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Assessment of interoperability 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. In this paper, the authors investigate interoperability in the context of cloud manufacturing to identify the key parameters that determine whether or not a change-over from traditional cloud manufacturing to interoperable cloud manufacturing is financially viable for a given scenario of service providers and manufacturing orders. The results obtained 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.

1. Introduction

Decentralisation and resource sharing are key drivers for success in today's globalised economy. As a result, small and medium-sized enterprises (SMEs) strive to overcome the increasing pressure of competition by exploring new ways of utilising shared manufacturing resources and assets through decentralised networks all over the world. Such distributed manufacturing aimed at sharing geographically dispersed manufacturing resources and capabilities represents a move away from manufacturing service provision on the basis of installed machines at a given site towards almost freely configurable requirements-based service provision and thus paving the way for a continuing transition from traditional on-site 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 [1–4]. As the provision of such services requires more information compared to the traditional view of dedicated manufacturing resource provision [2], informatisation of manufacturing is emerging as a strategic step for realising this new paradigm [5]. In order to bring this change about, recent advances in Information and Communication Technologies (ICT), including the Internet-of-Things and Cloud Computing are deployed.

This informatisation is an enhancement aimed at expanding the competitiveness of small and medium-size manufacturing enterprises (SMEs) [6].

As a result, SMEs gain the ability to provide manufacturing services and accommodate larger and more complex jobs, and such contribute to the continuing globalisation of the manufacturing sector and economy [7].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 cloud-based manufacturing enterprises.

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Subsequently, cloud manufacturing was introduced as a new service-oriented manufacturing paradigm. 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 [8]. Through the intelligent integration of manufacturing resources and capabilities, a shared pool of resources is created via a cloud manufacturing platform, enabling cloud users to offer or acquire manufacturing tasks on a service basis [6].

The cloud manufacturing approach strives to overcome some of the drawbacks of former approaches of networked manufacturing, such as the absence of stable manufacturing resource transactions on large-scale manufacturing operations [3], insufficient middle-ware interfaces or APIs to deploy heterogeneous manufacturing resources for network representation [9], and a lack of flexibility and agility between the manufacturing enterprise and the shop floor [10,11].

The emerging cloud paradigm has a prominent effect on manufacturing [3,6,12]. The move from hardware bound systems to requirements-based service provision represents a major paradigm shift with several open research challenges yet to be investigated. These include:

1. Unclear principles for the protection of the end user investment
2. Difficulty in communication and interaction between departments within the enterprise and among the stakeholders within the supply chain
3. Limited collaboration and interaction between business partners within cloud manufacturing networks.
4. Absence of a framework for cloud manufacturing service provision.
5. Difficulty in the deployment of physical resources, such as machines, monitors and facilities.

A networked manufacturing service provision system should allow various stakeholders to access the necessary manufacturing information according to their requirements, enabling the 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 has been identified as one of the essential requirements for enabling cloud manufacturing applications [13,14], providing a framework of open standards and application protocols to enable the easy migration and integration of manufacturing applications and data between different cloud service providers [3]. Furthermore, the development of a standardised representation of heterogeneous manufacturing resources and capabilities utilise different data or semantic models and structures that are described and represented without unified features, data types and specifications [13]. This representation results in a vast amount of data and unstructured information along the entire manufacturing life-cycle [12]. To date, interoperability has not been implemented at a sufficient level to allow for commercial cloud manufacturing across the industry in a broader sense. There still is a lack of standardised methodologies of information exchange between different cloud users [3]. Consequently, laying out a framework for interoperability in cloud manufacturing would help to promote further and facilitate this emerging paradigm, making it more attractive for SMEs worldwide.

However, the authors would like to emphasise that the gap 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 the researchers have proposed several approaches likely to succeed). But, rather in a lack of understanding of the required level of interoperability and integration for realising commercial manufacturing clouds. In other words, even though the technology for realising inter- operability at several levels already exists, it is not clear how much of it should be implemented in a given scenario. The work proposed in this paper concerns the identification of the key process parameters for deploying cloud manufacturing processes via a generic and costing-based operation and deployment model used to simulate interoperable cloud-based manufacturing scenarios for parts of different complexity, varying production numbers, and service composition setups typical to SMEs of varying sizes. 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 are that such a standard would need existing machines to be adopted, operators to be trained and translators to convert the current code to this standard.

In the remainder of the paper, Section 2 provides the background of interoperability within the cloud manufacturing context. In Section 3, an overview of the industrially inspired case study is shown followed by the development of the C-MARS activity-based model C-MARS-ABM. Moreover, the non-interoperable cloud manufacturing activity-based model (NC-MARS-ABM), based on the previously developed cloud manufacturing framework C-MARS (cloud manufacturing resource sharing). In Section 4, the Design of the test case scenarios for assessing C-MARS-ABM is presented. In Section 5, the results and analysis obtained for the test case scenarios are discussed. In Section 6, the conclusion and an outline of future work are presented.

2. State-of-the-art

2.1. Overview and background

Primarily since the last decade, information exchange is considered to be strategically crucial for the development of enterprises [15], as there is an increasing need for global sharing of technology and knowledge [16]. Since then, significant efforts have been made in the direction of developing various frameworks and systems aimed at sharing and exchanging of manufacturing information. The predecessor to cloud manufacturing was so-called mainly noted as networked manufacturing where a significant body of research generally exists in 5 main categories; agile manufacturing, virtual manufacturing, application service providers, collaborative manufacturing, and grid manufacturing.

Consequentially, cloud manufacturing is introduced as a new paradigm that enhances manufacturing resources and capabilities sharing of the whole product lifecycle between manufacturing structures and enterprise systems [4], Fig. 1 illustrates the evolution of networked manufacturing technologies to date. As stated in the previous section, cloud computing is promoted to be adopted by manufacturing enterprises to share resources and capabilities in order to enhance their response to market requirements and increase cost-effectiveness [6]. In addition, it aims to address the limitations of previous manufacturing technologies which lacked the requirements needed for modern manufacturing enterprises [17]. Since it has the “pay-as-you-go” service management across its levels, it allows for on-demand self-service and adapts dynamically to changes in demand [4]. These features can enhance cloud manufacturing to support the product life-cycle development by involving networks and decentralised information sharing, which will help SMEs to save money and increase their efficiency [18]. Furthermore, cloud manufacturing can potentially promote ubiquitous access to product design information, thus enhancing collaborative design techniques, it can also enhance resource sharing, rapid production of prototypes and reduced costs. Hence distributed manufacturing can be developed, and on the marketing and service sector, cloud manufacturing can reduce time-to-market, improve service, and enhance the user experience, advantageously impacts customer co-creation area [19].

Further, a key study on cost-benefit analysis has been introduced by

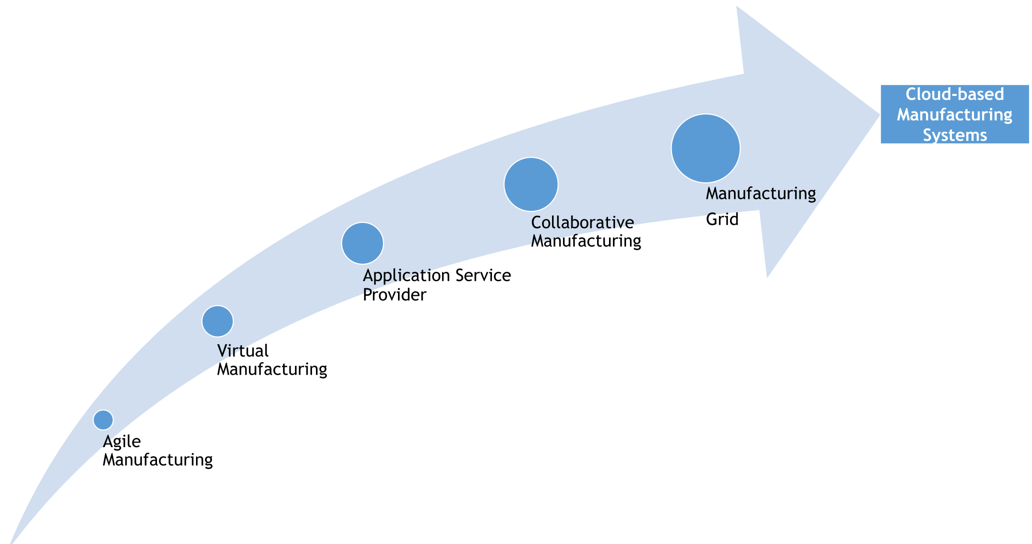


Fig. 1. Evolution of manufacturing information sharing systems.

Wu et al. [20] in order to imply an assessment for cloud manufacturing adoption. The study explored various key factors of the cost breakdown for implementing the cloud-based manufacturing approach in contrast to traditional centralised design and manufacturing. The study demonstrated the equivalent and matching cloud computing pricing plans as the pay-as-you-go for instance with the related service providers on different levels (i.e. IaaS, Paas, SaaS), which provided significant insights into the feasibility of cost reductions for adopting cloud manufacturing by SMEs over the traditional manufacturing in specific manufacturing situations. Although [21] implied that the cloud-based paradigm for manufacturing is not always a feasible solution for enterprises due to insufficient assessment and lack of skills for its implementation.

Another study on the impact of cloud manufacturing adoption, that illustrates the three different sectors that cloud manufacturing potentially may affect in both the short and long term; (i) the engineering and design sector, (ii) the manufacturing sector, and (iii) the marketing and service sector [19]. In the short term, cloud manufacturing can offer ubiquitous access to design information, improve efficiency, provide adequate computing resources for the engineering and design sector, thus facilitates a collaborative design approach in the long term. In the manufacturing sectors, a 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 potentially enhanced. Consequently, cloud manufacturing can provide customer co-creation environment.

Based on these insights, cloud manufacturing would thus play a significant role in the development and execution of product lifecycle processes, as in cloud manufacturing; product lifecycle activities and functions can be supported by virtualised manufacturing resources and the manufacturing capabilities layer allocated within the Cloud manufacturing system [22]. Thus, this can freely allow SMEs to access these services, relaying jobs of 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 [2]. Various approaches tried to address the resource virtualisation problem in cloud manufacturing, which is considered as one of the key role parameters for enhancing manufacturing resource sharing; Liu et al. [22] 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, there are many efforts aimed at addressing cloud manufacturing challenges from different aspects such as, Jiang et al. [23] introduced a cloud manufacturing system based on cloud-agent technology to realise resource sharing and collaboration for service integration. Tao et al. [2] 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 for more development in the current phase [13,24].

2.2. Cloud manufacturing interoperability

In this section, a review of the state-of-the-art concerning interoperability as key enabler for cloud manufacturing is provided. Wang and Xu [25] proposed a four-layered architecture for cloud manufacturing to address interoperability named ICMS (Interoperable Cloud-Based Manufacturing System) as shown in Fig. 2, 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, furtherer 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 logic control over the workflow and processes of the service. Moreover, 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 was integrated as a Virtual Service Combination.

Li et al. [26] 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. (3) Third, the addition of self-defined entities and schemas of a customer model that is

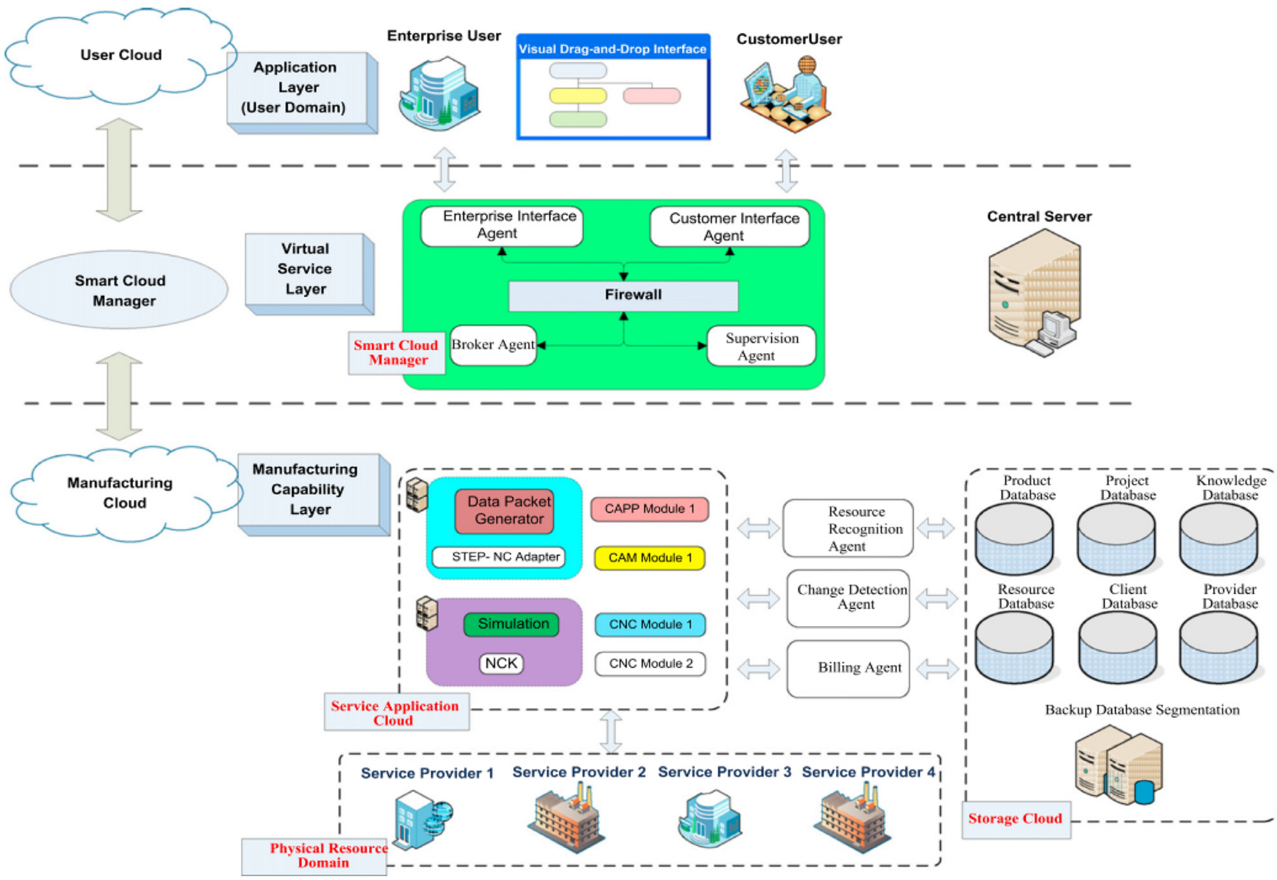


Fig. 2. ICMS architecture [25].

not presented within the STEP standards, hence, in the fourth phase (4) both STEP defined and self-defined models were integrated by utilising EXPRESS and EXPRESS-G languages to present the data model along with entities 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. [27] addressed interoperability for manufacturing task description within cloud manufacturing. This was achieved by applying an Ontology-based framework for semantic and universal task manufacturing description called GCMT. The proposed framework utilises various approaches and technologies; documenting pre-processing technologies, domain knowledge, automatic ontology construction approaches, sub-ontology matching methods, and other relevant computer technologies. This framework 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. [28] proposed interoperability through a Hybrid Manufacturing Cloud architecture that promote users to utilise different cloud modes namely, public, community, and private clouds. These different modes 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 an ROI (Return on Investment) analysis considers factors such as manufacturing capabilities, business strategy and security concerns.

Recently, Delaram and Valilai [29] 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 through the utilisation of the Internet as a medium for information transfer. They also introduced an architecture for third-party companies that are 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 evolution of technology within the manufacturing industry, although it is still in the juvenile stage for a large scale application [30], quantitative and robust assessment for electing the appropriate cloud deployment approach [24]. Extensive efforts, investments and collaborations are required in order to enable and implement interoperability within cloud manufacturing systems.

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 decentralised 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 enable the majority of SMEs stakeholders that are incapable of changing or updating their current manufacturing resources allocated in shop-floor to respond and adapt to the requirements of the global market changes [31], as the SMEs are considered of high contribution in the manufacturing firms within the global market [32].

Thus, 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) in case of a fully automated machine tool, the machining orders is sent directly from the cloud to the machine tool interface via network connection, (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.

Additionally, The literature revealed and emphasised the cost impact of deploying the cloud-based paradigm and how it benefits manufacturing enterprises [20]. It also emphasised 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 [21].

3. Development of activity-based models; C-MARS-ABM and NC-MARS-ABM

3.1. Introduction

The interoperable cloud manufacturing system, known as C-MARS, discussed by the authors in [33] demonstrated the flow of the machining process through a complete manufacturing cycle for prismatic parts. The interoperable cloud manufacturing system 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 industrially inspired case study is shown followed by the development of the C-MARS activity-based model namely; C-MARS-ABM. In order to assess the deployment of the interoperable approach for cloud manufacturing, an illustration of the non-interoperable cloud manufacturing activity-based model (NC-MARS-ABM) has been illustrated to identify the contrast between adopting both approaches for cloud manufacturing system. Finally, the quantification of the activities in reference to cost is described.

3.2. Interoperable cloud manufacturing activity-based model (C-MARS-ABM) overview

An overview of the industrially inspired case study is shown in this section. It is then utilised as an application scenario in the C-MARS machining processes. This section illustrates the industrially inspired case study used as a test case for the developed C-MARS framework. The prismatic sample part in ISO 14649-11 shown in Fig. 3 has been utilised to demonstrate the processes encapsulated in the C-MARS framework.

The machining operations identified for the STEP-NC file are as follows: (i) facing operation, (ii) 2D pocket flat end milling operation for the 2D pocket and (iii) drill hole and as for machine tool specification is: Dugard Eagle 850, 3-axis milling machine, cutting tools used are; face mill diameter 40 mm and Slot drill 8 mm.

The C-MARS framework was illustrating the CNC machining of prismatic parts. The C-MARS theoretical framework shown in Fig. 4 illustrates the service processing request by the service user in C-MARS for manufacturing the part.

The C-MARS framework 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 scheduled 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).

In order to compare the interoperable to non-interoperable approach for creating a machining cloud manufacturing service, two activity-based models are defined, illustrating the deploying approach of the manufacturing life-cycle from the interoperability perspective.

3.3. Development of C-MARS ABM: interoperable approach

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, the ISO14649 suite of standards [34] is used as they provide the necessary level of abstraction to describe the manufacturing requirements of prismatic parts. As shown in Fig. 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 are 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).

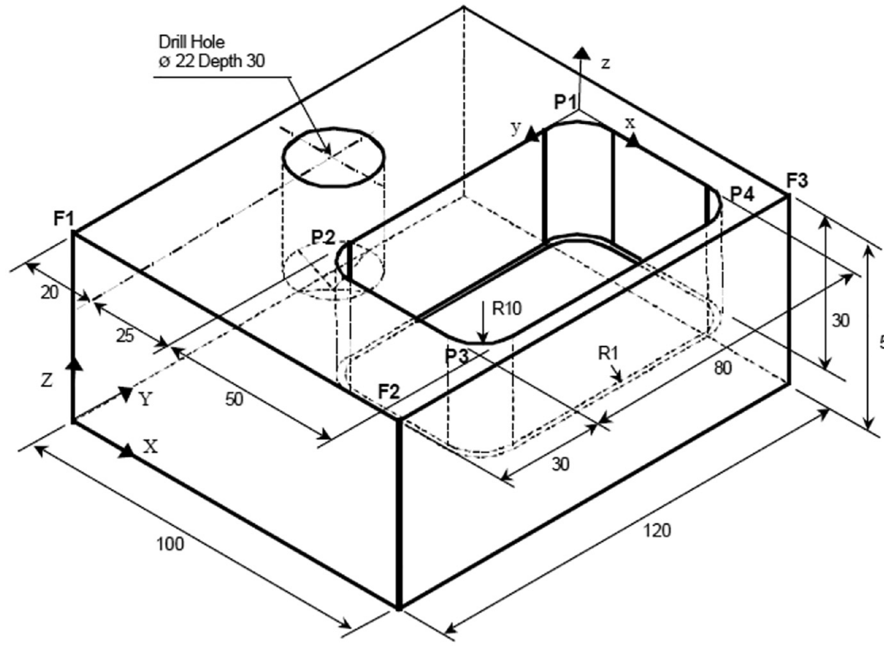


Fig. 3. ISO14649-11 sample part.

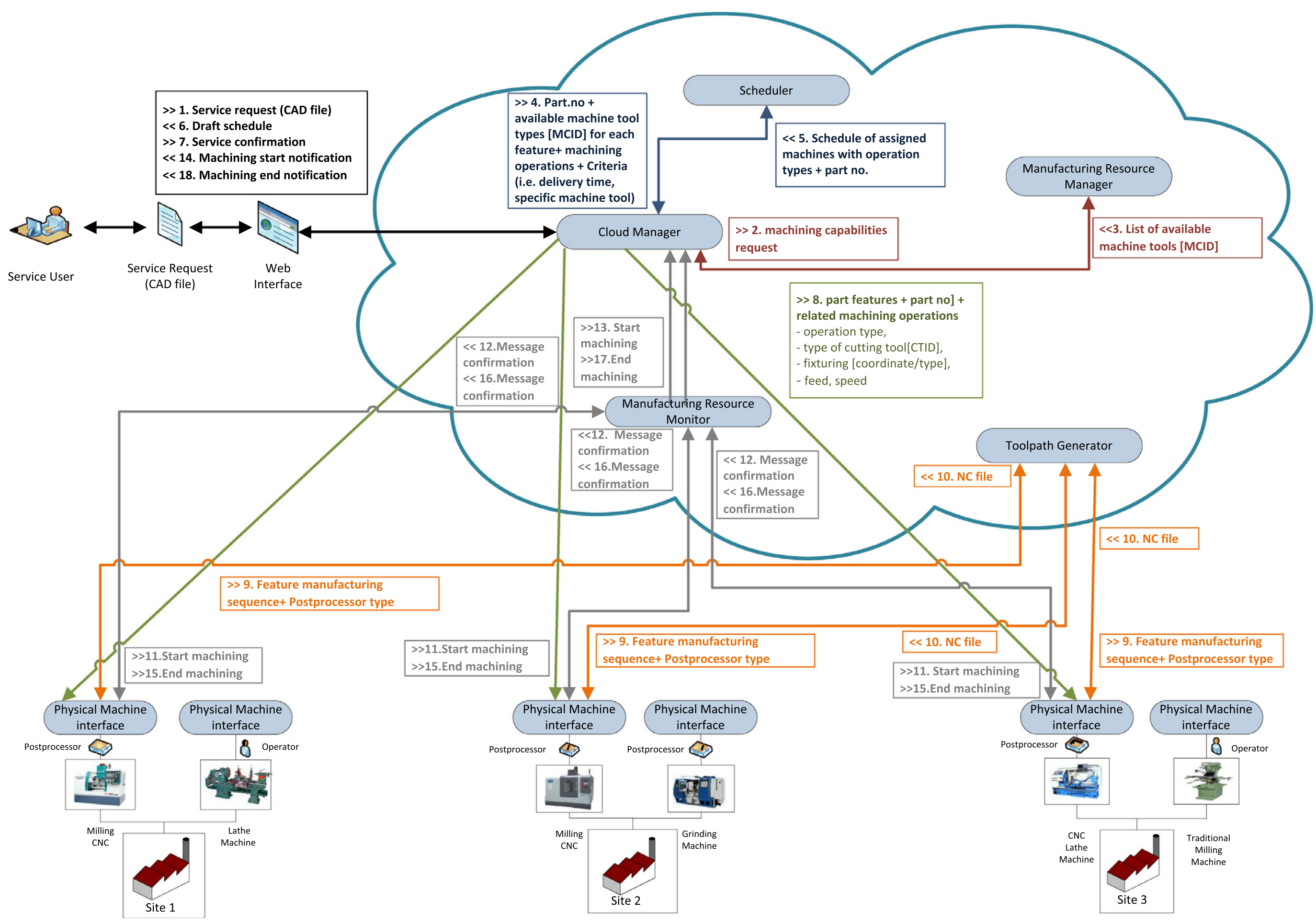


Fig. 4. C-MARS business model.

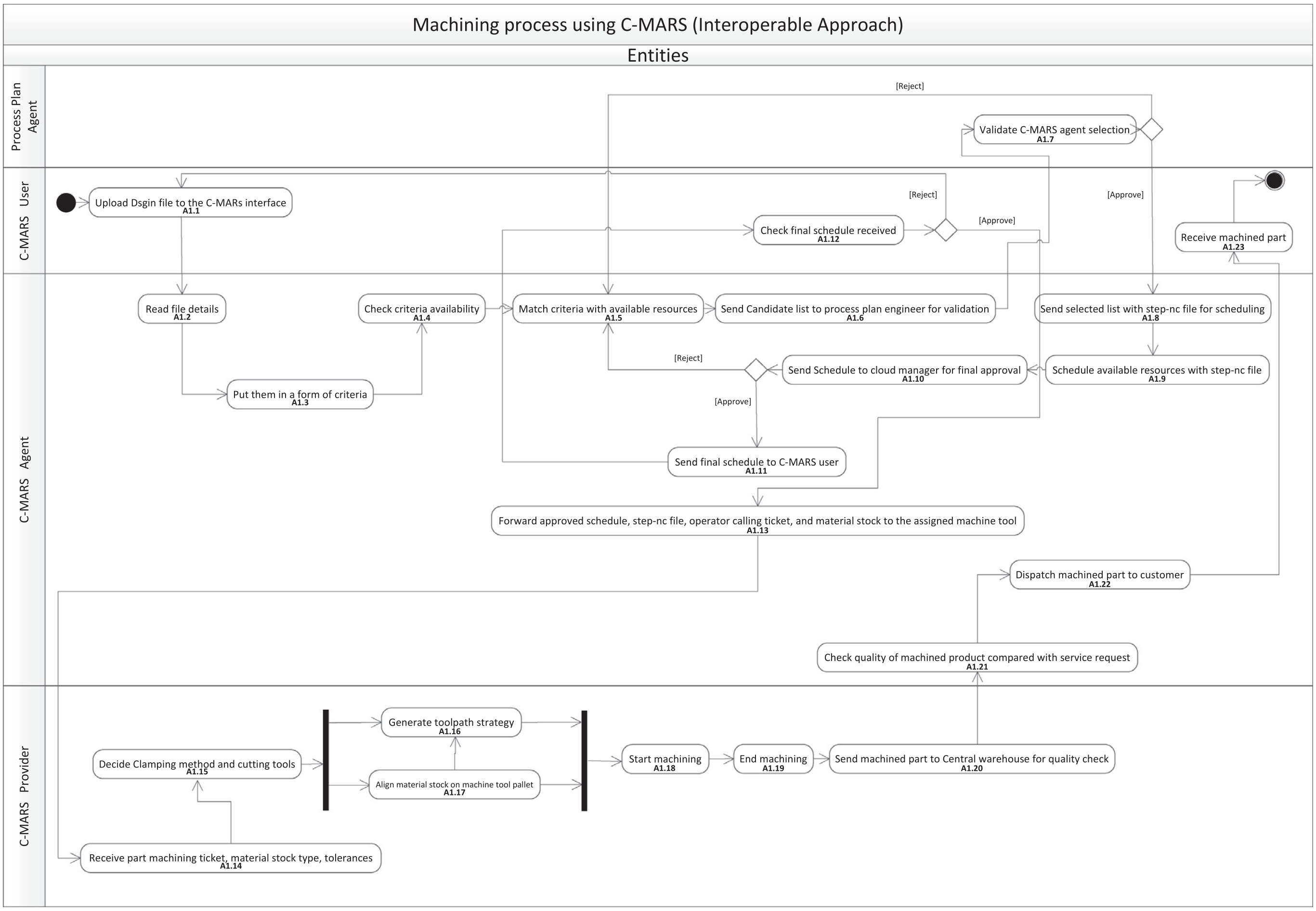


Fig. 5. C-MARS Interoperable approach.

The activities explicit description illustrated in Fig. 5 are described in Table 1 with regard to the industrially inspired case study in Section 3.2

3.4. Development of non-interoperable approach 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, the difference in the machining process occurs from the interoperable approach presented in Section 3.3.

Alternatively, for the non-interoperable approach, Fig. 6 illustrates 21 procedural machining activities, inspired by the traditional manufacturing CAx processes, that utilises the G&M codes for machining process execution. 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 the flow explicitly 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 2 illustrates the activities description involved in the machining process of NC-MARS.

4. Design of test case scenarios

The test case scenarios were designed to evaluate the C-MARS interoperable and non-interoperable activity models; C-MARS-ABM and NC-MARS-ABM. They are illustrated below along with an analysis of the results obtained.

The cloud manufacturing framework developed shown in Fig. 4 and conceptually realised in the activity models shown in Fig. 5 and Fig. 6, demonstrates the agility and competency of how an interoperable cloud manufacturing system can potentially be applied. Hence, a non-interoperable C-MARS model has been developed to clarify the difference between adopting an interoperable and non-interoperable approach for a cloud manufacturing system.

As the activity models developed for both approaches, C-MARS-ABM for the interoperable approach and NC-MARS-ABM for the 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 employing 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.

4.1. 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-

Table 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: 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 “sample1” 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: Steel stock, operator, machine tool ID.
A1.15	Sending clamping method, position, Cutting tools.
A1.16	Generate compiled 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.

interoperable cloud manufacturing. 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 an approximate representation of realistic approach of describing uncertainty in independent variables [35–37], thus meets the criteria required for C-MARS experimental representation.

In order to reduce the computational complexity and redundancy, these activities have been refined into 11 main parameters, grouped in three main categories;

- Orders: which includes parameters that resemble the ordering process set as the number of order, the number of parts in each order, time of machining required, and time required for clamping workpiece.
- Service providers: states the size of an 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 system, 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 an 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, setup of STEP-NC writer/software, Process planner approves machine tool selection.

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 3. The developed formulae are then used to calculate the total cloud cost based on sampling the random variables.

4.2. Experimental scenario development

Based on industrially inspired case scenarios the experimental model was developed utilising the Montecarlo simulation technique. As the simulation model used to conduct the case scenarios consists of 31 enabling parameters categorised within 3 main categories; orders, C-MARS service providers, and ordering scenarios. For each instance of an order received by C-MARS, the mentioned parameters have 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) in respect to cost value.

4.3. Equations formulation

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

4.3.1. Orders

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

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

$$M_{tr} \sim \mathcal{U}(5, 25) \tag{2}$$

Where:

Q_r is an integer random variable representing the quantity per order (parts) $\mathcal{U}(\alpha, \beta)$ indicates a uniform probability distribution between α and β

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)

$$A_o = \begin{cases} 1 & \text{if } R_1 > 0.65, \text{ where } R_1 \sim \mathcal{U}(0, 1) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

Where:

A_o is Assignment (binary)

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

$$R_p = A_s Q_r \tag{4}$$

$$T_{Mt} = Q_r M_{tr} A_s \tag{5}$$

Where:

R_p is required number of parts

T_{Mt} is total machining time (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:

$$C_t = \begin{cases} 1 & \text{if } 0 < M_{tr} \leqslant 5 \\ 2 & \text{if } 5 < M_{tr} \leqslant 10 \\ 3 & \text{if } 10 < M_{tr} \leqslant 15 \\ 4 & \text{otherwise} \end{cases} \tag{6}$$

Where:

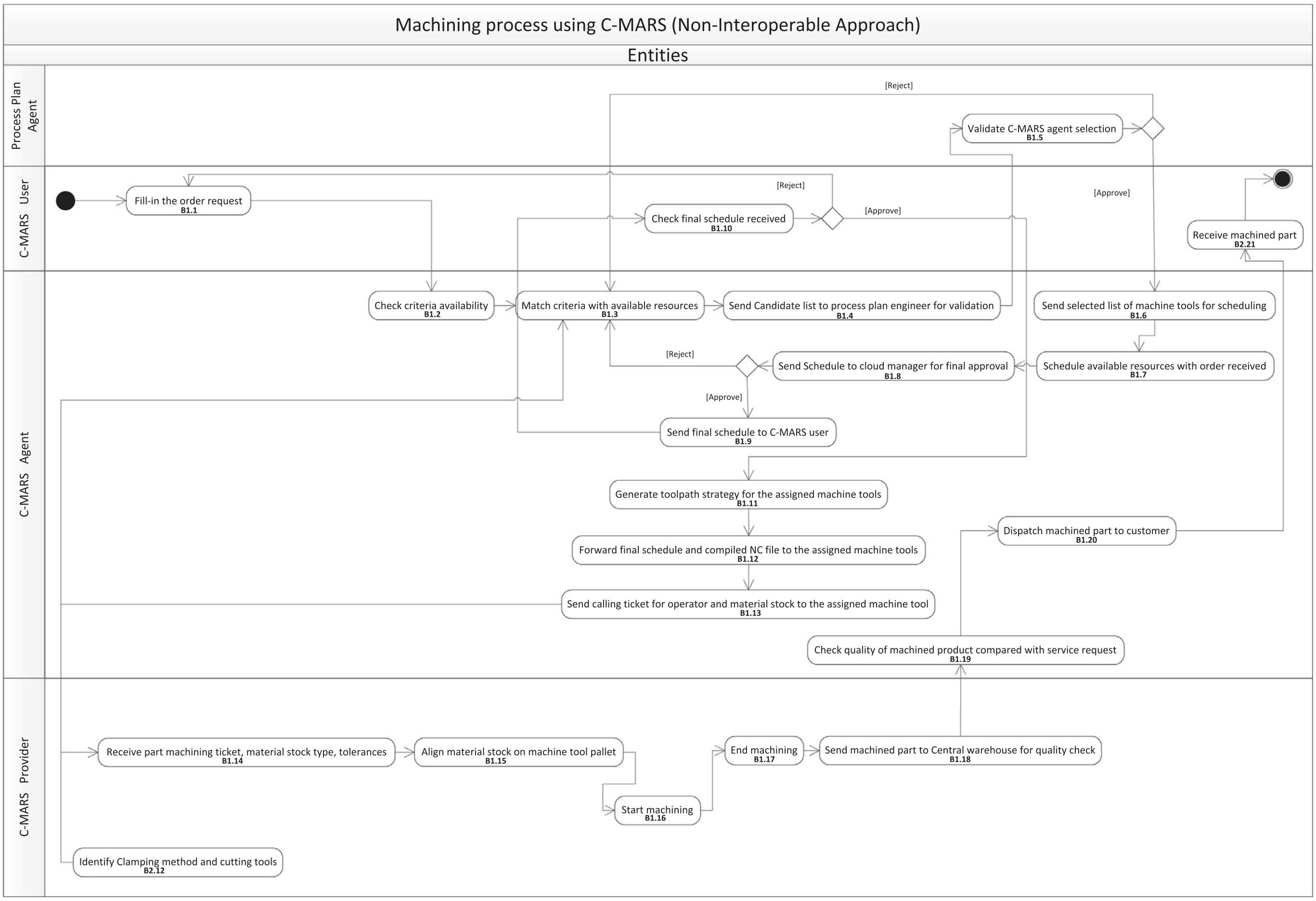


Fig. 6. NC-MARS Non-Interoperable approach.

Table 2
Activities for Machining process of sample part 1 using NC-MARS-ABM.

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 "sample1" 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.

C_t is the clamping time required (minutes)

4.3.2. C-MARS service providers

This category concerns the parameters that represent C-MARS cloud size, which is formulated in 8 equations as follows:

$$O_p = \lfloor R_2 \cdot E_p \rfloor, \text{ where } R_2 \sim \mathcal{U}(0.65,\ 0.85) \tag{7}$$

Where:

O_p is the number of operators in enterprise floor-shop.

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.

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

$$M_d = \left\lfloor \frac{R_3 \cdot O_p}{S_f} \right\rfloor, \text{ where } R_3 \sim \mathcal{U}(1.2,\ 1.4) \tag{8}$$

Where:

M_d is the number of enterprises 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.

$$E_x = \left\lfloor \frac{M_d}{R_4} \right\rfloor, \text{ where } R_4 \sim \mathcal{U}(4,\ 8) \tag{9}$$

Where:

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

Table 3
The list of parameters used in Monte Carlo simulation of CMARS-ABM.

Category	Parameter	Description
	Orders	Number of orders received every day by the cloud system
Orders	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 workholding
	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
Service providers	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

assumption that for each 4–8 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)

$$S_f = \begin{cases} 2 & \text{if } R_5 \cdot E_p > 8 \\ 1 & \text{otherwise} \end{cases} + \begin{cases} 1 & \text{if } R_6 \cdot E_p > 50 \\ 0 & \text{otherwise} \end{cases} \text{where } R_5, R_6 \sim \mathcal{U}(0, 1) \tag{10}$$

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.

$$A_C = \begin{cases} 1 & \text{if } R_7 > 0.875 \\ 0 & \text{otherwise} \end{cases} \text{where } R_7 \sim \mathcal{U}(0, 1) \tag{11}$$

Where:
A_C is Assignment of SMEs (binary)
The total machining time available (M_{ta}) is formulated in Eq. (12), based on 8 h shift per day.

$$M_{ta} = 8 \times 60 \times M_d \times S_f \times A_c \tag{12}$$

Where:
M_{ta} is the machining time available (minutes)
Consequently, Eq. (13) illustrates the total number of machine tools assigned per instance and Eq. (14) formulates the total number of CAD/CAM assigned experts per instance (E_{xa}).

$$M_{da} = M_d A_c \tag{13}$$

Where:
M_{da} is the number of machine tools assigned.

$$E_{xa} = E_x A_c \tag{14}$$

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

4.3.3. C-MARS ordering scenarios

The formulas within this category reflect the parameters that derive the cost values utilised from both interoperable (C-MARS-ABM) and non-interoperable (NC-MARS-ABM) approaches. Eq. (15) refers to the utilisation of the C-MARS machining time (U_m).

$$U_m = \frac{\sum_{i=1}^{n} M_{tr}}{\sum_{k=1}^{n} M_{ta}} \tag{15}$$

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 Eqs. (16)–(18) are formulated. As Eq. (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.

$$M_{ds} = \left\lceil \frac{\sum_{k=1}^{n} M_d \cdot U_m}{\sum_{i=1}^{n} O_r} \right\rceil \tag{16}$$

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 Eq. (17), considering different post-processor per machine tool.

$$Tp_r = M_{ds} O_r \tag{17}$$

Where:
Tp_r is the number of tool-paths required by C-MARS. Therefore, the estimated process planning time ($P_t r$) required can be formulated in Eq. (18) as follows:

$$P_t r = 60 O_r + 2 Tp_r \tag{18}$$

Where:
$P_t r$ is the process planning time required by C-MARS (minutes).
As an estimate of 60 min required by the assigned C-MARS process planners to develop the feature recognition and machining operations per order design, followed by 2 min for compiling the NC-file for machining.
In addition, the number of assigned process planners ($P_t r$) can be identified by (19), with the total number of machine tools assigned can be illustrated in Eq. (20)

$$P_p r = \frac{P_t r}{24 \times 60} \tag{19}$$

$$M_a = \sum_{k=1}^{n} M_{da} \cdot U_m \tag{20}$$

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

4.4. Overview of experimental scenarios

In this section, the generic overview and the preliminary results of the experimental case scenarios are illustrated. As a pool of 500 replicated runs were developed with each representing a 24 h operating

Table 4
SME category [38].

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

Table 5
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

cycle. Additionally, the experimental scenarios developed comprised of 4 different perspectives of SME size that are connected with the C-MARS system. The three main categories of SMEs are shown in Table 4, which represents three different perspectives of the experimental scenarios. Additionally, a fourth perspective resembles a hybrid scenario involving the 3 categories presented below.

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 5 illustrates the cost enabling values required for enabling the costing formulas for both approaches.

Hence, results can be obtained simultaneously for both interoperable and non-interoperable approaches based on the costing formulas (21) and (22): Eq. (21) shows the total cost of the 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 time.

$$Z_c = 100\overline{E_x} + 600\overline{M_{da}} + 50\overline{C_t} \tag{21}$$

Where:

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

Eq. (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.

$$Z_n c = 50\cdot\overline{P_t r} \tag{22}$$

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 Fig. 7. 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 cloud manufacturing may be financially beneficial and advisable given a specific scenario. As 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.

In particular, Fig. 7(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. Similarly, Fig. 7(b) shows that the complexity of the jobs handled by the cloud also has 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 min 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 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.

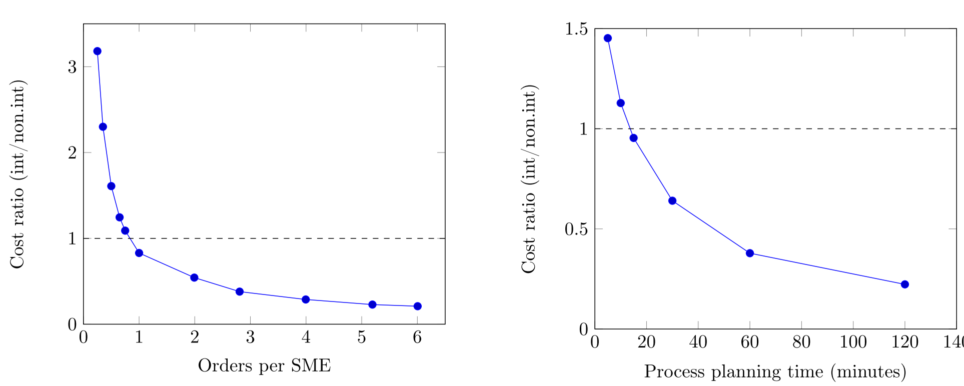
Clearly, the overall scenarios developed indicates that values of parameters as the Web-connection cost is inconsequential in relative to parameters as process planning time required and installation of STEP-NC writer. Hence, based on the results obtained the significant independent parameters that furtherly studied are: (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 order to identify the significant parameters to perform a rigorous decision-making process of the feasible deployment approach for cloud manufacturing system.

5. Analysis and evaluation of results

This section explains the analysis of results obtained from the simulation test case scenarios. As the full-factorial design experiment has been 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 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 (cost ratio).

5.1. Full factorial design

A three-level 3^k factorial design has been utilised to model the



(a) (b)

Fig. 7. Preliminary analysis of simulation results.

Table 6
Parameters value.

Category	Variable	Name	Level 1	Level 2	Level 3
	X1	Number of orders	100	1000	2000
Orders	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

interactions among the allocated significant parameters. The 3 levels of level 1, level 2 and level 3 in Table 6 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.

The setting of these values is 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 can acquire. The number of employees reflects the size of SMEs deployed within the C-MARS system, whether its micro, small or medium SME. 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 min) and ending with highly complex part features (2000 min).

Based on the estimated values of the parameters, a 3-level full factorial design has been developed resulting in 243 treatment combinations. Table 7 illustrates the first 10 scenario treatments (runs), The five significant parameters (X1–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.

For instance, in the first run, the cost ratio response is 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 0.39121 which emphasise that interoperable is much more favourable than the non-interoperable deployment approach. In addition, the response factor has been used for the analysis of variance in order to identify specifically the most significant parameters that deflect the response ratio.

5.2. 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 deflection 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.

Table 8
ANOVA report.

Source	SumSq.	d.f.	Mean Sq.	F	Prob > F	Contribution
X1	3154.5	2	1577.27	859.69	0	12.35600331
X2	10.9	2	5.47	2.98	0.0547	0.042694702
X3	9.4	2	4.69	2.56	0.0822	0.036819284
X4	1735.4	2	867.68	472.93	0	6.79746652
X5	4733.7	2	2366.85	1290.06	0	18.541643
X1*X2	9.9	4	2.48	1.35	0.2563	0.038777756
X1*X3	14.1	4	3.53	1.92	0.1112	0.055228926
X1*X4	2162.6	4	540.64	294.68	0	8.470785465
X1*X5	5935.9	4	1483.96	808.84	0	23.2505944
X2*X3	12.6	4	3.15	1.72	0.151	0.049353508
X2*X4	6.3	4	1.58	0.86	0.4884	0.024676754
X2*X5	21.4	4	5.36	2.92	0.0243	0.083822625
X3*X4	7	4	1.76	0.96	0.4338	0.027418616
X3*X5	17.9	4	4.48	2.44	0.0509	0.070113317
X4*X5	3267.5	4	816.87	445.24	0	12.7986181
X1*X2*X3	17.9	8	2.24	1.22	0.293	0.070113317
X1*X2*X4	8.1	8	1.01	0.55	0.8141	0.031727255
X1*X2*X5	19.5	8	2.44	1.33	0.2354	0.076380429
X1*X3*X4	11.8	8	1.48	0.8	0.5996	0.046219952
X1*X3*X5	26.8	8	3.35	1.82	0.0798	0.104974129
X1*X4*X5	4071.8	8	508.97	277.42	0	15.94901704
X2*X3*X4	16.3	8	2.04	1.11	0.3607	0.063846205
X2*X3*X5	25.6	8	3.2	1.75	0.0955	0.100273794
X2*X4*X5	14.3	8	1.79	0.98	0.458	0.056012315
X3*X4*X5	13.2	8	1.66	0.9	0.5171	0.051703675
Error	205.5	112	1.83			
Total	25530.1	242				

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 8 illustrates the computed F ratio and *P*-value of the given parameters indicate the impact proportion of each parameter and their relative interactions.

As the *F* ratio is close to 1, refers to a null hypothesis which indicates no significant difference in the given parameter as 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 (2112) 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.

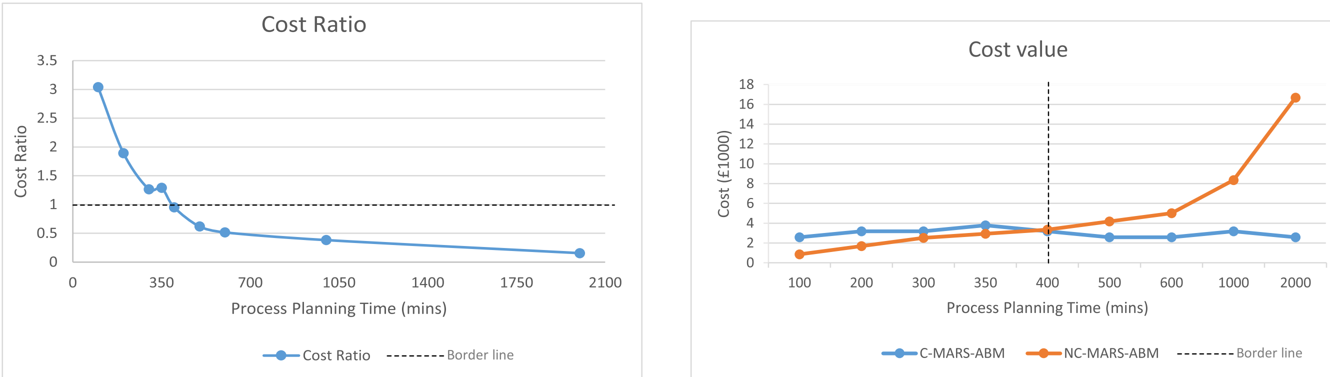
Further, the contribution percentage is calculated based on the sum of square generated in the ANOVA table in order to explicitly identify the rank of significance for each of the determined parameters; X5 (18%), X1 (12.35%) and X4 (6.79%). Finally, the obtained ANOVA results have been utilised as a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

5.3. Analysis of results

This section illustrates the effect of the identified significant

Table 7
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	3.33333
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	32666.6667	83500	0.0391218
7	100	1000	20	5	2000	5833.3333	1668333.33	0.034965
8	1000	50	90	5	2000	32666.6667	1668333.33	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



(a) Level 1 Cost ratio

(b) Level 1 Cost value

Fig. 8. Level1 instance.

parameters namely; process planning time (X5) and the number of orders (X1) to the cost ratio of deployment. Based on the three-level full factorial design developed in Section 5.1, three sets of scenarios have been outlined and discussed in order to assert the deflection (change) point of interoperable to non-interoperable deployment approach.

5.3.1. Scenario level 1

The first explored scenario assumes the lowest level value (level 1) for the least effective parameters in Table 6: average quantity per order (X2), time for machining (X3), and number of employees (X4). Fig. 8 shows the successive change of the most significant parameter's value obtained from ANOVA namely; number of orders against 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 increases above 400 min per day the non-interoperable is favourable in terms of cost.

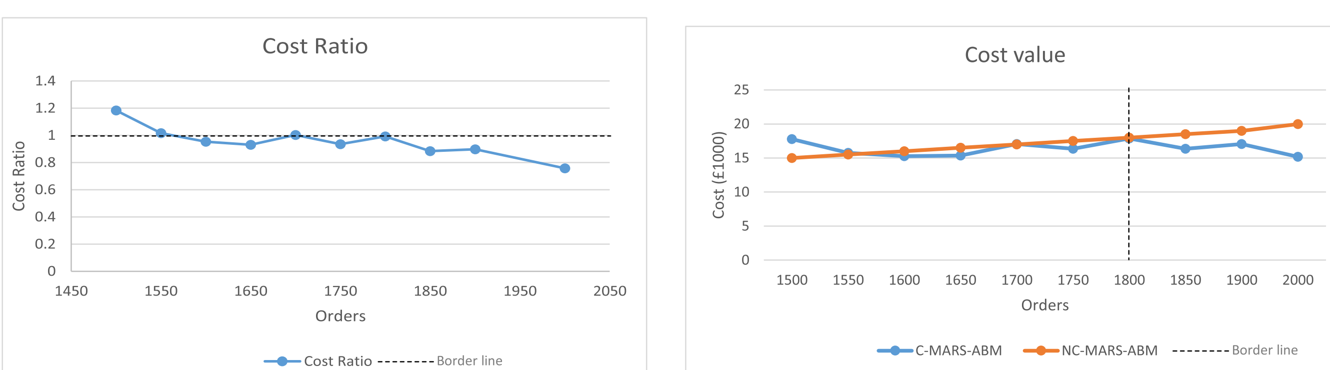
5.3.2. Scenario level 2

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 min of process planning time and number of orders beyond 1700 orders per day, as Fig. 9 shows that at Scenario run 7 (number of orders = 1800) the C-MARS-ABM is favoured over the NC-MARS-ABM approach. Similarly, As shown in Fig. 10 NC-MARS-ABM is favourable when the process planning time is less than 250 min with 100 orders per day, as the deflection occurs at scenario runs 4 (process planning time = 200 min) and 6 (process planning time = 275 min).

5.3.3. 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:

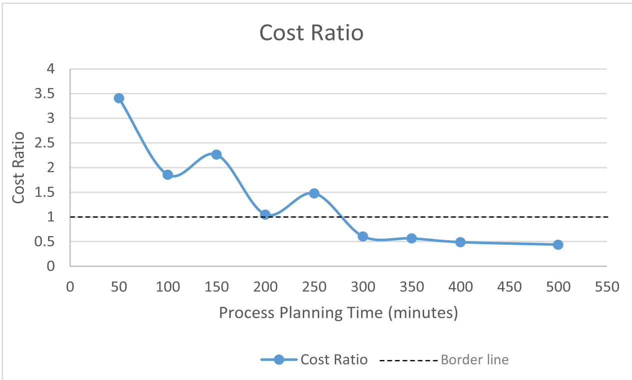
(1) Process planning time below 700 min and number of orders around 100 orders per day, which deflects at scenario run 7, as shown in Fig. 11.
(2) Process planning time below 100 min and orders are around 1000, As shown in Fig. 12, there are multiple deflection occurring at scenario runs 3 (process planning time = 60 min) and 5 (process planning time = 80 min), which stabilize at scenario run 7 (process planning time = 100 min) and favour the interoperable approach C-MARS-ABM.
(3) Process planning time above 50 min compared to 2000 orders per day, As shown in Fig. 13 which defines the turning points from non-interoperable to interoperable approach at scenario runs between 3 and 5.
(4) Finally, when the process planning time is 500 min and orders are below 150 per day, the non-interoperable activity-based model (NC-MARS-ABM)is more feasible in respect to cost, as Fig. 14 shows the deflection occurrence is between scenario runs 2 and 3.



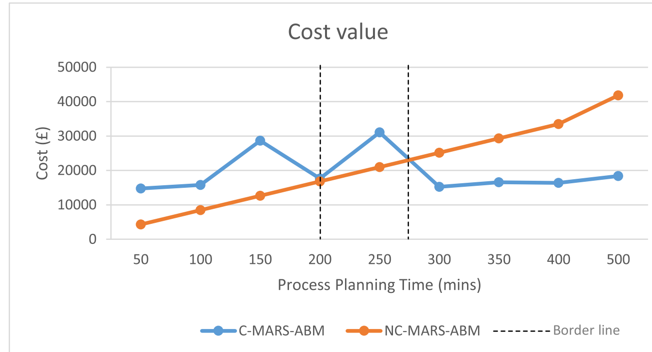
(a) Level 2 Cost ratio

(b) Level 2 Cost value

Fig. 9. Level 2 number of orders instance.



(a) Level 2 Cost ratio



(b) Level 2 Cost value

Fig. 10. Level 2 process planning time instance.

5.3.4. 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 Eqs. (21) and (22), the interoperable to non-interoperable cost ratio C_r shown below can be used a response factor for indicating the feasible deployment approach.

$$C_r = \frac{Z_c}{Z_n c} \tag{23}$$

Where:

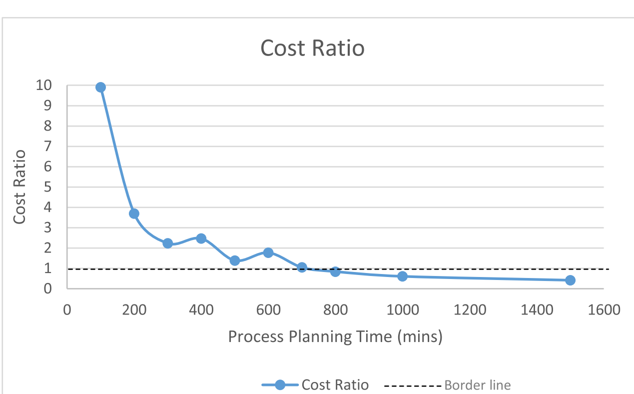
C_r is the cost ratio of deployment approaches.

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.

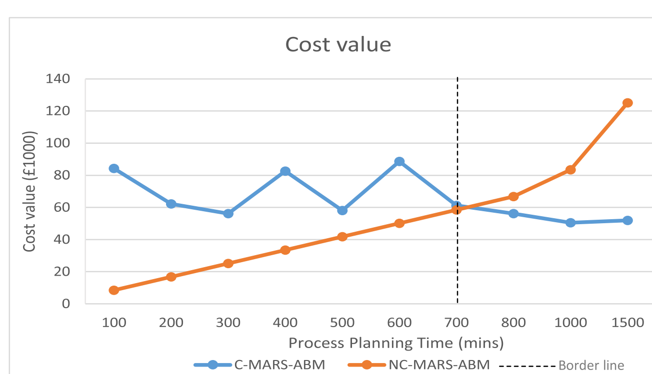
6. Discussion and conclusions

In the current state, there is redundant data representation and description of manufacturing resources and capabilities due to proprietary semantics and data formats. Many 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 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 current manufacturing information 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. Cloud manufacturing can have a substantial impact on manufacturing, as cloud integration hardware and software resources improve manufacturing resource sharing and the product development process. Furthermore the 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 the Cloud Manufacturing system.

Furthermore and most importantly, a logical and experimentation is needed to develop good practice for validation and assessment, in order to enhance the integrity of cloud manufacturing by developing practical frameworks. The following main conclusions can be drawn from the

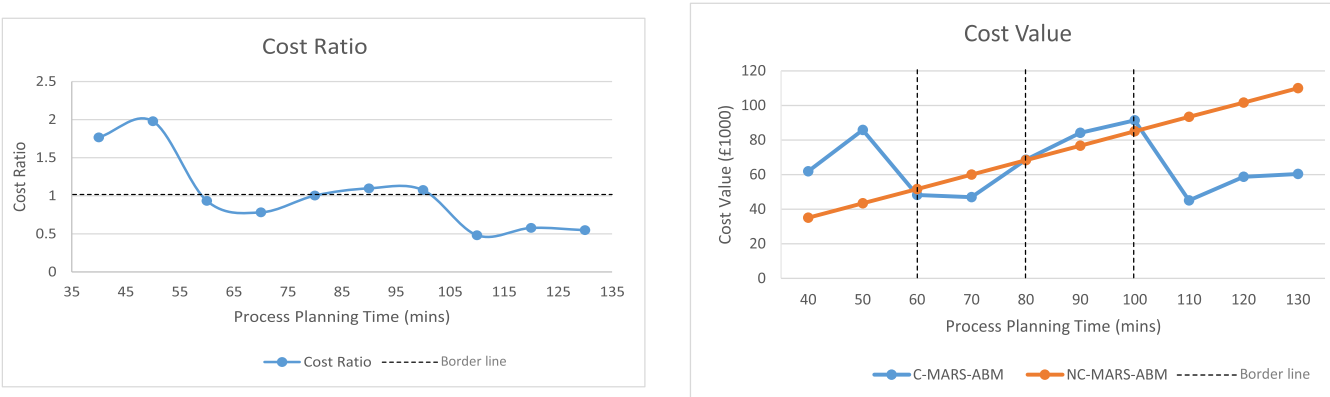


(a) Level 3 Cost ratio



(b) Level 3 Cost value

Fig. 11. Level 3 instance view 1.



(a) Level 3 Cost ratio

(b) Level 3 Cost value

Fig. 12. Level 3 instance view 2.

results obtained:

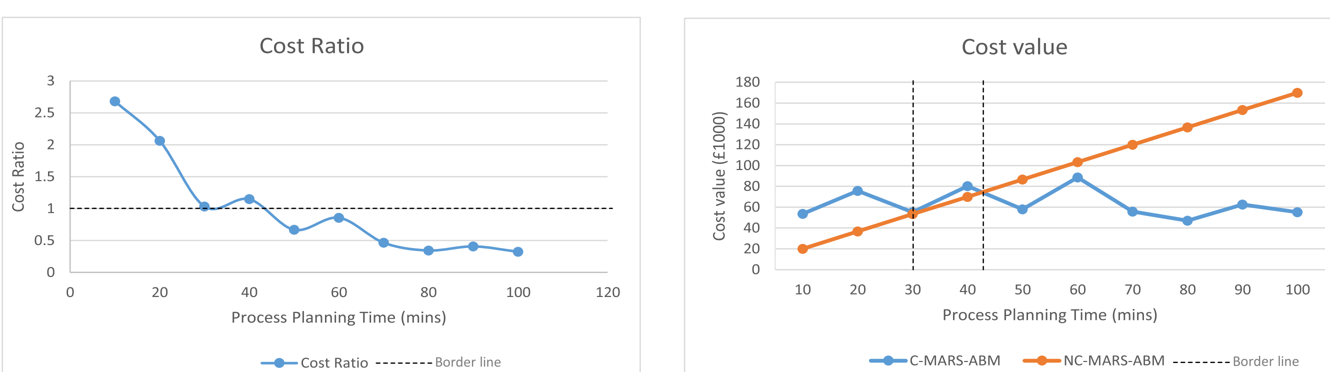
- The implementation of cloud manufacturing systems in industry is hampered by a lack of formal models, methods and unified standards for the representation, seamless integration and interoperability of distributed manufacturing resources across an enterprise (vertical integration) and beyond (horizontal integration).
- Interoperability between manufacturing resources in cloud manufacturing systems can be facilitated through a theoretical framework (C-MARS) and the adoption of STEP-NC as a standardised communication language.
- 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 onsite 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 work conducted in this paper 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 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 an 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.

The work proposed in this paper was inspired by the aspect of assessment for the feasible deployment approach of cloud manufacturing, as a lot of redundant efforts can be avoided and rigorous evaluation of the potential impact of the cloud deployment approach can be found. Based on the research conducted throughout this project.

6.1. Limitations of C-MARS framework

Whilst the author took reasonable care to perform the analysis in as robust a manner as possible, due to the numerous variables that affect the adoption of cloud manufacturing, authors have focused exclusively on the cost of the machining process to reduce complexity and prove novelty. A number of limitations that could have possible effects on the results in practice have been identified:

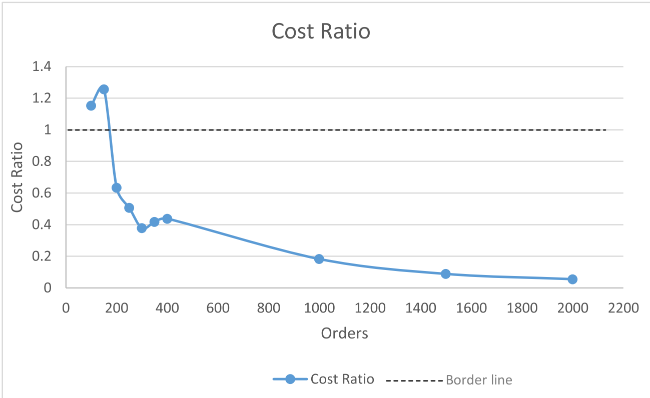
- The developed simulation scenarios assumed the continuous availability of the deployed machine tools and did not consider machine



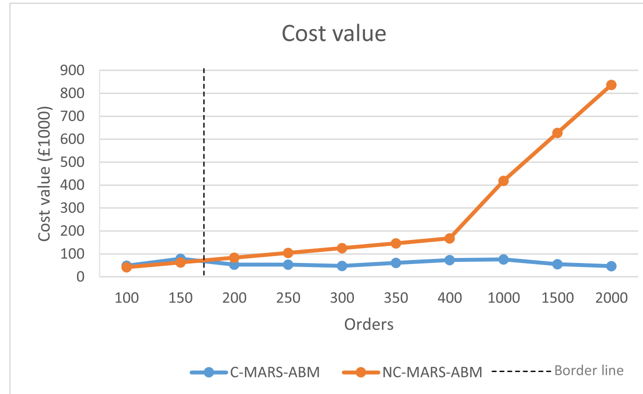
(a) Level 3 Cost ratio

(b) Level 3 Cost value

Fig. 13. Level 3 instance view 3.



(a) Level 3 Cost ratio



(b) Level 3 Cost value

Fig. 14. Level 3 instance view 4.

failures or quality issues and part defects.

- The geographical location of machine tools was not considered in regards to assigning a specific machine tool based on location.
- The Design of experiments in assessing the C-MARS-ABM did not consider the unit cost of machine tools.
- The tool life contributing to cost and quality was not included in the assessment cost criteria.
- Changes/degradation in machine capability was not considered in the monitoring of machining process, only the start and end of the machining service.
- Operator skill level was not considered in the research scope, as the hourly wage was fixed for all C-MARS operators.
- 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)
- Logistical issues and locations of end users were not illustrated in both activity models C-MARS-ABM and NC-MARs-ABM.

6.2. Future work

As for future work, the involvement of other manufacturing tasks such as assembly lines, material handling and additive manufacturing within C-MARS is a necessity along the development of prototype software that encompasses the implementation of the theoretical framework model, as the model main components (i.e cloud manager component) will be explicitly expanded to a low level aspect. Furthermore, the compulsory components (i.e tool path generator, manufacturing resource model,etc) will be utilised, in order to develop and demonstrate a verified C-MARS prototype software. Thus, provide value to the broader production engineering community by a) supporting the strategic decision making process in the industry, and b) enabling a faster cloud manufacturing technology transfer to industry.

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.
- The 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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