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ORIGINAL ARTICLE

Additive manufacturing scenarios for distributed production of spare parts

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Abstract Spare parts manufacturing and in-time provision are complex activities for several industries. One of the decisions that need to be made on a spare parts production is related to the location of the production. The distributed manufacturing of spare parts in locations closer to the final user may have several advantages, such as reduced delivery lead times and reduced logistics costs. However, distributed manufacturing by the adoption of advanced manufacturing technologies raises challenges in terms of information exchange, communication, and control between the production sites. The connected industrial environment, brought by what has been called the 4th Industrial Revolution, might be the answer for this challenge. Therefore, the aim of this paper is to characterize centralization and independence levels between a central factory and a distributed production site for the manufacturing of spare parts leveraging additive manufacturing as main production process. Use cases have been developed with design and engineering—providing the product model—in Germany and the additive manufacturing (AM) site—providing the manufacturing structure and machines—in Brazil, together forming a distributed development and manufacturing network. Four implemented use cases demonstrate the evolution of the independence level between the central factory and the distributed site. The analyses focus on implications for work organization, network performance, and intellectual property protection. Results show that the connection, communication, and control brought by advanced manufacturing technologies and connected industrial environment to distributed manufacturing change the organizational structure of both sites creating a flexible focused factory with the production closer to the final client and the specialization centered at the central factory.

Keywords Distributed manufacturing · Additive manufacturing · Advanced manufacturing · *Industrie 4.0* · Spare parts · Organizational structure

1 Introduction

Advanced manufacturing technologies aims at improving value chains and value-added networks in industry to ensure industrial competitiveness. Key challenges are the integration of seamless digital workflows throughout the product lifecycle, the development of highly flexible and adaptive manufacturing processes, and the capabilities to manufacture individualized products at the price of mass production [1].

Production sites are becoming rapidly adaptive while remaining economically productive. This situation enables to decentralize production—through autonomous tasks based on cyber physical production systems [2], improved quality control [3–5], and reduced inventories [4]. Smart factories will be networked in cross-company collaboration, sharing relevant information to a database, and thus creating a dynamic environment [6].

Increased product variety, reduced lifecycle times and geographically distributed markets brought by a dynamic

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environment, increases the demands for post-sales services as the manufacturing of spare parts. The management of spare parts is a challenge for most of the products, due to the unpredictable demand and diversity of items. To raise the perception of the value for the customer, one strategy that can be adopted is the geographically distributed manufacturing, transferring the production closer to the client and reducing the time to deliver parts [7]. However, the distribution of the production by the adoption of advanced manufacturing technologies (AMT) raises problems in the information exchange, communication, and control between the production sites, changing the work organization structures [8].

Work organization is based on the similarity of activities. The greater interdependence between two tasks implies greater returns to integrated coordination. However, an increase in the number of interdependent relationships implies more coordination responsibilities for the managers once the more complex the task system, the more difficult it is for individual managers to handle the constraints on their cognitive capacity. The production system involves the transfer of information and decisions as well as materials; it is, therefore, a richer representation of the firm as a system of interdependent tasks [9, 10]. The challenge with distributed production is to implement communication and integration technologies that reduce the coordination effort and provides a focused factory [7].

This paper simulates the use of AMT in connected environments to produce spare parts in a distributed environment [11, 12]. The applied research approach is based on designing, implementing, and testing a distributed manufacturing of spare parts experiment. The experiment has been based on additive manufacturing and Internet communication technologies.

The objective of this paper is to compare the organizational structure and independence levels between a central factory and a distributed site for the manufacturing of spare parts considering the application of novel production and communication technologies. The experiment has been implemented in four use cases representing different levels of integration and quality control independence, evolving from a non-connected to a fully connected environment. These use cases that simulate a distributed production scenario between Germany and Brazil, which represents the Internet-based collaboration between central factory and distributed production site [11, 12].

This article is structured in six sections. Section 2 presents a literature review on the topics used to construct a distributed manufacturing scenario. Section 3 details the research method and the solution developed. Section 4 focuses on data gathering and results analysis of the scenario. Section 5 discusses the application of the proposed method on the dependence level between the central factory and the distributed site. Finally, Section 6 presents the conclusions and suggestions for further research.

2 Distributed manufacturing

In this section, the theoretical bases for distributed and controlled manufacturing are described.

2.1 Supply chain of spare parts

The supply chain of products encompasses all activities associated with the flow and transformation of goods from raw materials to the end user, as well as the associated information flow that runs along the production chain [13].

It is necessary to consider a combination of different requirements from the adopted technology, desirable quality, production, and market, for the production chain to be balanced [14]. These combinations of requirements can be characterized by the five Ps of the supply chain [15]:

- Product—which product will be offered, in which velocity and flexibility;
- Partnership—selecting partners and analyze the risk of sharing information;
- Plants and stocks—focused factories and appropriate stocks;
- Process—point of interaction with the client;
- and Planning and control—information exchange during the manufacturing process.

The five Ps suitably designed avoid production variability without ending flexibility [15, 16] which adds complexity to the production of spare parts.

Spare parts manufacturing and in-time provision are complex challenges faced by several industries. The unpredictability of the demand for spare parts in conjunction with the distributed location of clients are main issues dealing with spare parts [7].

One of the decisions that need to be made on a spare parts production is considering the location of the production facilities. The production can be centralized, serving the world from a single place, or distributed, in various locations that are closer to the final market, being the great challenge to keep the focus of the factory.

A focused factory as defined by Pesch [17] is a factory with a limited and consistent set of demands that derive from the plant's five Ps. The concept of focus does not mean just reducing the number of tasks performed or products produced. It is, instead, the homogeneity and the repetition in completing these tasks that can provide standardize processes [15, 18].

Centralized production facilitates the implementation of standard processes and procedures and quality assurance. It comes, however, at the cost of longer delivery lead times, higher inventory, and higher logistic costs.

On the other hand, distributed manufacturing benefits the production system by providing greater responsiveness to deal with the variety of the spare parts, flexibility, improved efficiency, and higher supply chain reliability [19]. Bringing production closer to consumer markets and implementing a technical solution substantially help the system overcome the demand unpredictability.

Distributed manufacturing challenges are to guarantee standards and quality in distributed sites transforming an unfocused manufacturing process by essence on a focused process control at the central factory. In this context, *Industrie 4.0* provides concepts and technologies that facilitate distributed manufacturing once that productivity increases in proportion to the velocity of the information is carried in the process [15, 20, 21].

2.2 Advanced manufacturing

All previous industrial revolutions, triggered by the advent of technical developments, led to profound changes in society and massive gains in productivity [22]. In the late eighteenth century, manufacturing was mechanized by steam power. In the late nineteenth century, production was marked by electrification and division of labor. Starting from the 1970s up to now, the third industrial revolution has been characterized by rapid advancements in Information Technology (IT), electronics, and digitalization, which automated manufacturing processes [20]. The adoption of AMT in connected environments, creating smart factories, is triggering a new industrial revolution enabling the receiving of different information from various sources and producing items that are more complex in a reduced time [20, 23].

Advanced Manufacturing Technologies are computer-assisted technologies used by industrial companies to produce their products [24, 25]. The term AMT can be described as a group of technologies used to control and monitor manufacturing activities (storing and handling data) being capable of increasing efficiency and efficacy of the adopting companies [26–30].

The characteristics of AMT applied in a connected environment, which are culminating in the recently fourth industrial revolution, have been captured in the research initiative *Industrie 4.0* as part of the High-Tech strategy of the German government [20]. To implement *Industrie 4.0* solutions, a suitable information and communication technology (ICT) infrastructure is mandatory. This enables to network people, resources, and machines in cyber physical production systems (CPPS) as well as highly flexible production environments [2].

Connected environments, provided by *Industrie 4.0*, consider the production of more individualized products without stopping the production for setups, as customers will be directly connected to the production planning via a network [20]. Production sites are becoming rapidly adaptive while remaining economically productive. This situation enables to decentralize production—through autonomous tasks based on CPPSs [2], improved quality control [3–5], and reduced inventories [4]. Smart factories will be networked in cross-company collaboration, sharing relevant information to a database and thus creating a dynamic environment [20].

AMT are usually classified according to the developed function in the manufacturing process. The three most cited in the literature are design technologies, manufacturing technologies, and management technologies [4, 26, 31]. One of the manufacturing technologies that enables the individual production of complex parts is Additive Manufacturing (AM) [32]. The dissemination of AM is having a great impact on the production. At first, it was applied mainly to prototyping, but nowadays it can be applied to produce different final parts, including airplane engine components [33].

The main advantage of AM is producing complex shapes in small lot sizes [34]. Besides, depending on the production system, it may contribute to reducing the time-to-market and material savings [35]. These have a relevant meaning to *Industrie 4.0* as they provide the opportunity of individualized production [36].

Another important impact of the adoption of AMT is the change in work organization. AMT reduces the work in progress, integrates informational systems in different activities, and improves worker force, changing coordination efforts and affecting the production system [8].

2.3 Organizational structure and implications

Work organization is based on the similarity of activities. Employees dealing with similar requirements should be grouped in the same division, creating interdependencies in different activities at the same plant [10, 37].

The greater interdependence between two tasks implies greater returns to integrated coordination. However, an increase in the number of interdependent relationships implies more coordination responsibilities for the managers once the more complex the task system, the more difficult it is for individual managers to handle the constraints on their cognitive capacity. Employees carrying out interdependent tasks must engage in ongoing communication to understand the factors affecting each other's decisions and to track the decisions that are made [10, 38].

The production system involves the transfer of information and decisions as well as materials; it is therefore a richer representation of the company as a system of interdependent tasks [9, 10]. Recent research has focused on the relationship between adoption of AMT and overall operations [39, 40]. However, the literature does not cover the changes brought by distributed manufacturing. The challenge that remains with distributed production is to implement communication and integration technologies that reduce the coordination effort and provide a focused factory [7].

3 Research methods

This paper simulates the use of AM technologies to produce spare parts in a distributed environment [11, 12, 23]. The applied research approach is based on designing, implementing, and testing a distributed manufacturing of spare parts experiment in different levels of integration between the central factory and the distributed site. This experiment focuses on the organizational and business process aspects of the distributed production environment. The objective is to discuss organizational changes and its implications of a distributed manufacturing approach. Four different use cases were implemented and simulated, considering different levels of decentralization [11].

In the first use case, conventional distributed production is simulated. The central factory has little influence on the manufacturing process at the distributed site, sending the production requests and the corresponding product data model (intellectual property) to be produced. The distributed site receives the information, sets up the machine, and starts the production. All the machine parameters are defined by the distributed site, and only a final report feedback is sent to the central factory.

In the second use case, the central factory has more control over the production parameters by remotely monitoring the process, but without having influence over the process. Any deviation from the expected parameters has to be solved by the local team at the distributed site. The monitoring of the manufacture parameters occurs through integrated machine sensors, and the relevant data is automatically sent online to the central factory via the Internet. The environment parameters are monitored through temperature sensors and accelerometers and are also send to the central factory.

In the third use case, the central factory has the control over all the production parameters, including quality reports. The monitoring in this use case is similar to the previous one, using the Internet and integrated machine sensors for machine monitoring with real-time requirements, and the temperature sensors and accelerometers to monitor environment conditions. For quality control, the central factory can follow the inspection process in a video conference procedure. Considering the change in the control situation, there is no longer the need for decisions based on quality control at the distributed site. The decisions on continuity or discard are made by the central factory, considering the data collected by sensors on the distributed site.

The fourth use case represents the increased connection between the central factory and the distributed site. The central factory has full access to the monitored data and can autonomously conduct and control the production. With this, a cyber-physical production system is implemented. The production information is sent over the Internet from the central factory directly to the machine on the distributed site. The distributed site has no control over the machines or what is being produced. It is only responsible for setting up the machine and preparing the component for the quality control.

The experiment was implemented at a central factory located in Germany and a distributed site in Brazil. This experiment is part of a broader research project within the research collaboration framework in manufacturing called BRAGECRIM (Brazilian–German Collaborative Research Initiative in Manufacturing Technology).

The experiment consists of the production of the bottom of a pneumatic cylinder (Fig. 1). This part is a standard item already used at the Center for Industrial Productivity (CiP) located at *Technische Universität* Darmstadt. Simplifications were made to the model to facilitate AM production with the equipment available and to avoid intellectual property issues, as the part used at CiP is real. The bottom of the pneumatic cylinder was selected as it fulfills the needed characteristics to be manufactured within a distributed AM process with adequate size, complexity, and value.

This is a 1-year research conducted in two different experiment sets implemented in 2015 and 2016. The main difference between these two sets of experiments is the use of an automatically quality control process on the second experiment aiming at giving greater control to the central factory.

The experiment was based on low-cost AM and communication technologies, as the main objective of the project is to analyze organizationally and process impacts in different use cases [11, 12]. A low-cost FDM machine was used. The communication technologies were based on low-cost sensors, Arduino, and a Raspberry Pi, besides open-source software, creating a connected environment using the Internet.

4 Experiment description and analysis

The experiment of distributed manufacturing of spare parts was implemented in four different use cases. Every use case represents an increase on the independence of the central factory comparing to the previous one, represented by the different activities developed at the sites. Besides, all use cases possess the twelve activities described in Table 1, varying the location that the activities are realized.

Use case 1, Regular Production, represents the current stage of the manufacturing process of spare parts. The central factory is responsible for designing the component and receiving the request for the production of a spare part. The distributed site is responsible for receiving the request and

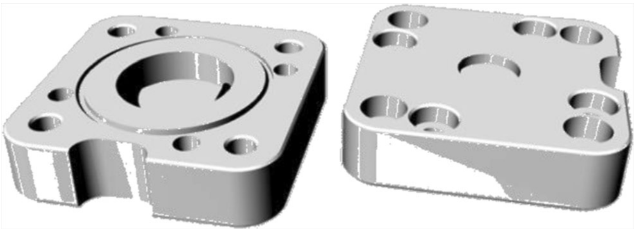


Fig. 1 Bottom of a pneumatic cylinder from CiP [41]

Table 1 Activities developed during the scenario

Activities developed during the scenarios	Activity details
1. Define product specification	Define the main attributes of the product.
2. Define product design	Design and create a 3D model of the product.
3. Process customer order for spare parts	Receive the customer request for spare parts and authorize the production.
4. Define production planning and control	Plan and schedule the production considering the machine line and the amount of components that need to be manufactured.
5. Process manufacturing files	Convert the 3D model files into manufacturing files.
6. Supply of raw material	Supply the machine with raw material.
7. Setup the machine	Setup the initial conditions of the machine—temperature, platform inclination, connection conditions.
8. Monitoring of production process condition—part I	Monitoring the process conditions and parameters—machine temperature, environment temperature, vibration, and visual inspection.
9. Monitoring of production process condition—part II	Act during any abnormality of the process—unpredicted stop of the production.
10. Perform quality control	Process quality control process.
11. Perform part approval	Approve or refuse the component.
12. Perform machine maintenance	Conduct machine maintenance procedures, including preventive and corrective maintenance.

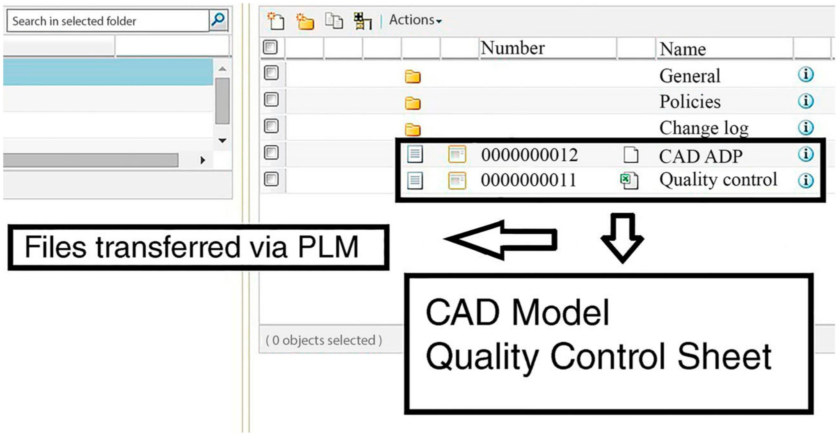
coordinating the production—defining the scheduling, generating the manufacturing files, etc.; manufacturing; and sharing the final feedback of the component—being delivered or not—via a PLM software. Figure 2 represents the file exchange interface.

The central factory is structured in three departments responsible for defining product specifications, product design, and processing customers' request for manufacturing. They are interdependent activities that need to be close to each other to reduce the decisions time. The distributed site is structured in manufacturing and quality control, both centered on a coordinator responsible for sharing the information with the central factory. Manufacturing and quality control are interdependent activities that can be performed distant from the design department.

Use case 2, 3D model independence, represents a small evolution on the independence of the central factory and the intellectual property risk. In this use case, central factory continues to be responsible for conceiving and designing the component. To the attributions of the central factory, the processing of the manufacturing files is added, once only the machine code is sent to the distributed site. The central factory is also responsible for monitoring the process remotely, see process condition monitoring—part I (Table 1). Figure 3 presents a view of the control screen from the central factory. The distributed site must schedule the production, prepare the machine, and ensure the communication between the sensors and the central factory. Besides, it must realize the quality control tests and approve or reject the component, sending the feedback to the central factory.

The central factory gets one more department, the manufacturing department, responsible for processing the manufacturing files and monitoring the process conditions and parameters. The distributed site has a structure to plan the

Fig. 2 PLM interface



Number	Name
	General
	Policies
	Change log
0000000012	CAD ADP
0000000011	Quality control

Fig. 3 View of the control screens from the central factory

Machine State: **Operational**
File:
Filament (Tool 0): -
Estimated Print Time: -
Timelapse: -
Height: **-0.10mm**
Print Time: -
Print Time Left: -
Printed: -

Name	Size	Action

🟥 Actual T: 213.0°C
🟥 Target T: 215.0°C
🟦 Actual Bed: 170.0°C
🟦 Target Bed: off

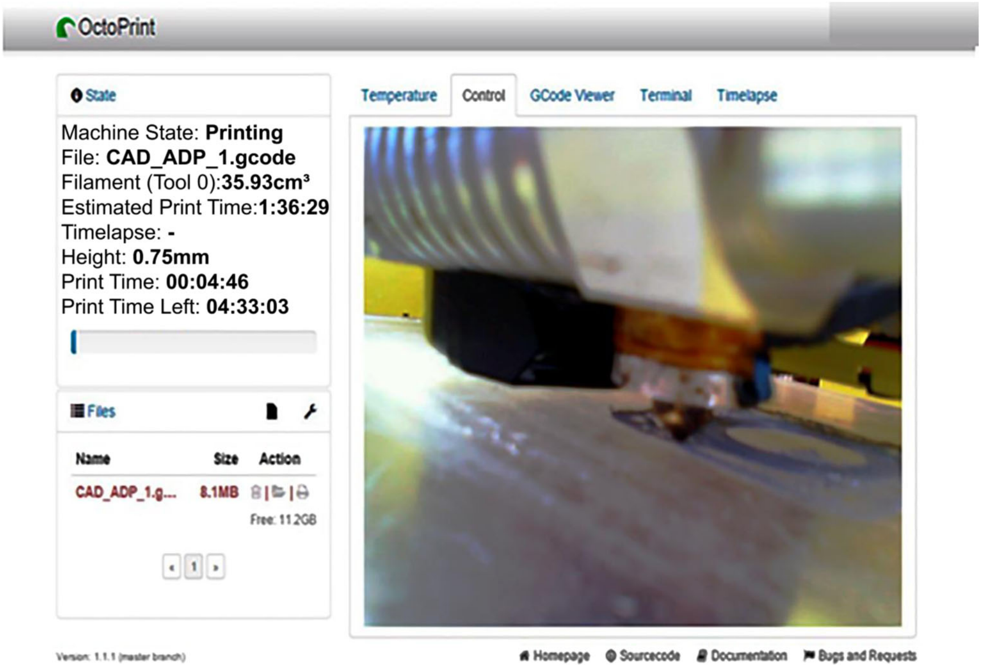
	Actual	Target	Offset
Hotend	213.0°C	215 °C	0 °C
Bed	170.0°C	off °C	0 °C

production, a structure to control the production, and a structure to perform quality control analyses. The existence of distance departments of planning and controlling creates a coordination and communication risk, once these two activities are deeply correlated. Besides, the distance between the quality control and the manufacturing monitoring increases the difficulty of correlation between the errors and the machine conditions.

Use case 3, production independence, is the novelty of the distributed manufacturing of spare parts. In this use case, the control of manufacturing process is transferred from the distributed site to the central factory. The central factory is responsible for manufacturing the component even away from the physical machine. Figure 4 represents the independence of the central factory. The distributed site is responsible for acting on any abnormality of the machine and performing the quality control process. However, the approval of the component is a responsibility of the central factory, which receives the quality control via PLM software and decides the destiny of the produced component.

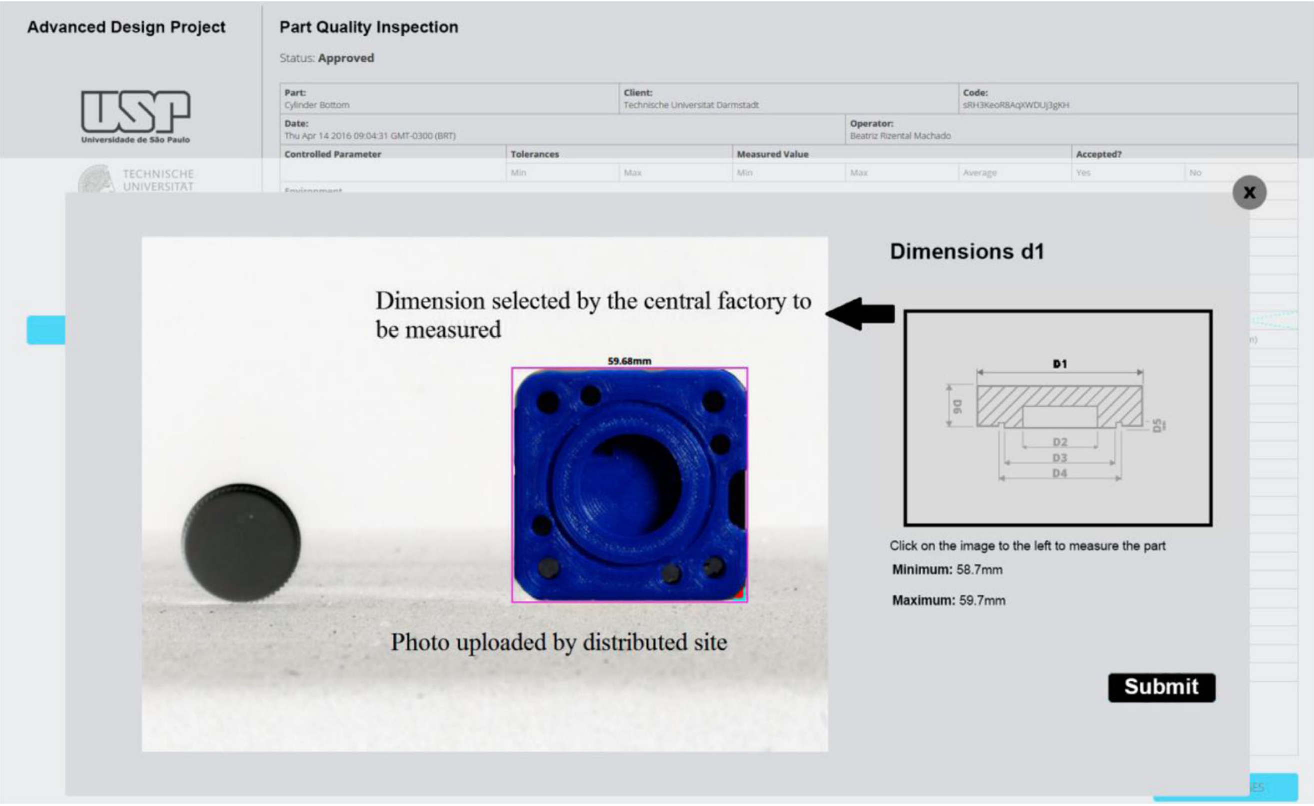
The manufacturing department of the central factory is now responsible for planning the production and integrating the process monitoring with the new manufacturing of

Fig. 4 Independence of the central factory—screen of control only accessed at the central factory



Machine State: **Printing**
File: **CAD_ADP_1.gcode**
Filament (Tool 0):**35.93cm³**
Estimated Print Time:**1:36:29**
Timelapse: **-**
Height: **0.75mm**
Print Time: **00:04:46**
Print Time Left: **04:33:03**

Name	Size	Action
CAD_ADP_1.g...	8.1MB	



Part Quality Inspection

Status: **Approved**

Part: Cylinder Bottom	**Client:** Technische Universitat Darmstadt	**Code:** sRH3KeoR8AqXWDUj3gKH
Date: Thu Apr 14 2016 09:04:31 GMT-0300 (BRT)		**Operator:** Beatriz Rizental Machado

Dimensions d1

Click on the image to the left to measure the part

Minimum: 58.7mm

Maximum: 59.7mm

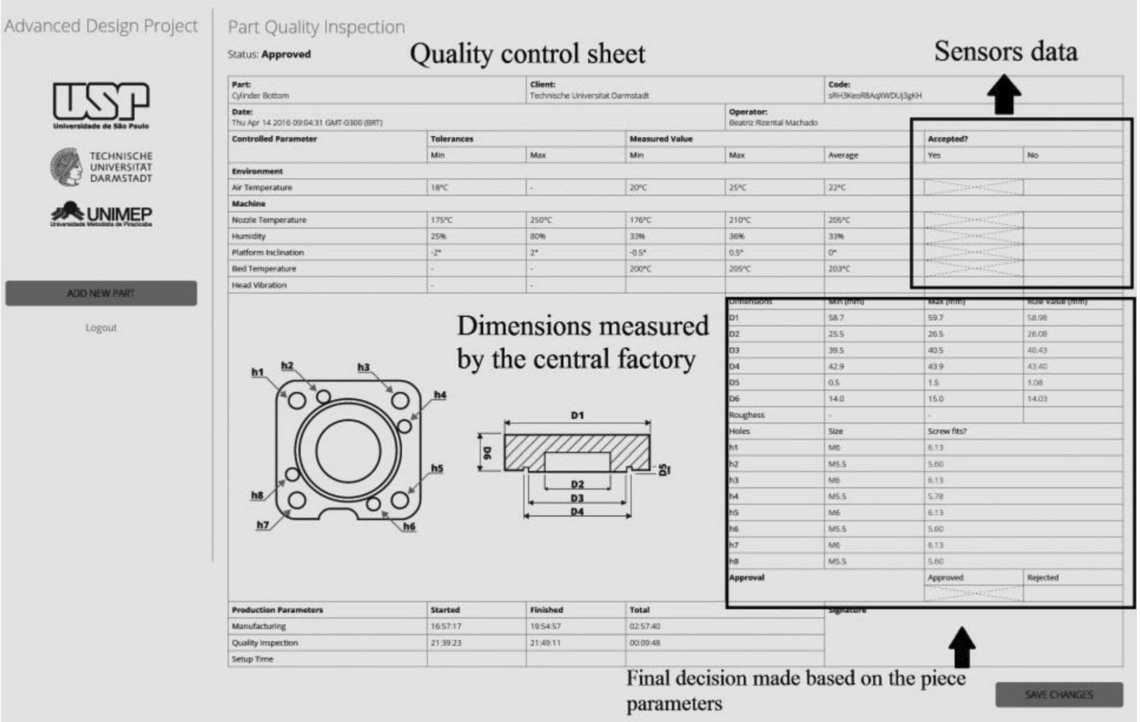
Dimension selected by the central factory to be measured

Photo uploaded by distributed site

Fig. 5 Automatically quality control—measuring

components. However, the quality control process remains at the distributed site, maintaining the challenges of communication and decision as described in the use case 2.

Use case 4, quality control independence, represents the independence of the controlling and decisions on the manufacturing process. The central factory is responsible for



Part Quality Inspection

Status: **Approved**

Quality control sheet

Sensors data

Part: Cylinder Bottom	**Client:** Technische Universitat Darmstadt	**Code:** sRH3KeoR8AqXWDUj3gKH
Date: Thu Apr 14 2016 09:04:31 GMT-0300 (BRT)		**Operator:** Beatriz Rizental Machado

Controlled Parameter	**Tolerances**		**Measured Value**			**Accepted?**	
	Min	Max	Min	Max	Average	Yes	No
Environment							
Air Temperature	18°C	-	20°C	25°C	22°C		
Machine							
Nozzle Temperature	175°C	250°C	176°C	210°C	205°C		
Humidity	25%	80%	33%	36%	33%		
Platform Inclination	-2°	2°	-0.5°	0.5°	0°		
Bed Temperature	-	-	200°C	205°C	203°C		
Head Vibration	-	-					

Dimensions measured by the central factory

Dimensions	Min (mm)	Max (mm)	Real Value (mm)
D1	58.7	59.7	58.98
D2	25.5	26.5	26.08
D3	39.5	40.5	40.43
D4	42.9	43.9	43.40
D5	0.5	1.5	1.08
D6	14.0	15.0	14.03
Roughess	-	-	
Holes	Size	Screw fits?	
h1	M6	6.13	
h2	M5.5	5.60	
h3	M6	6.13	
h4	M5.5	5.78	
h5	M6	6.13	
h6	M5.5	5.60	
h7	M6	6.13	
h8	M5.5	5.60	
Approval		Approved	Rejected

Production Parameters	**Started**	**Finished**	**Total**	**Signature**
Manufacturing	16:57:17	19:54:57	02:57:40	
Quality Inspection	21:39:23	21:49:11	00:09:48	
Setup Time				

Final decision made based on the piece parameters

Fig. 6 Automatically quality control—sheet all the activities that can be remotely controlled. Therefore, it is liable for creating the model, planning the production, processing the manufacturing files, monitoring the process conditions, and realizing the quality control process remotely.

The quality control process is based on image recognition. The distributed site is responsible for uploading the pictures and the central factory for choosing the dimensions to be measured. Figure 5 is showing how a dimension is measured by the central factory at the developed interface. The central factory's user selects the dimension to be analyzed and gets the dimension of the component based on the dimension of a control component. Figure 6 represents the quality control sheet and the interface that appears to the central factory.

The central factory is structured in three departments: design and elicitation—continuing the activities developed at use case 1; manufacturing—responsible in creating the manufacturing files, planning the production, and monitoring the process; and quality control—responsible for approving or rejecting the component. The distributed site now works only with one department, setting up the machines and acting in case of any abnormality. With the movement of the activities to the central factory, the interdependent activities are together and the manufacturing of a component can be controlled by a specialized department of the central factory.

In possession of the description of the use cases (Table 2), it is possible to define the activities that were developed at the central factory, the activities that were developed at the distributed site, and the intellectual property issues evolved on every use case (see Table 3).

The four different use cases evolve in the direction of increasing the independence level of the central factory comparing to the distributed site. This is reflected by the factor central/distributed at Table 3 that increases with the development of the use cases. Besides, it shows an increasing on intellectual property protection and on the use of sensing technology.

5 Dependence level evolution

To analyze the supply chain of production, it is necessary to consider a requirements mix between adopted technology, desirable quality, production, and market [14]. The requirement mix can be characterized by the five Ps previously presented in Section 2.1 [15].

The experiment of distributed manufacturing of spare parts was implemented in four different use cases. All use cases possess the twelve activities described in Table 1 that can be related to the 5Ps. Being the first tasks related to product design and customers' request (activities 1–3), and the other activities related with how the partnership, the plants, the process, and the control are handled during the experiments.

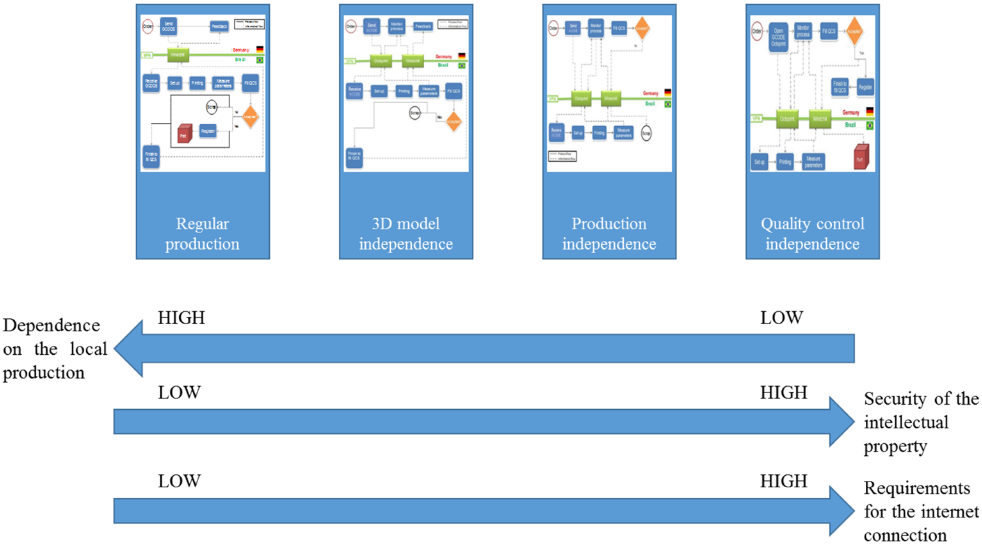
Table 2 Description of the use cases

	Regular production	3D model independence	Production independence	Quality control independence
Scenario description	The 3D part data for production is sent from the central factory, and the control is exerted at the distributed site.	3D part data is sent via additive manufacturing web interface, and the central factory receives a few control parameters (e.g., temperature and acceleration).	The manufacturing file is sent via additive manufacturing web interface and the central factory guides the quality control process.	The manufacturing is totally controlled by the central factory via Internet. The distributed site is responsible for setting up the machine and sensors. The quality control is automatically processed in a web browser.
Technical aspects	•Temperature sensors •Accelerometers •Arduino •PLM software	•Temperature sensors •Accelerometers •Arduino •PLM software	•Temperature sensors •Accelerometers •Arduino •PLM software •Raspberry Pi •Additive manufacturing web interfaces for parameters control •Video conference for quality control	•Temperature sensors •Accelerometers •Arduino •Raspberry Pi •Additive manufacturing web interface for parameters control •Web interfaces for quality control •Additive manufacturing web interface for controlling the machine via Internet

Table 3 Activities on the use cases

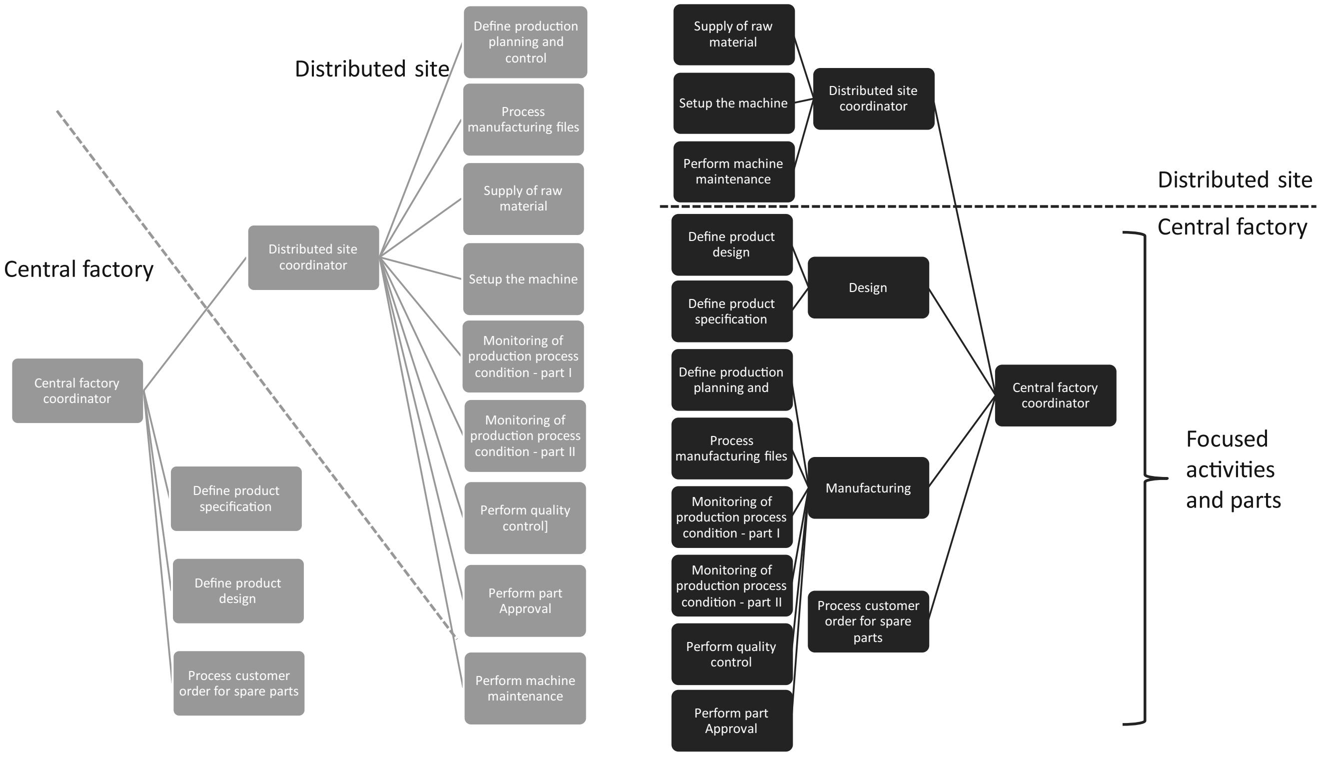
	Regular production	3D model independence	Production independence	Quality control independence
Central factory task	1. Define product specification 2. Define product design 3. Process customer order for spare parts	1. Define product specification 2. Define product design 3. Process customer order for spare parts 5. Process manufacturing files 8. Monitoring of production process condition—part I	1. Define product specification 2. Define product design 3. Process customer order for spare parts 4. Define production planning and control 5. Process manufacturing files 8. Monitoring of production process condition—part I	1. Define product specification 2. Define product design 3. Process customer order for spare parts 4. Define production planning and control 5. Process manufacturing files 8. Monitoring of production process condition—part I 10. Perform quality control 11. Perform part approval
Distributed site task	4. Define production planning and control 5. Process manufacturing files 6. Supply of raw material 7. Set up machine 8. Monitoring of production process condition—part I 9. Monitoring of production process condition—part II 10. Perform quality control 11. Perform part approval 12. Perform machine maintenance	4. Define production planning and control 6. Supply of raw material 7. Set up machine 9. Monitoring of production process condition—part II 10. Perform quality control 11. Perform part approval 12. Perform machine maintenance	6. Supply of raw material 7. Set up machine 9. Monitoring of production process condition—part II 10. Perform quality control 11. Perform part approval 12. Perform machine maintenance	6. Supply of raw material 7. Set up machine 9. Monitoring of production process condition—part II 12. Perform machine maintenance
Intellectual property	The 3D file (IP) is sent to the distributed site via a PLM software.	No 3D file (IP) is sent to the distributed site, only the manufacturing file via a web interface.	No 3D file (IP) is sent to the distributed site, only the manufacturing file, directly to the machine.	No 3D file (IP) is sent to the distributed site, only the manufacturing file, directly to the machine.
Activities at central site/activities at distributed site (#)	3/9	5/7	6/6	8/4

Fig. 7 Use cases comparison



The greater interdependence between two tasks implies greater returns to integrated coordination. Employees carrying out interdependent tasks must engage in ongoing communication to understand the factors affecting each other's decisions and to track the decisions that are made [10, 38]. The production system involves the transfer of information and decisions as well as materials; it is, therefore, a richer representation of the firm as a system of interdependent tasks [9, 10]. Therefore, when moving out of the product P to the other Ps in a distributed scenario changing the locations of the activities—as developed in this paper, a high communication process is requested as related in Fig. 7.

From Table 3, it is possible to infer that the number of activities that are developed at the central factory increases on every use case. Use case 1 (Regular production) starts with three activities developed at the central factory—related to the product design and specification and the customers' requirements—and all other activities taking place at the distributed site.



Regular production Quality control independence

Fig. 8 Organizational comparison

Use case 4 (Quality control independence) on the other hand creates focused groups working on design, manufacturing, and order control. All the monitoring activities are transferred from the distributed site to the central factory—transferring the control to the central factory, only the physical production remaining at the distributed site. The interdependence between the manufacturing and monitoring processes is solved with a communication system providing real-time control of the machines so that a no specialized distributed factory can be controlled by a central factory that possesses the knowledge to produce the components.

Figure 8 presents a comparison between use case 1 and use case 4. At this figure, it is possible to visualize that the actual control of use case 4 is at the central factory while the distributed site is only responsible for taking care of the machine. Also, at use case 1, the distributed site is responsible for all the manufacturing activities, being the central factory responsible only for the design of the product. Therefore, the manufacturing activities are developed by people distant from the design.

The communication process must be robust enough to deal with the amount of requests and information that is generated during the development of the manufacturing process. At the development of this paper's scenarios, an overloaded network was used for communication proposes. The conditions of the network harmed the development of use cases 3 and 4 once the request for manufacturing and the manufacturing monitoring were interrupted many times.

The challenge with distributed production is therefore resolved with a communication and integration technologies reducing the coordination effort and creating distributed focused factories—with flexible production systems at distributed site (providing variability) controlled by focused divisions at the central factory (providing supply chain control).

6 Conclusions

Spare parts manufacturing and in-time provision are complex challenges faced by several industries. The unpredictability of the demand for spare parts in conjunction with the distributed location of clients are main issues dealing with spare parts [7].

Production sites are becoming rapidly adaptive while remaining economically productive. This situation enables to decentralize production—through autonomous tasks based on cyber physical production systems [2], improved quality control [3–5], and reduced inventories [4].

Industrie 4.0 aims at improving value chains and value-added networks in industry to ensure industrial competitiveness. Key challenges are the integration of seamless digital workflows throughout the product lifecycle, development of highly flexible and adaptive manufacturing processes, and capabilities to manufacture individualized products at the price of mass production [1]. However, the distribution of the production by the adoption of AMT raises problems in the information exchange, communication, and control between the production sites, changing the work organization [8].

By the development of the experiment, the organizational structure is changed. It gets more complex at the central factory (with three departments controlling the design, the manufacturing, and the quality control) and less complex at the distributed site. At the central factory, the coordination depends heavily on integration and communication technologies providing real-time manufacturing data for supply chain control. At the distributed sites, flexible production systems controlled by focused divisions at the central factory provide production variability. However, for future research, it is recommended to analyze the assembly of the components and other relations between the central factory and the distributed site, especially at the communication aspect.

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