.
- Although STEP-NC was used during the development of the C-MARS-ABM, the model is not dependent on any specific features of the standard. Other standards can thus be incorporated into the model. Applying additional standardization approaches other than STEP-NC on C-MARS-ABM would allow enterprises to explicitly identify and warrant the investment in a new interoperable manufacturing framework compared to the non-interoperable vision.
- The platform can be extended by including other manufacturing tasks such as assembly lines, material handling and additive manufacturing within C-MARS.

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# Appendix A

# Publications

A number of scientific peer reviewed papers were published by the author during the course of the research documented in this thesis.

- **M**ourad, **M**., Nassehi, A., & Schaefer, D. (2016). Interoperability as a Key Enabler for Manufacturing in the Cloud. Procedia CIRP, 52, 30-34.
- **M**ourad, **M**., Nassehi, A., Newman, S., & Schaefer, D. (2017). C-MARS-ABM: A deployment approach for cloud manufacturing. Advances in Transdisciplinary Engineering, 6, 213-218.

# Appendix B

# Full Factorial Experiment Table

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 500 | 5 | 5 | 10 | 3333.3333 | 1000 | 3.3333333 |
| 2 | 100 | 1000 | 5 | 50 | 1000 | 32666.667 | 83500 | 0.3912176 |
| 3 | 2000 | 500 | 90 | 250 | 10 | 52166.667 | 20000 | 2.6083333 |
| 4 | 1000 | 1000 | 5 | 250 | 2000 | 66666.667 | 1668333.3 | 0.03996 |
| 5 | 100 | 50 | 20 | 250 | 1000 | 71266.667 | 83500 | 0.853493 |
| 6 | 100 | 50 | 20 | 5 | 1000 | 3266.6667 | 83500 | 0.0391218 |
| 7 | 100 | 1000 | 20 | 5 | 2000 | 5833.3333 | 166833.33 | 0.034965 |
| 8 | 1000 | 50 | 90 | 5 | 2000 | 3266.6667 | 1668333.3 | 0.001958 |
| 9 | 2000 | 50 | 90 | 250 | 1000 | 57766.667 | 1670000 | 0.0345908 |
| 10 | 1000 | 500 | 20 | 5 | 2000 | 4766.6667 | 1668333.3 | 0.0028571 |
| 11 | 1000 | 500 | 20 | 250 | 1000 | 70466.667 | 835000 | 0.0843912 |
| 12 | 2000 | 50 | 90 | 50 | 1000 | 14366.667 | 1670000 | 0.0086028 |
| 13 | 1000 | 500 | 5 | 250 | 2000 | 86133.333 | 1668333.3 | 0.0516284 |
| 14 | 1000 | 50 | 20 | 5 | 1000 | 3866.6667 | 835000 | 0.0046307 |
| 15 | 1000 | 50 | 90 | 250 | 1000 | 79266.667 | 835000 | 0.0949301 |
| 16 | 2000 | 1000 | 90 | 250 | 1000 | 87633.333 | 1670000 | 0.052475 |
| 17 | 1000 | 50 | 20 | 50 | 2000 | 14466.667 | 1668333.3 | 0.0086713 |
| 18 | 100 | 500 | 90 | 50 | 1000 | 17766.667 | 83500 | 0.2127745 |
| 19 | 2000 | 1000 | 20 | 50 | 2000 | 36633.333 | 3336666.7 | 0.010979 |
| 20 | 100 | 1000 | 90 | 250 | 10 | 46533.333 | 1000 | 46.533333 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 21 | 2000 | 50 | 90 | 250 | 2000 | 50466.667 | 3336666.7 | 0.0151249 |
| 22 | 2000 | 50 | 90 | 250 | 10 | 55766.667 | 20000 | 2.7883333 |
| 23 | 2000 | 50 | 90 | 50 | 10 | 14466.667 | 20000 | 0.7233333 |
| 24 | 100 | 500 | 5 | 5 | 1000 | 3933.3333 | 83500 | 0.0471058 |
| 25 | 100 | 1000 | 5 | 250 | 10 | 52466.667 | 1000 | 52.466667 |
| 26 | 100 | 50 | 90 | 5 | 1000 | 3266.6667 | 83500 | 0.0391218 |
| 27 | 1000 | 500 | 5 | 250 | 10 | 53733.333 | 10000 | 5.3733333 |
| 28 | 100 | 1000 | 20 | 50 | 1000 | 30133.333 | 83500 | 0.3608782 |
| 29 | 2000 | 500 | 5 | 250 | 2000 | 60533.333 | 3336666.7 | 0.0181419 |
| 30 | 1000 | 1000 | 5 | 250 | 1000 | 49266.667 | 835000 | 0.059002 |
| 31 | 1000 | 500 | 20 | 50 | 2000 | 18466.667 | 1668333.3 | 0.0110689 |
| 32 | 1000 | 500 | 5 | 50 | 2000 | 13733.333 | 1668333.3 | 0.0082318 |
| 33 | 1000 | 1000 | 20 | 50 | 10 | 28633.333 | 10000 | 2.8633333 |
| 34 | 100 | 50 | 90 | 5 | 2000 | 2666.6667 | 166833.33 | 0.015984 |
| 35 | 1000 | 500 | 5 | 5 | 10 | 3333.3333 | 10000 | 0.3333333 |
| 36 | 100 | 1000 | 5 | 5 | 10 | 4766.6667 | 1000 | 4.7666667 |
| 37 | 2000 | 50 | 5 | 50 | 2000 | 14283.333 | 3336666.7 | 0.0042807 |
| 38 | 2000 | 1000 | 90 | 5 | 2000 | 5833.3333 | 3336666.7 | 0.0017483 |
| 39 | 100 | 50 | 5 | 250 | 2000 | 52383.333 | 166833.33 | 0.313986 |
| 40 | 100 | 50 | 20 | 50 | 10 | 17966.667 | 1000 | 17.966667 |
| 41 | 1000 | 1000 | 5 | 5 | 1000 | 4766.6667 | 835000 | 0.0057086 |
| 42 | 1000 | 1000 | 20 | 5 | 2000 | 7033.3333 | 1668333.3 | 0.0042158 |
| 43 | 2000 | 50 | 20 | 5 | 1000 | 2666.6667 | 1670000 | 0.0015968 |
| 44 | 100 | 50 | 90 | 250 | 2000 | 75666.667 | 166833.33 | 0.4535465 |
| 45 | 100 | 500 | 20 | 250 | 2000 | 56166.667 | 166833.33 | 0.3366633 |
| 46 | 1000 | 50 | 5 | 5 | 1000 | 3183.3333 | 835000 | 0.0038124 |
| 47 | 1000 | 500 | 90 | 250 | 10 | 50166.667 | 10000 | 5.0166667 |
| 48 | 100 | 1000 | 90 | 250 | 1000 | 52133.333 | 83500 | 0.6243513 |
| 49 | 2000 | 1000 | 5 | 5 | 10 | 5366.6667 | 20000 | 0.2683333 |
| 50 | 1000 | 50 | 90 | 250 | 2000 | 56166.667 | 1668333.3 | 0.0336663 |
| 51 | 100 | 1000 | 90 | 250 | 2000 | 53733.333 | 166833.33 | 0.3220779 |
| 52 | 2000 | 50 | 5 | 5 | 2000 | 3183.3333 | 3336666.7 | 0.000954 |
| 53 | 2000 | 50 | 90 | 5 | 10 | 2666.6667 | 20000 | 0.1333333 |
| 54 | 1000 | 1000 | 20 | 50 | 2000 | 20733.333 | 1668333.3 | 0.0124276 |
| 55 | 1000 | 50 | 5 | 50 | 1000 | 15983.333 | 835000 | 0.0191417 |
| 56 | 1000 | 500 | 20 | 50 | 1000 | 15966.667 | 835000 | 0.0191218 |
| 57 | 100 | 500 | 5 | 50 | 10 | 16433.333 | 1000 | 16.433333 |
| 58 | 1000 | 1000 | 20 | 250 | 10 | 77833.333 | 10000 | 7.7833333 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 59 | 100 | 1000 | 20 | 5 | 10 | 6433.3333 | 1000 | 6.4333333 |
| 60 | 1000 | 500 | 90 | 50 | 10 | 16566.667 | 10000 | 1.6566667 |
| 61 | 2000 | 50 | 5 | 250 | 2000 | 53483.333 | 3336666.7 | 0.016029 |
| 62 | 100 | 1000 | 90 | 50 | 1000 | 35533.333 | 83666.667 | 0.4247012 |
| 63 | 100 | 50 | 5 | 250 | 1000 | 49983.333 | 83500 | 0.5986028 |
| 64 | 1000 | 50 | 20 | 250 | 2000 | 78266.667 | 1668333.3 | 0.0469131 |
| 65 | 1000 | 500 | 90 | 50 | 2000 | 18466.667 | 1668333.3 | 0.0110689 |
| 66 | 100 | 1000 | 5 | 50 | 2000 | 17666.667 | 166833.33 | 0.1058941 |
| 67 | 1000 | 500 | 5 | 50 | 10 | 17733.333 | 10000 | 1.7733333 |
| 68 | 2000 | 500 | 5 | 50 | 2000 | 15633.333 | 3336666.7 | 0.0046853 |
| 69 | 1000 | 50 | 5 | 50 | 10 | 14783.333 | 10000 | 1.4783333 |
| 70 | 1000 | 500 | 90 | 5 | 1000 | 4766.6667 | 835000 | 0.0057086 |
| 71 | 1000 | 1000 | 20 | 5 | 1000 | 6433.3333 | 835000 | 0.0077046 |
| 72 | 2000 | 500 | 20 | 250 | 1000 | 47666.667 | 1670000 | 0.0285429 |
| 73 | 100 | 50 | 20 | 250 | 10 | 54366.667 | 1000 | 54.366667 |
| 74 | 2000 | 500 | 90 | 5 | 10 | 4166.6667 | 20000 | 0.2083333 |
| 75 | 2000 | 1000 | 5 | 50 | 2000 | 16066.667 | 3336666.7 | 0.0048152 |
| 76 | 1000 | 500 | 5 | 5 | 1000 | 3933.3333 | 835000 | 0.0047106 |
| 77 | 100 | 500 | 5 | 5 | 2000 | 3933.3333 | 166833.33 | 0.0235764 |
| 78 | 1000 | 1000 | 5 | 250 | 10 | 57766.667 | 10000 | 5.7766667 |
| 79 | 2000 | 500 | 20 | 5 | 1000 | 4766.6667 | 1670000 | 0.0028543 |
| 80 | 1000 | 500 | 90 | 250 | 1000 | 58666.667 | 835000 | 0.0702595 |
| 81 | 1000 | 50 | 90 | 5 | 10 | 3266.6667 | 10000 | 0.3266667 |
| 82 | 100 | 1000 | 20 | 5 | 1000 | 7033.3333 | 83500 | 0.0842315 |
| 83 | 100 | 1000 | 20 | 250 | 2000 | 54433.333 | 166833.33 | 0.3262737 |
| 84 | 2000 | 1000 | 90 | 250 | 2000 | 70233.333 | 3336666.7 | 0.021049 |
| 85 | 2000 | 1000 | 5 | 250 | 1000 | 49166.667 | 1670000 | 0.0294411 |
| 86 | 2000 | 500 | 20 | 50 | 2000 | 15166.667 | 3336666.7 | 0.0045455 |
| 87 | 1000 | 50 | 20 | 50 | 1000 | 16766.667 | 835000 | 0.0200798 |
| 88 | 2000 | 500 | 5 | 50 | 10 | 18633.333 | 20000 | 0.9316667 |
| 89 | 100 | 500 | 5 | 250 | 10 | 49633.333 | 1000 | 49.633333 |
| 90 | 2000 | 500 | 90 | 250 | 1000 | 79466.667 | 1670000 | 0.0475848 |
| 91 | 2000 | 500 | 20 | 250 | 2000 | 52766.667 | 3336666.7 | 0.0158142 |
| 92 | 1000 | 1000 | 5 | 50 | 2000 | 15266.667 | 1668333.3 | 0.0091508 |
| 93 | 100 | 500 | 5 | 50 | 2000 | 16233.333 | 166833.33 | 0.0973027 |
| 94 | 100 | 500 | 90 | 50 | 10 | 14566.667 | 1000 | 14.566667 |
| 95 | 2000 | 1000 | 5 | 5 | 2000 | 4766.6667 | 3336666.7 | 0.0014286 |
| 96 | 2000 | 500 | 5 | 5 | 10 | 3333.3333 | 20000 | 0.1666667 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 97 | 2000 | 50 | 5 | 50 | 10 | 17283.333 | 20000 | 0.8641667 |
| 98 | 100 | 500 | 20 | 5 | 10 | 4766.6667 | 1000 | 4.7666667 |
| 99 | 1000 | 1000 | 90 | 50 | 10 | 17533.333 | 10000 | 1.7533333 |
| 100 | 100 | 50 | 90 | 50 | 10 | 16166.667 | 1000 | 16.166667 |
| 101 | 2000 | 500 | 90 | 5 | 1000 | 4766.6667 | 1670000 | 0.0028543 |
| 102 | 2000 | 50 | 20 | 250 | 10 | 46566.667 | 20000 | 2.3283333 |
| 103 | 1000 | 50 | 5 | 250 | 10 | 53283.333 | 10000 | 5.3283333 |
| 104 | 100 | 1000 | 5 | 250 | 1000 | 51566.667 | 83500 | 0.6175649 |
| 105 | 2000 | 1000 | 90 | 250 | 10 | 81833.333 | 20000 | 4.0916667 |
| 106 | 100 | 500 | 20 | 250 | 1000 | 85866.667 | 83500 | 1.0283433 |
| 107 | 2000 | 500 | 5 | 5 | 2000 | 3933.3333 | 3336666.7 | 0.0011788 |
| 108 | 1000 | 50 | 90 | 50 | 1000 | 32766.667 | 835000 | 0.0392415 |
| 109 | 100 | 500 | 5 | 250 | 1000 | 78833.333 | 83500 | 0.9441118 |
| 110 | 2000 | 50 | 20 | 50 | 1000 | 26666.667 | 1670000 | 0.0159681 |
| 111 | 2000 | 500 | 20 | 5 | 10 | 4766.6667 | 20000 | 0.2383333 |
| 112 | 2000 | 1000 | 90 | 5 | 1000 | 6433.3333 | 1670000 | 0.0038523 |
| 113 | 1000 | 50 | 20 | 250 | 1000 | 52366.667 | 835000 | 0.0627146 |
| 114 | 1000 | 1000 | 90 | 50 | 2000 | 17433.333 | 1668333.3 | 0.0104496 |
| 115 | 100 | 50 | 90 | 250 | 10 | 46866.667 | 1000 | 46.866667 |
| 116 | 1000 | 500 | 20 | 5 | 1000 | 4166.6667 | 835000 | 0.00499 |
| 117 | 100 | 1000 | 20 | 250 | 10 | 68633.333 | 1000 | 68.633333 |
| 118 | 2000 | 500 | 20 | 50 | 1000 | 33166.667 | 1670000 | 0.0198603 |
| 119 | 100 | 500 | 20 | 5 | 1000 | 4766.6667 | 83500 | 0.0570858 |
| 120 | 100 | 500 | 90 | 5 | 1000 | 4766.6667 | 83500 | 0.0570858 |
| 121 | 2000 | 50 | 20 | 5 | 2000 | 3266.6667 | 3336666.7 | 0.000979 |
| 122 | 2000 | 50 | 20 | 250 | 2000 | 54366.667 | 3336666.7 | 0.0162937 |
| 123 | 1000 | 500 | 20 | 250 | 10 | 58766.667 | 10000 | 5.8766667 |
| 124 | 1000 | 50 | 90 | 250 | 10 | 51966.667 | 10000 | 5.1966667 |
| 125 | 100 | 1000 | 90 | 5 | 10 | 5833.3333 | 1166.6667 | 5 |
| 126 | 2000 | 50 | 5 | 5 | 10 | 3183.3333 | 20000 | 0.1591667 |
| 127 | 100 | 1000 | 5 | 5 | 2000 | 4766.6667 | 166833.33 | 0.0285714 |
| 128 | 1000 | 50 | 20 | 50 | 10 | 13766.667 | 10000 | 1.3766667 |
| 129 | 1000 | 500 | 20 | 5 | 10 | 4166.6667 | 10000 | 0.4166667 |
| 130 | 100 | 500 | 90 | 250 | 1000 | 56866.667 | 83500 | 0.6810379 |
| 131 | 100 | 50 | 5 | 5 | 2000 | 3183.3333 | 166833.33 | 0.0190809 |
| 132 | 100 | 50 | 5 | 5 | 10 | 3183.3333 | 1000 | 3.1833333 |
| 133 | 1000 | 50 | 20 | 250 | 10 | 46366.667 | 10000 | 4.6366667 |
| 134 | 100 | 50 | 90 | 250 | 1000 | 45066.667 | 83500 | 0.5397206 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 135 | 2000 | 500 | 5 | 50 | 1000 | 17433.333 | 1670000 | 0.0104391 |
| 136 | 2000 | 1000 | 20 | 5 | 1000 | 6433.3333 | 1670000 | 0.0038523 |
| 137 | 1000 | 1000 | 20 | 50 | 1000 | 16833.333 | 835000 | 0.0201597 |
| 138 | 100 | 500 | 20 | 50 | 10 | 17666.667 | 1000 | 17.666667 |
| 139 | 1000 | 1000 | 5 | 50 | 10 | 17266.667 | 10000 | 1.7266667 |
| 140 | 100 | 500 | 20 | 50 | 1000 | 15366.667 | 83500 | 0.1840319 |
| 141 | 2000 | 50 | 20 | 50 | 2000 | 13766.667 | 3336666.7 | 0.0041259 |
| 142 | 1000 | 1000 | 5 | 5 | 10 | 4766.6667 | 10000 | 0.4766667 |
| 143 | 2000 | 1000 | 90 | 50 | 2000 | 18933.333 | 3336666.7 | 0.0056743 |
| 144 | 2000 | 1000 | 90 | 5 | 10 | 6433.3333 | 20000 | 0.3216667 |
| 145 | 100 | 1000 | 20 | 50 | 2000 | 18133.333 | 166833.33 | 0.1086913 |
| 146 | 2000 | 500 | 90 | 50 | 10 | 15266.667 | 20000 | 0.7633333 |
| 147 | 2000 | 500 | 90 | 250 | 2000 | 88566.667 | 3336666.7 | 0.0265435 |
| 148 | 2000 | 1000 | 20 | 250 | 10 | 56133.333 | 20000 | 2.8066667 |
| 149 | 1000 | 50 | 20 | 5 | 10 | 3266.6667 | 10000 | 0.3266667 |
| 150 | 2000 | 50 | 90 | 50 | 2000 | 13866.667 | 3336666.7 | 0.0041558 |
| 151 | 2000 | 50 | 5 | 250 | 1000 | 52383.333 | 1670000 | 0.0313673 |
| 152 | 2000 | 1000 | 20 | 250 | 2000 | 50833.333 | 3336666.7 | 0.0152348 |
| 153 | 2000 | 50 | 90 | 5 | 1000 | 2666.6667 | 1670000 | 0.0015968 |
| 154 | 100 | 500 | 90 | 50 | 2000 | 15966.667 | 166833.33 | 0.0957043 |
| 155 | 100 | 50 | 90 | 5 | 10 | 3266.6667 | 1000 | 3.2666667 |
| 156 | 2000 | 1000 | 20 | 50 | 10 | 32033.333 | 20000 | 1.6016667 |
| 157 | 100 | 500 | 20 | 50 | 2000 | 18566.667 | 166833.33 | 0.1112887 |
| 158 | 2000 | 500 | 5 | 5 | 1000 | 3933.3333 | 1670000 | 0.0023553 |
| 159 | 100 | 1000 | 90 | 50 | 2000 | 18133.333 | 166833.33 | 0.1086913 |
| 160 | 1000 | 500 | 90 | 50 | 1000 | 16566.667 | 835000 | 0.0198403 |
| 161 | 2000 | 500 | 5 | 250 | 1000 | 50533.333 | 1670000 | 0.0302595 |
| 162 | 1000 | 50 | 20 | 5 | 2000 | 2666.6667 | 1668333.3 | 0.0015984 |
| 163 | 2000 | 50 | 20 | 5 | 10 | 3866.6667 | 20000 | 0.1933333 |
| 164 | 2000 | 1000 | 5 | 250 | 2000 | 56266.667 | 3336666.7 | 0.0168631 |
| 165 | 1000 | 500 | 5 | 5 | 2000 | 3933.3333 | 1668333.3 | 0.0023576 |
| 166 | 1000 | 500 | 90 | 5 | 10 | 4766.6667 | 10000 | 0.4766667 |
| 167 | 100 | 50 | 5 | 5 | 1000 | 3183.3333 | 83500 | 0.0381238 |
| 168 | 1000 | 500 | 5 | 250 | 1000 | 92533.333 | 835000 | 0.1108184 |
| 169 | 1000 | 1000 | 90 | 5 | 1000 | 6433.3333 | 835000 | 0.0077046 |
| 170 | 100 | 500 | 20 | 5 | 2000 | 4766.6667 | 166833.33 | 0.0285714 |
| 171 | 2000 | 500 | 20 | 5 | 2000 | 4766.6667 | 3336666.7 | 0.0014286 |
| 172 | 100 | 1000 | 20 | 50 | 10 | 20533.333 | 1000 | 20.533333 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 173 | 2000 | 50 | 5 | 50 | 1000 | 16083.333 | 1670000 | 0.0096307 |
| 174 | 2000 | 500 | 5 | 250 | 10 | 46533.333 | 20000 | 2.3266667 |
| 175 | 2000 | 500 | 20 | 250 | 10 | 51766.667 | 20000 | 2.5883333 |
| 176 | 2000 | 50 | 20 | 50 | 10 | 16166.667 | 20000 | 0.8083333 |
| 177 | 1000 | 1000 | 90 | 50 | 1000 | 19233.333 | 835000 | 0.0230339 |
| 178 | 1000 | 1000 | 90 | 250 | 1000 | 54133.333 | 835000 | 0.0648303 |
| 179 | 2000 | 50 | 90 | 5 | 2000 | 3266.6667 | 3336666.7 | 0.000979 |
| 180 | 100 | 500 | 90 | 5 | 10 | 4766.6667 | 1000 | 4.7666667 |
| 181 | 1000 | 1000 | 20 | 250 | 1000 | 83633.333 | 835000 | 0.1001597 |
| 182 | 1000 | 50 | 90 | 50 | 10 | 14266.667 | 10000 | 1.4266667 |
| 183 | 100 | 1000 | 90 | 5 | 1000 | 6433.3333 | 83666.667 | 0.0768924 |
| 184 | 1000 | 1000 | 90 | 250 | 2000 | 48833.333 | 1668333.3 | 0.0292707 |
| 185 | 100 | 50 | 90 | 50 | 1000 | 14866.667 | 83500 | 0.1780439 |
| 186 | 1000 | 1000 | 90 | 5 | 2000 | 6433.3333 | 1668333.3 | 0.0038561 |
| 187 | 1000 | 50 | 5 | 50 | 2000 | 13583.333 | 1668333.3 | 0.0081419 |
| 188 | 100 | 500 | 20 | 250 | 10 | 44666.667 | 1000 | 44.666667 |
| 189 | 2000 | 1000 | 5 | 5 | 1000 | 4766.6667 | 1670000 | 0.0028543 |
| 190 | 1000 | 1000 | 5 | 50 | 1000 | 19066.667 | 835000 | 0.0228343 |
| 191 | 100 | 1000 | 20 | 250 | 1000 | 61433.333 | 83500 | 0.7357285 |
| 192 | 100 | 50 | 5 | 50 | 2000 | 14383.333 | 166833.33 | 0.0862138 |
| 193 | 100 | 50 | 20 | 50 | 1000 | 13166.667 | 83500 | 0.1576846 |
| 194 | 100 | 50 | 20 | 50 | 2000 | 16166.667 | 166833.33 | 0.0969031 |
| 195 | 2000 | 50 | 5 | 5 | 1000 | 2583.3333 | 1670000 | 0.0015469 |
| 196 | 1000 | 1000 | 20 | 5 | 10 | 6433.3333 | 10000 | 0.6433333 |
| 197 | 100 | 50 | 20 | 250 | 2000 | 45766.667 | 166833.33 | 0.2743257 |
| 198 | 1000 | 50 | 5 | 250 | 2000 | 48583.333 | 1668333.3 | 0.0291209 |
| 199 | 100 | 500 | 90 | 5 | 2000 | 4766.6667 | 166833.33 | 0.0285714 |
| 200 | 2000 | 1000 | 90 | 50 | 1000 | 21333.333 | 1670000 | 0.0127745 |
| 201 | 2000 | 500 | 90 | 50 | 1000 | 17666.667 | 1670000 | 0.0105788 |
| 202 | 100 | 50 | 5 | 250 | 10 | 56183.333 | 1000 | 56.183333 |
| 203 | 100 | 1000 | 5 | 5 | 1000 | 5366.6667 | 83500 | 0.0642715 |
| 204 | 1000 | 50 | 90 | 50 | 2000 | 13066.667 | 1668333.3 | 0.0078322 |
| 205 | 1000 | 500 | 5 | 50 | 1000 | 15533.333 | 835000 | 0.0186028 |
| 206 | 2000 | 50 | 20 | 250 | 1000 | 46566.667 | 1670000 | 0.0278842 |
| 207 | 2000 | 1000 | 20 | 50 | 1000 | 16833.333 | 1670000 | 0.0100798 |
| 208 | 2000 | 1000 | 5 | 250 | 10 | 76566.667 | 20000 | 3.8283333 |
| 209 | 1000 | 50 | 5 | 5 | 10 | 3183.3333 | 10000 | 0.3183333 |
| 210 | 2000 | 1000 | 5 | 50 | 10 | 17066.667 | 20000 | 0.8533333 |

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 211 | 100 | 1000 | 90 | 50 | 10 | 16833.333 | 1000 | 16.833333 |
| 212 | 2000 | 500 | 90 | 50 | 2000 | 15166.667 | 3336666.7 | 0.0045455 |
| 213 | 1000 | 1000 | 5 | 5 | 2000 | 5366.6667 | 1668333.3 | 0.0032168 |
| 214 | 100 | 500 | 90 | 250 | 10 | 49866.667 | 1000 | 49.866667 |
| 215 | 100 | 50 | 5 | 50 | 1000 | 14283.333 | 83500 | 0.1710579 |
| 216 | 2000 | 1000 | 20 | 250 | 1000 | 46933.333 | 1670000 | 0.0281038 |
| 217 | 1000 | 50 | 5 | 250 | 1000 | 58883.333 | 835000 | 0.070519 |
| 218 | 1000 | 500 | 90 | 5 | 2000 | 4166.6667 | 1668333.3 | 0.0024975 |
| 219 | 2000 | 1000 | 20 | 5 | 2000 | 6433.3333 | 3336666.7 | 0.0019281 |
| 220 | 2000 | 1000 | 90 | 50 | 10 | 19433.333 | 20000 | 0.9716667 |
| 221 | 1000 | 50 | 5 | 5 | 2000 | 3183.3333 | 1668333.3 | 0.0019081 |
| 222 | 2000 | 1000 | 5 | 50 | 1000 | 32766.667 | 1670000 | 0.0196208 |
| 223 | 100 | 500 | 90 | 250 | 2000 | 47766.667 | 166833.33 | 0.2863137 |
| 224 | 1000 | 500 | 20 | 250 | 2000 | 60866.667 | 1668333.3 | 0.0364835 |
| 225 | 100 | 1000 | 90 | 5 | 2000 | 5833.3333 | 167000 | 0.0349301 |
| 226 | 100 | 50 | 90 | 50 | 2000 | 14966.667 | 166833.33 | 0.0897103 |
| 227 | 2000 | 1000 | 20 | 5 | 10 | 6433.3333 | 20000 | 0.3216667 |
| 228 | 1000 | 500 | 90 | 250 | 2000 | 45266.667 | 1668333.3 | 0.0271329 |
| 229 | 1000 | 1000 | 90 | 250 | 10 | 46433.333 | 10000 | 4.6433333 |
| 230 | 1000 | 500 | 20 | 50 | 10 | 16466.667 | 10000 | 1.6466667 |
| 231 | 1000 | 50 | 90 | 5 | 1000 | 3266.6667 | 835000 | 0.0039122 |
| 232 | 2000 | 50 | 5 | 250 | 10 | 70883.333 | 20000 | 3.5441667 |
| 233 | 100 | 50 | 20 | 5 | 2000 | 3266.6667 | 166833.33 | 0.0195804 |
| 234 | 1000 | 1000 | 20 | 250 | 2000 | 80733.333 | 1668333.3 | 0.0483916 |
| 235 | 1000 | 1000 | 90 | 5 | 10 | 6433.3333 | 10000 | 0.6433333 |
| 236 | 100 | 50 | 20 | 5 | 10 | 3266.6667 | 1000 | 3.2666667 |
| 237 | 2000 | 500 | 20 | 50 | 10 | 19566.667 | 20000 | 0.9783333 |
| 238 | 100 | 500 | 5 | 50 | 1000 | 18633.333 | 83500 | 0.2231537 |
| 239 | 100 | 500 | 5 | 250 | 2000 | 44533.333 | 166833.33 | 0.2669331 |
| 240 | 100 | 50 | 5 | 50 | 10 | 14883.333 | 1000 | 14.883333 |
| 241 | 2000 | 500 | 90 | 5 | 2000 | 4166.6667 | 3336666.7 | 0.0012488 |
| 242 | 100 | 1000 | 5 | 250 | 2000 | 48566.667 | 166833.33 | 0.2911089 |
| 243 | 100 | 1000 | 5 | 50 | 10 | 16366.667 | 1000 | 16.366667 |

# Appendix C

# Analysis Experimental Tables

Table C.1: Level 1 instance

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 50 | 5 | 5 | 100 | 2583.3333 | 850 | 3.0392157 |
| 2 | 10 | 50 | 5 | 5 | 200 | 3183.3333 | 1683.3333 | 1.8910891 |
| 3 | 10 | 50 | 5 | 5 | 300 | 3183.3333 | 2516.6667 | 1.2649007 |
| 4 | 10 | 50 | 5 | 5 | 350 | 3783.3333 | 2933.3333 | 1.2897727 |
| 5 | 10 | 50 | 5 | 5 | 400 | 3183.3333 | 3350 | 0.9502488 |
| 6 | 10 | 50 | 5 | 5 | 500 | 2583.3333 | 4183.3333 | 0.6175299 |
| 7 | 10 | 50 | 5 | 5 | 600 | 2583.3333 | 5016.6667 | 0.5149502 |
| 8 | 10 | 50 | 5 | 5 | 1000 | 3183.3333 | 8350 | 0.3812375 |
| 9 | 10 | 50 | 5 | 5 | 2000 | 2583.3333 | 16683.333 | 0.1548452 |

Table C.2: Level 2 number of orders instance

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1500 | 500 | 20 | 50 | 10 | 17766.667 | 15000 | 1.1844444 |
| 2 | 1550 | 500 | 20 | 50 | 10 | 15766.667 | 15500 | 1.0172043 |
| 3 | 1600 | 500 | 20 | 50 | 10 | 15266.667 | 16000 | 0.9541667 |
| 4 | 1650 | 500 | 20 | 50 | 10 | 15366.667 | 16500 | 0.9313131 |
| 5 | 1700 | 500 | 20 | 50 | 10 | 17066.667 | 17000 | 1.0039216 |
| 6 | 1750 | 500 | 20 | 50 | 10 | 16366.667 | 17500 | 0.9352381 |
| 7 | 1800 | 500 | 20 | 50 | 10 | 17866.667 | 18000 | 0.9925926 |
| 8 | 1850 | 500 | 20 | 50 | 10 | 16366.667 | 18500 | 0.8846847 |
| 9 | 1900 | 500 | 20 | 50 | 10 | 17066.667 | 19000 | 0.8982456 |
| 10 | 2000 | 500 | 20 | 50 | 10 | 15166.667 | 20000 | 0.7583333 |

Table C.3: Level 2 Process planning instance

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 500 | 20 | 50 | 10 | 33266.667 | 1000 | 33.266667 |
| 2 | 100 | 500 | 20 | 50 | 50 | 14766.667 | 4333.3333 | 3.4076923 |
| 3 | 100 | 500 | 20 | 50 | 100 | 15766.667 | 8500 | 1.854902 |
| 4 | 100 | 500 | 20 | 50 | 150 | 28666.667 | 12666.667 | 2.2631579 |
| 5 | 100 | 500 | 20 | 50 | 200 | 17666.667 | 16833.333 | 1.049505 |
| 6 | 100 | 500 | 20 | 50 | 250 | 31066.667 | 21000 | 1.4793651 |
| 7 | 100 | 500 | 20 | 50 | 300 | 15266.667 | 25166.667 | 0.6066225 |
| 8 | 100 | 500 | 20 | 50 | 350 | 16566.667 | 29333.333 | 0.5647727 |
| 9 | 100 | 500 | 20 | 50 | 400 | 16366.667 | 33500 | 0.4885572 |
| 10 | 100 | 500 | 20 | 50 | 500 | 18366.667 | 41833.333 | 0.4390438 |

Table C.4: Level 3 instance view 1

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 1000 | 90 | 250 | 100 | 84233.333 | 8500 | 9.9098039 |
| 2 | 100 | 1000 | 90 | 250 | 200 | 62233.333 | 16833.333 | 3.6970297 |
| 3 | 100 | 1000 | 90 | 250 | 300 | 56133.333 | 25166.667 | 2.2304636 |
| 4 | 100 | 1000 | 90 | 250 | 400 | 82633.333 | 33500 | 2.4666667 |
| 5 | 100 | 1000 | 90 | 250 | 500 | 58033.333 | 41833.333 | 1.387251 |
| 6 | 100 | 1000 | 90 | 250 | 600 | 88633.333 | 50166.667 | 1.7667774 |
| 7 | 100 | 1000 | 90 | 250 | 700 | 61233.333 | 58500 | 1.0467236 |
| 8 | 100 | 1000 | 90 | 250 | 800 | 56133.333 | 66833.333 | 0.8399002 |
| 9 | 100 | 1000 | 90 | 250 | 1000 | 50533.333 | 83500 | 0.6051896 |
| 10 | 100 | 1000 | 90 | 250 | 1500 | 51933.333 | 125166.67 | 0.4149134 |

Table C.5: Level 3 instance view 2

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1000 | 1000 | 90 | 250 | 40 | 61833.333 | 35000 | 1.7666667 |
| 2 | 1000 | 1000 | 90 | 250 | 50 | 85733.333 | 43333.333 | 1.9784615 |
| 3 | 1000 | 1000 | 90 | 250 | 60 | 48233.333 | 51666.667 | 0.9335484 |
| 4 | 1000 | 1000 | 90 | 250 | 70 | 46933.333 | 60000 | 0.7822222 |
| 5 | 1000 | 1000 | 90 | 250 | 80 | 68533.333 | 68333.333 | 1.0029268 |
| 6 | 1000 | 1000 | 90 | 250 | 90 | 84133.333 | 76666.667 | 1.0973913 |
| 7 | 1000 | 1000 | 90 | 250 | 100 | 91333.333 | 85000 | 1.0745098 |
| 8 | 1000 | 1000 | 90 | 250 | 110 | 45033.333 | 93333.333 | 0.4825 |
| 9 | 1000 | 1000 | 90 | 250 | 120 | 58733.333 | 101666.67 | 0.5777049 |
| 10 | 1000 | 1000 | 90 | 250 | 130 | 60333.333 | 110000 | 0.5484848 |

Table C.6: Level 3 instance view 3

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 2000 | 1000 | 90 | 250 | 10 | 53633.333 | 20000 | 2.6816667 |
| 2 | 2000 | 1000 | 90 | 250 | 20 | 75633.333 | 36666.667 | 2.0627273 |
| 3 | 2000 | 1000 | 90 | 250 | 30 | 55133.333 | 53333.333 | 1.03375 |
| 4 | 2000 | 1000 | 90 | 250 | 40 | 80333.333 | 70000 | 1.147619 |
| 5 | 2000 | 1000 | 90 | 250 | 50 | 57933.333 | 86666.667 | 0.6684615 |
| 6 | 2000 | 1000 | 90 | 250 | 60 | 88533.333 | 103333.33 | 0.8567742 |
| 7 | 2000 | 1000 | 90 | 250 | 70 | 55833.333 | 120000 | 0.4652778 |
| 8 | 2000 | 1000 | 90 | 250 | 80 | 47033.333 | 136666.67 | 0.3441463 |
| 9 | 2000 | 1000 | 90 | 250 | 90 | 62533.333 | 153333.33 | 0.4078261 |
| 10 | 2000 | 1000 | 90 | 250 | 100 | 55133.333 | 170000 | 0.3243137 |

Table C.7: Level 3 instance view 4

| Run Order | X1 | X2 | X3 | X4 | X5 | C-MARS-ABM | NC-MARS-ABM | Ratio Response (int/non) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 1000 | 90 | 250 | 500 | 48233.333 | 41833.333 | 1.152988 |
| 2 | 150 | 1000 | 90 | 250 | 500 | 78833.333 | 62750 | 1.2563081 |
| 3 | 200 | 1000 | 90 | 250 | 500 | 53033.333 | 83666.667 | 0.6338645 |
| 4 | 250 | 1000 | 90 | 250 | 500 | 53033.333 | 104583.33 | 0.5070916 |
| 5 | 300 | 1000 | 90 | 250 | 500 | 47433.333 | 125500 | 0.3779548 |
| 6 | 350 | 1000 | 90 | 250 | 500 | 61133.333 | 146416.67 | 0.4175299 |
| 7 | 400 | 1000 | 90 | 250 | 500 | 73233.333 | 167333.33 | 0.4376494 |
| 8 | 1000 | 1000 | 90 | 250 | 500 | 76433.333 | 418333.33 | 0.1827092 |
| 9 | 1500 | 1000 | 90 | 250 | 500 | 55433.333 | 627500 | 0.08834 |
| 10 | 2000 | 1000 | 90 | 250 | 500 | 46233.333 | 836666.67 | 0.055259 |