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# A cloud service control approach for distributed and adaptive equipment control in cloud environments

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## Abstract

A developing trend within the manufacturing shop-floor domain is the move of manufacturing activities into cloud environments, as scalable, on-demand and pay-per-usage cloud services. This will radically change traditional manufacturing, as borderless, distributed and collaborative manufacturing missions between volatile, best suited groups of partners will impose a multitude of advantages. The evolving Cloud Manufacturing (CM) paradigm will enable this new manufacturing concept, and on-going research has described many of its anticipated core virtues and enabling technologies. However, a major key enabling technology within CM which has not yet been fully addressed is the dynamic and distributed planning, control and execution of scattered and cooperating shop-floor equipment, completing joint manufacturing tasks.

In this paper, the technological perspective for a cloud service-based control approach is described, and how it could be implemented. Existing manufacturing resources, such as soft, hard and capability resources, can be packaged as cloud services, and combined to create different levels of equipment or manufacturing control, ranging from low-level control of single machines or devices (e.g. Robot Control-as-a-Service), up to the execution of high level multi-process manufacturing tasks (e.g. Manufacturing-as-a-Service). A multi-layer control approach, featuring adaptive decision-making for both global and local environmental conditions, is proposed. This is realized through the use of a network of intelligent and distributable decision modules such as event-driven Function Blocks, enabling run-time manufacturing activities to be performed according to actual manufacturing conditions. The control system's integration to the CM cloud service management functionality is also described.

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*Keywords:* Adaptive control; Adaptive manufacturing; Cloud manufacturing

## 1. Introduction

The on-going manufacturing trend of focusing on solely performing core manufacturing activities, relying on company specific competences, while out-sourcing related and supporting activities, is all in line with the abilities of the evolving Cloud Manufacturing (CM) paradigm. For some companies, critical manufacturing resources are limited and too costly, while other companies may possess spare manufacturing capacity, knowledge and competence. To lower the overall cost for manufacturing, companies may provide and share their resources to increase the resource utilization rate, with companies with lack and need of these resources. Seamless sharing of a multitude of distributed manufacturing resources covering the complete product development life-cycle is a CM key feature, which will allow cloud users to retrieve manufacturing services on-demand on the Internet. Inheriting Cloud Computing (CC) properties such as: on-demand access to distributed resources, scalable applications to better match requested usage, and a cost-effective and transparent pay-per-usage pricing model, will facilitate collaborative manufacturing in borderless joint ventures between geographically distributed and cooperating shop-floors [1-3]. As manufacturing orientation is also changing, going from mass production to mass customization, the complexity of realizing adaptive control for such distributed and collaborative real-time environments is dramatically increased. The level of uncertainty will become significantly

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higher, and changes and unforeseen events may be inflicted by all participating companies' internal and external variations. Therefore, a prominent property for a CM control structure is the dynamic coordination and distribution of decision-making to both global and local environment instances [4]. This would enable adaptive system control as adjustments to any changes, not least shop-floor run-time variations, would be possible.

The focus of this work is adaptive control of distributed manufacturing equipment in a CM environment, using a cloud service-based approach. This paper presents how cloud services can be used and is described for robotic operations, as Robot Control-as-a-Service (RCaaS). The presented control concept is however not restricted to robots only, but is also applicable to other types of computer controlled and networked manufacturing equipment.

The paper is arranged as follows: A review of the status and definitions of CM, and the drivers and background for its formation is presented in section 2. Section 3 describes the concept of adaptive equipment control through the combination of event-driven Function Blocks (FBs) and Manufacturing Features (MfgFs). In Section 4 the concept of RCaaS is explained. Section 5 presents the authors' conclusions, followed by acknowledgements and references.

## 2. Cloud Manufacturing

The last couple of years, research focused on resource-sharing and collaborative manufacturing missions for the complete product development lifecycle has increased dramatically. Advances within modern communication and information technology (e.g. CC, Internet of Things, service orientation, Semantic Web, etc.) have opened up new opportunities, making possible service and information driven manufacturing. The concept of CM has become an internationally established and steadily increasing research topic and already made some progress, and it is clear that CM has the ability to transform the manufacturing industry as we know it today.

Especially SME's will benefit from CM, as their competitiveness often solely relies on their own capabilities and resources [5]. Insufficient resources, small collaborating partner networks and large investments often hamper their ability to expand and to successfully handle critical manufacturing tasks, e.g.: increasingly complex product designs, matching manufacturing orders with resource capability and capacity, lack of a resource and capability sharing mode, high sub-contracting costs, and expensive and complex IT systems. CM provided services for coordinated collaboration and scalable and economical resource sharing could solve this, and the advantages of economy-of-scale could be in reach also for SMEs. Small companies could take advantage of resources that used to be too expensive or complex, as costly and rapidly depreciating equipment or IT-system investments could be reduced by service subscriptions and pay-as-you-go solutions. Groups of companies could dynamically team up to create more competitive, virtual enterprises, and spare manufacturing capacity could be made available for others to use.

Many research initiatives focus on describing the CM concept, architectures and platforms for its implementation, and the description of resources and services and their matching and composition [6-10]. No international CM definition exists, but there is a consensus amongst researchers and members of the manufacturing community that the core property of the CM concept is the principle of Manufacturing-as-a-Service (MaaS). This should be realized through an operator run CM platform, facilitating the sharing of distributed manufacturing resources as configurable services, between resource providers and resource consumers. Different descriptions of the classification of a variety of heterogeneous manufacturing resources which can be provisioned and consumed in CM as services exist [11,12]. These are typically divided into soft and hard manufacturing resources, and manufacturing capabilities. Soft resources include software (applications for analysis, product design, simulation, etc.) knowledge (models, standards, expertise, etc.) and personnel (operators, engineers, project teams, etc.). Hard resources comprise physical equipment required for the production process, such as manufacturing equipment, computers, servers, networks, raw materials, etc. Manufacturing capabilities represent dynamic and intangible recourses representing abilities to perform specific tasks (e.g. performing product designs, machining, assembly, simulations, maintenance, etc.), through the intelligent use of hard and/or soft resources. Resource providers can thus offer services based on soft, hard or capability resources, and any combinations of these.

To instantiate services, resources are virtualized and encapsulated, in one of three fundamentally different mapping relationships [1,7,11]. When only one manufacturing requirement matches the functionality or capability of one resource, there is a One-to-One resource-service mapping. If a resource holds multiple functions or capabilities, which each match different unique manufacturing requirements independently, a One-to-Many mapping is established. If a combination of resources is required to match a manufacturing requirement, there is a Many-to-One mapping. Combining different services from different providers into a hierarchical set of services is a fundamental CM property, in which new and higher levels of manufacturing functionality can be realized. The best match and mix of resources according to the consumers' specific performance requirements, such as cost, quality, time, sustainability, resource localization, security, etc. can be used. Resources can be invoked no matter of their physical localization, supporting concepts like DAMA (Design Anywhere, Manufacture Anywhere) [13].

Within the CM platform, services should be effectively organized for consumers to buy and use at their own discretion. Services could then support the fulfilment of varying manufacturing tasks, ranging from anything between complex worldwide collaborative manufacturing missions to a simple one-off job operation. As both global and local changes in demand, parameters and conditions may affect the result of a manufacturing situation, the CM platform needs to bring sensing, monitoring, planning and control together for the complete working environment. A critical objective within

CM is the coordinated and detailed planning and execution of discrete and scattered manufacturing operations in collaborative and networked manufacturing missions, in which variations will necessitate changed process plans, as well as the re-programming of manufacturing equipment. Traditional CAPP (Computer Aided Process Planning) tools are not suited for CM, due to their centralized decision making, static system structure and off-line data handling [14]. Their ability to adapt pre-made process plans to shop-floor run-time variations is therefore weak, as they are unable to cope with unpredictable events [6]. To be able to exercise control in CM, intelligent interaction between collaborating resources must exist. The real-time information of resources' could then support intelligent decisions for service composition, coordination and execution control. However, dynamic and adaptive control of cloud distributed manufacturing equipment has not yet attracted so much attention, but will be an important research issue for the successful realization of CM [11,15].

## 3. Adaptive equipment control

Traditional control of manufacturing equipment is rigid regarding structure, content, and adaptability to changes, as it usually relies on controllers executing pre-determined control programs. Since manufacturing in a CM environment often involves many cooperating resource providers, the number of variations and unpredictable events that could disturb and inflict negative impacts is increased. Therefore, an adaptive control approach is required that can generate correct control instructions in real-time, and be distributed to different parts of the system. By combining event-driven IEC61499 FBs and MfgFs, an adaptive control system which can perform dynamic decision-making can be created, capable of instantly generating control in response to prevailing requirements and conditions.

### 3.1. IEC 61499 Event-driven Function Blocks

The IEC 61499 standard [16] defines a component-oriented approach for distributed control systems. Event-driven FBs with different applications and functionality are described as software components which are distributable and able to encapsulate intelligence. As such, they can be used in a networked control system for distributed and decentralized monitoring and control. The fundamental parts of the FB are an Execution Control Chart (ECC) which controls the scheduling and execution, and algorithms. The functionality of the FB is programmed into its algorithms, which will be triggered to execute by arriving input events. The algorithms will then read and use input data for creating new output data. Using this event-driven approach, output data can be defined as equipment control code, generated in real-time according to the manufacturing situation. The FB then acts as a small decision-making module. A variety of applications using IEC 61499 FBs has been reported. The majority of these have been focusing on low-level device control [17].

### 3.2. Manufacturing Features

Features is used in manufacturing and product design for identifying the relations between product features and the manufacturing operations required for creating these. These relations can be used for automating manufacturing tasks, in which features and operations are mapped to each other. Basic manufacturing operations necessary for the creation of varying product features can be categorized and stored for re-use in a feature library. By selecting and combining amongst these features, discrete manufacturing operations or complete high-level applications can be easily created. In "Design by Features" [18], product designs are defined by combining manufacturing features for producing the product. The opposite process is performed in "Feature Recognition" [19], in which existing product designs are examined and evaluated for identifying the necessary manufacturing operations for creating the product. Different manufacturing domains can be defined by different categories of manufacturing features. Assembly Features (AFs) can be used for assembly tasks [20] and Machining features (MFs) for machining tasks [21,22]. In a complex manufacturing task, a sequence of different basic operations is necessary to complete the task. All these basic operations can be identified and mapped to different MfgFs.

### 3.3. Adaptive Control

To implement the concept of MfgFs for manufacturing applications, an approach for planning and execution of MfgFs is necessary. By combining the distributed run-time decision-making properties of event-driven FBs with the manufacturing know-how of MfgFs, the adaptive manufacturing control unit MfgF-FB can be created. The MfgFs provide the manufacturing "know-how" and the FBs provide encapsulating of functionality through algorithms, data transfer, and event-driven process and execution control by the ECC. This approach reduces the creation of complete manufacturing applications to the selection and combination of a group of MfgF-FBs. Complex manufacturing applications could then be controlled by combining different MfgF-FBs into a control network, see Fig. 1.

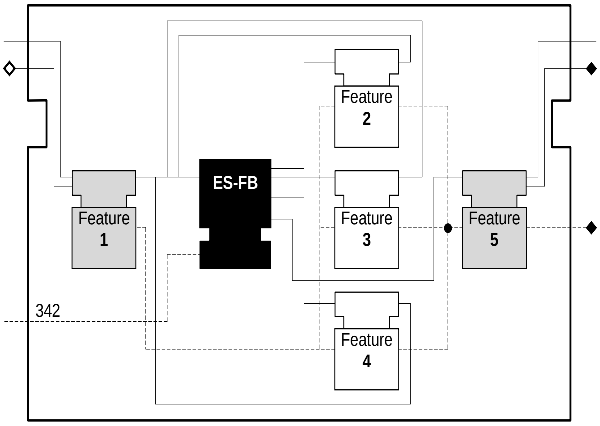

Fig. 1. Combining MfgF-FBs for creating manufacturing control application.

However, the control systems adaptability with this MfgF-FB approach is not unrestricted. It mainly depends on available real-time information which may be accessed and processed to generate decisions, and also the sophistication of the construction of the FB ECC and the algorithms. (In this research, adaptivity is limited to the manufacturing system's ability to adapt to changes made possible by the functionality of the control system. Physical reconfigurations or different hardware architectural perspectives of manufacturing equipment are not considered.)

Combining IEC 61499 FBs with MfgFs for realizing adaptive control has been successfully demonstrated for some different manufacturing scenarios [21-25].

## 4. Equipment Control-as-a-Service

Automatic decomposition of requested manufacturing tasks and composition of services to complete this task is one of the most attractive properties of CM. The manufacturing requests from cloud consumers are then analyzed and divided into sub-tasks, and then distributed to matching manufacturing resources, for a coordinated manufacturing completion. Administering all service activities is performed by the CM platform Cloud Service Management (CSM) module. Dynamically coordinating manufacturing planning and execution requires constant monitoring of run-time conditions and scheduled activities of all resources, which must all be accessible on-line. Cloud service interaction through the CSM is schematically depicted in a flowchart in Fig. 2.

The distributable nature of the IEC 61499 standard is important for its application in networked cloud environments. Networked MfgF-FBs can be integrated in a CM platform for planning and execution of manufacturing tasks as the standard defines the interaction and communication between distributed FBs. Amongst a multitude of possible cloud control scenarios for a manufacturing request, two extreme alternative solutions

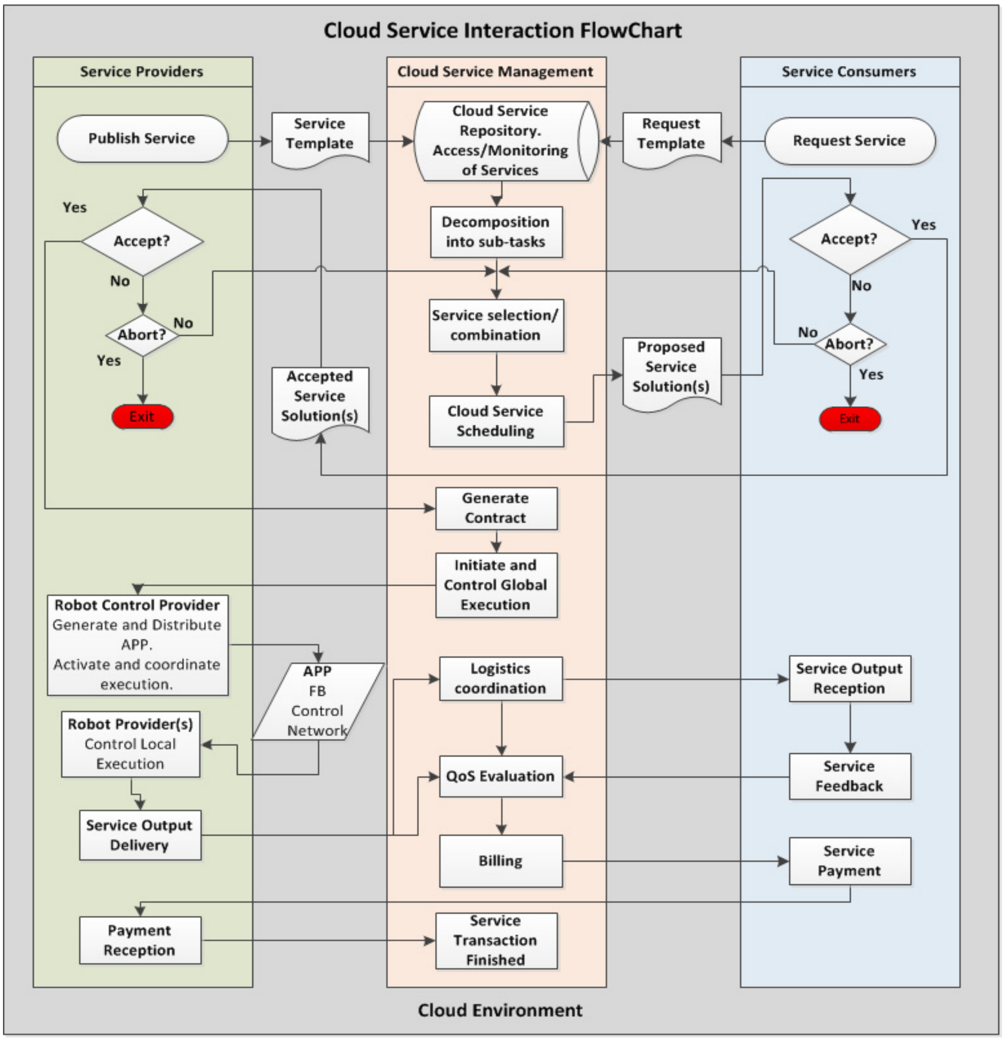

Fig. 2. Cloud Service Interaction Flowchart

exist: a higher level cloud service, for which one provider performs all necessary manufacturing tasks (e.g. a provider offering Manufacturing/Assembly-as-a-Service in a resource-service Many-to-One mapping), and a lower level for which a combination of providers each provide low-level services to collaboratively complete the high-level task (e.g. RCaaS together with Robot Software-as-a-Service (RSaaS) and Robot Hardware-as-a-Service (RHaaS), a combination of many One-to-One mappings). (RHaaS means that a provider offers the use of a robot, which could be provided by dedicated manufacturing centers or by providers sharing spare equipment capacity.)

The authors have chosen to focus on the lower levels alternative in this work, to emphasize the resource sharing and collaborative focus of CM. In the following description of the cloud service control approach, it is assumed that a robot control provider supplies the robot control capability as RCaaS, and one or many robot providers supply the robot hardware as RHaaS.

RCaaS contains 5 cooperating modules, each performing specific tasks (Fig. 3):

- Supervisory Cloud Planning (SCP), (in the cloud)
- Feature Id and Sequencing (FIS), (in the cloud)
- AF-FB Library (AFL)(in the cloud)
- Cloud Robotics Control (CRC), (in the cloud)
- Local Operation Planning (LOP), (local, at the controlled resource)

The procedure is initiated by a task request from a resource consumer. This is analysed by the CSM, which selects and triggers the necessary services. Within RCaaS, a sequence of activities is performed, executed in a two-level FB-enabled planning procedure for the generation of an AF-FB based control structure. In this process generic and robot-specific information is separated into Supervisory Cloud Planning (SCP) and Local Operation Planning (LOP), to enable efficient decision making. The complete control procedure includes the following activities:

1. The SCP is performed once for the received assembly task:

- Unique assembly operations are identified and sequenced by the FIS module.
- By using pre-defined AF-FBs from the AFL module the SCP creates an Assembly Process Plan (APP) by mapping sequenced operations into a network of AF-FBs.

The APP only contains necessary AF-FBs and their critical assembly sequence. It is not tied to a specific robot, and can be reused and ported to different alternative robots, making it

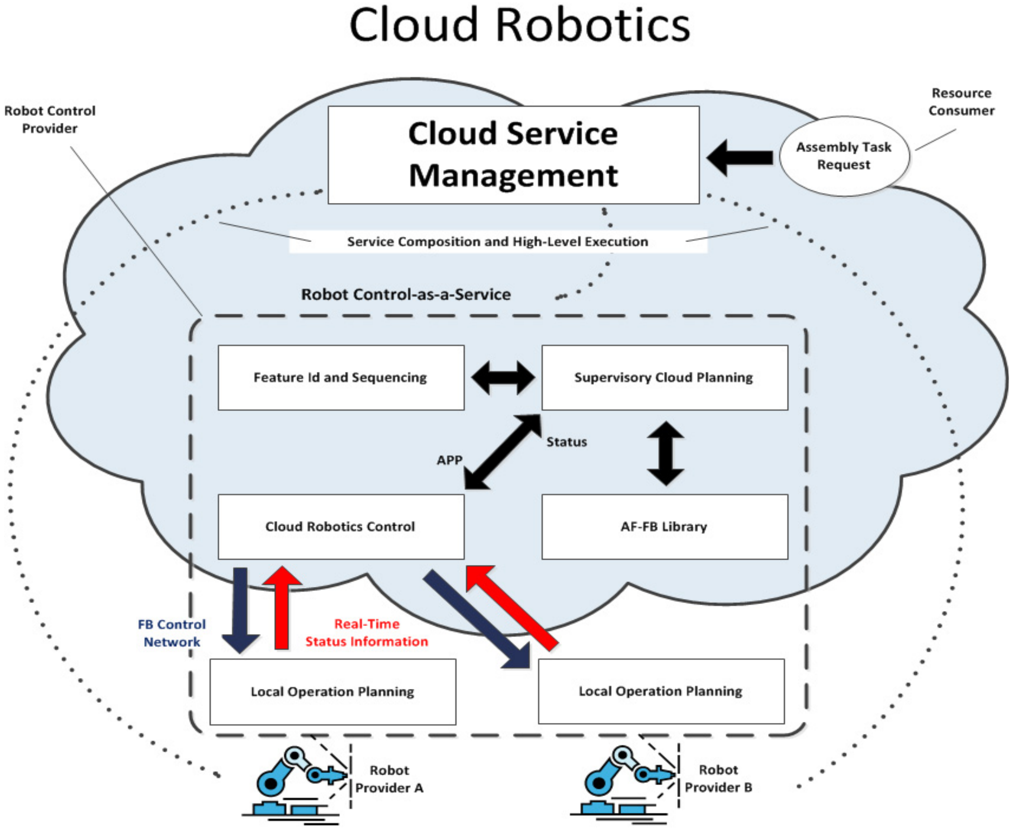

Fig. 3. Robot Control-as-a-Service within CM environment

generic. (It is assumed that the "Feature Id and Sequencing" is performed and input to the SCP module. This is a process beyond the scope of this research).

2. When the CRC receives the APP from the SCP, it has the following responsibilities:

- Distribute generated FB control structures to the robot providers.
- Coordinate AF-FBs to realize operation planning locally at each robot provider.
- Coordinate AF-FBs between different providers.
- Dynamic scheduling of included resources and activities.
- Perform FB execution control (start, stop, pause, resume, etc.).
- Perform robot initializations.
- Monitor local robot execution and status and feedback to SCP.
- Update APP/AF-FBs in case of cloud level change (new or revised plans).

3. LOP performs robot operation planning and execution:

- The received APP is detailed through robot-level operation planning, as the embedded algorithms read their data inputs from their local environment.
- Robot-specific control instructions are generated at run-time through controller-level decision-making, as LOP executes the AF-FBs one by one.

Detailing the generic APP as LOP is being performed provides adaptability to changes, as the planning and execution is performed on demand at each service provider, based on real-time information.

## 5. Conclusions

There are many strong drivers for collaborative manufacturing and the sharing of its required resources. The concept of resource-availability through networked and distributed services boosts the proliferation of CM. So far, networked manufacturing has been hampered by the absence of effective control and coordination mechanisms. For the successful realization of CM, an adaptive control approach for distributed manufacturing equipment populating cloud environments is an uttermost pre-requisite.

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## References

[1] Xu X. From Cloud Computing to Cloud Manufacturing. Robotics and Computer-Integrated Manufacturing. 2012; 28:75–86.

[2] Tao F, Zhang L, Venkatesh VC, Luo Y, Cheng Y. Cloud Manufacturing: A Computing and Service-Oriented Manufacturing Model. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2011;225(10):1969-76.

[3] Zhang L, Luo Y, Tao F, Li BH, Ren L, Zhang X, Guo H, Cheng Y, Hu A, Liu Y. Cloud Manufacturing: A New Manufacturing Paradigm. Enterprise Information Systems. 2012. p.1-21. doi:10.1080/17517575.2012.683812.

[4] Monostori L, et al. Towards adaptive and digital manufacturing. Annual Reviews in Control. 2010;34:118-28.

[5] Tao F, Zhang L, Nee AYC. A Review of the Application of Grid Technology in Manufacturing. International Journal of Production Research. 2011;49(13):4119-55.

[6] Valilai OF, Houshmand M. A Collaborative and Integrated Platform to Support Distributed Manufacturing System Using a Service-Oriented Approach Based on Cloud Computing Paradigm. Robotics and Computer-Integrated Manufacturing. 2013;29:110-27.

[7] Ren L, Zhang L, Wang L, Tao F, Chai X. Cloud Manufacturing: Key Characteristics and Applications. International Journal of Computer Integrated Manufacturing. 2014. doi: 10.1080/0951192X.2014.902105.

[8] Wang L, Wang XV, Gao L, Váncza J. A Cloud-Based Approach for WEEE Remanufacturing. CIRP Annals - Manufacturing Technology. 2014;63(1):409-12. doi: 10.1016/j.cirp.2014.03.114.

[9] Huang B, Li C, Yin C, Zhao X. Cloud Manufacturing Service Platform for Small- and Medium-Sized Enterprises. The International Journal of Advanced Manufacturing Technology. 2013;65(9-12):1261-72.

[10] Wu D, Greer MJ, Rosen DW, Schaefer D. Cloud Manufacturing: Drivers, Current Status, and Future Trends. Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference (MSEC2013). Madison, WI, June 10-14. 2013. Paper Number MSEC2013-1106.

[11] Tao F, Zuo Y, Xu LD, Zhang L. IoT-Based Intelligent Perception and Access of Manufacturing Resource Toward Cloud Manufacturing. IEEE Transactions on Industrial Informatics. 2014;10(2):1547-77. doi:10.1109/TII.2014.2306397.

[12] Lu Y, Xu X, Xu J. Development of a Hybrid Manufacturing Cloud. Journal of Manufacturing Systems. 2014;33(4):551-66.

[13] Heinrichs W. Do It Anywhere. IEE Electronics Systems and Software. 2005;3(4):30-3.

[14] Xu X, Wang L, Newman ST. Computer-Aided Process Planning − A Critical Review of Recent Developments and Future Trends. International Journal of Computer Integrated Manufacturing. 2011;24(1):1-31.

[15] Oliveira T, Thomas M, Espadanal M. Assessing the Determinants of Cloud Computing Adoption: An Analysis of the Manufacturing and Services Sectors. Information & Management. 2014;51(5):497-510. doi: 10.1016/j.im.2014.03.006.

[16] International Electrotechnical Commission, Function Blocks – Part 1: Architecture, IEC 61499-1, Switzerland, 2005.

[17] Vyatkin V. IEC 61499 as Enabler of Distributed and Intelligent Automation: State of the Art Review. IEEE transactions on Industrial Informatics. 2011;7(4):768-81.

[18] Shah JJ, Rogers MT. Expert Form Feature Modeling Shell. Computer Aided Design. 1988;20(9):515-24.

[19] Kyprianou L. Shape Classification in Computer-Aided Design. Ph.D. Dissertation, Cambridge University, United Kingdom. 1980.

[20] Holland van W, Bronsvoort WF. Assembly Features in Modelling and Planning. Robotics and Computer-Integrated Manufacturing. 2000;16(4): 277-94.

[21] Wang L, Jin W, Feng HY. Embedding Machining Features in Function Blocks for Distributed Process Planning. International Journal of Computer Integrated Manufacturing. 2006;19(5):443-52.

[22] Tapoglou N, et al. Cloud based platform for optimal machining parameter selection based on function blocks and real time monitoring. J. Manuf. Sci. Eng. 2015,137(4), DOI: 10.1115/1.4029806.

[23] Wang L, Keshavarzmanesh S, Feng HY. A Function Block Based Approach for Increasing Adaptability of Assembly Planning and Control. International Journal of Production Research. 2011;49(16):4903-24.

[24] Adamson G, Holm M, Wang L, Moore P. Adaptive Assembly Feature Based Function Block Control of Robotic Assembly. Proceedings of the 13th Mechatronics Forum. 2012;1:8-13.

[25] Adamson G, Wang L, Holm M, Moore P. Function Block Approach for Adaptive Robotic Control in Virtual and Real Environments. Proceedings of the 14th Mechatronics Forum, 2014;1:473-9.