Performance Analysis of CyberManufacturing Systems: A Simulation Study

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Abstract. CyberManufacturing System (CMS) is an advanced vision for future manufacturing where physical components are fully integrated and seamlessly networked with computational processes, forming an on-demand, intelligent and communicative manufacturing resource and capability repository with optimal, sustainability-oriented manufacturing solutions. CMS utilizes recent developments in Internet of Things, Cloud Computing, Fog Computing, Service-Oriented Technologies, etc. Manufacturing resources and capabilities can be encapsulated, registered and connected to each other directly or through the Internet, thus enabling intelligent behaviors of manufacturing components and systems such as self-awareness, self-prediction, self-optimization, and self-configuration among others. This research presents a definition of CMS, an architecture and unique functions of CMS, and performance analysis of CMS using simulation models. Five examples have been developed and used for illustration and validation of CMS. The results show significant improvement in enhanced functionality and cooperative performance.

Keywords: CyberManufacturing System, Cloud Manufacturing, Cyber-Physical System, Modeling and Simulation

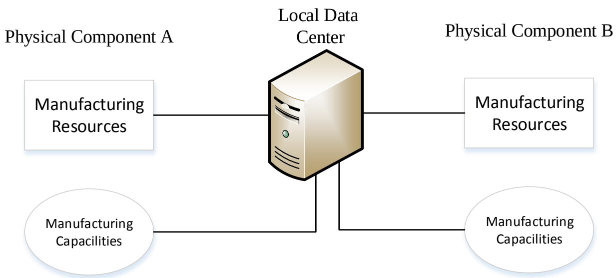
1 Introduction

CyberManufacturing System is a vision for future manufacturing where physical components are fully integrated and seamlessly networked with computational processes, forming an on-demand, intelligent and communicative manufacturing resource and capability repository with optimal, sustainability-oriented manufacturing solutions. By leveraging recent developments in Internet of Things, Cloud Computing, Fog Computing, Cyber-Physical System, Service-Oriented Technologies, Modeling and Simulation, Virtual Reality, Embedded Systems, Sensor Networks, Wireless Communications, Machine Learning, Data Analytics, Advanced Manufacturing Processes, etc., CMS performs as a convergence of promising and advanced Information and Communication Technologies. Particularly, Cyber-Physical System helps CMS enable manufacturing resources and capabilities to be sensed and connected to each other offline or online (Figure 1).

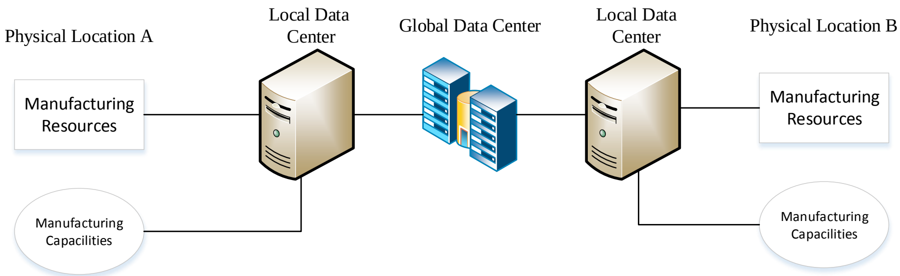
Among the previous implemented manufacturing systems, FMS (Flexible Manufacturing System) consists of CNC machines connected by automated material-handling system, controlled by computer to create an integrated system for processing palletized parts across various work stations in the systems [1]. However, the design of FMSs, which is based on the machines tools and technological components available on-site, restricts the variety of the parts to be manufactured [2], whereas CMS coordinates a pool of potentially unlimited shared, reconfigurable and scalable manufacturing resources and capabilities. Furthermore, in FMS, the automation and flexibility in control are not designed to utilize recent developments in big data analytics.

In the environment of CMS, manufacturing components and systems operate in an intelligent way and own functions such as self-awareness, self-prediction, self-optimization, and self-configuration. Various initiatives in different countries have been created to reflect and recognize this future vision, including "*Industrie 4.0*" by Germany [3], "*Monozukuri*" by Japan [4], "*Factories of the Future*" by EU [5], and "*Industrial Internet*" by GE [6].

CMS integrates complete information of product life cycle activities and manufacturing component activities by harnessing and taking advantage of the development of advanced communication and sensor techniques. CMS possesses useful characteristics such as service-orientated manufacturing, proactive and preventive maintenance (Table 1).



a. Offline (local network)



b. Online (over the Internet)

Fig. 1. CMS network

Table 1. Supporting Techniques, Information Coverage and Characteristics of CMS

Support Techniques	Manufacturing Information	CMS Service Characteristics
Sensor Network	Product Lifecycle Activities	Service-orientated Manufacturing
Embedded Systems	Opportunity Identification	Virtual Manufacturing
Virtual Realty	Concept Development	Real Time Simulation
Modeling and Simulation	Manufacturing Processes	Networked Manufacturing System
Fog Computing	Inventory Design	Proactive and Preventive Maintenance
Cloud Computing	Supply Chain Management…	Energy Management
Data Mining and Analytics	Manufacturing Component Activities	Fleet Tracking
Machine Learning	Manufacturing Operations	Supply Optimization
Advanced Manufacturing Processes	Availability	Prediction and Clustering
Service-orientated Technologies	Planned Maintenance	
	Product Quality…	

2 Architecture of CMS

The proposed architecture in this section is a hierarchical structure for showing the internal mechanism of CMS, as illustrated in Figure 2. This architecture provides as step-by-step guidance for companies or manufacturers to set up CMSs or migrate to CMSs from current manufacturing systems. In this architecture, the both ends of CMS - the physical provider layer and application/user layer - possess less fixed components and structure but more adaptability. However, the intermediate layers - core services layer - stay in a steady state and only vary by adding or removing storage or computing power. Additional intermediate or supporting components or layers can be added to the structure based on the business needs, user requirements or research emphases.

This architecture consists of five layers, mainly divided by the substances, pivotal activities and major enabling techniques within each layer. Interlinked relationships between layers also show all the possible interactive activities and information or material flow across layers. By organizing the manufacturing resources and capabilities and linking them by informational components following the proposed architecture, a CMS can thus be established and generates expected benefits.

2.1 Application/User Layer

This layer is intended to directly communicate with the users, including product developer, designer and consumers. Product development and manufacturing missions are two main issues to be addressed in this layer, depending on different phases of product life cycle. These tasks and missions are published to the application interface layer and a list of favorable solutions with auxiliary information or finished products will be returned or delivered for selection or picked up by the users, respectively.

2.2 Application Interface Layer

This layer plays a connecting role between application/user layer and core service layer, acting as a buffer of inventory and information processing. If the mission required from application/user Layer originates from the concept developing stage, opportunities will first be identified. After that, information will be extracted if the opportunity is estimated feasible. Initial concept will be formed and then iterated and enhanced.

Similarly, during the manufacturing stage, manufacturing mission will be described, digitalized for quoting and answering, bargaining, and then supervised by manufacturing processes virtualization and visualization.

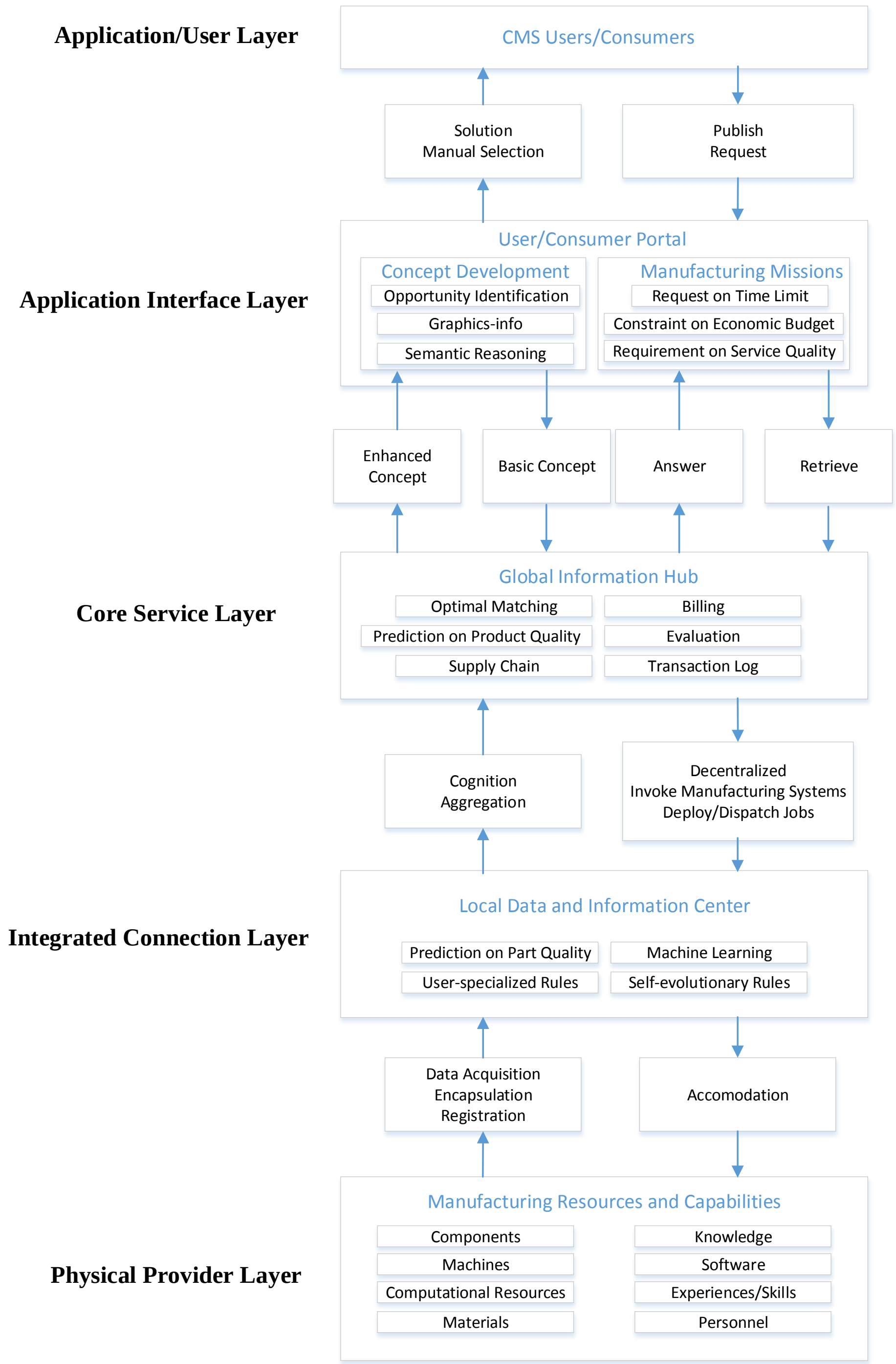

Application/User Layer
CMS Users/Consumers
Solution
Manual Selection
Publish
Request
Application Interface Layer
User/Consumer Portal
Concept Development
Opportunity Identification
Graphics-info
Semantic Reasoning
Manufacturing Missions
Request on Time Limit
Constraint on Economic Budget
Requirement on Service Quality
Enhanced
Concept
Basic Concept
Answer
Retrieve
Core Service Layer
Global Information Hub
Optimal Matching
Billing
Prediction on Product Quality
Evaluation
Supply Chain
Transaction Log
Cognition
Aggregation
Decentralized
Invoke Manufacturing Systems
Deploy/Dispatch Jobs
Integrated Connection Layer
Local Data and Information Center
Prediction on Part Quality
Machine Learning
User-specialized Rules
Self-evolutionary Rules
Data Acquisition
Encapsulation
Registration
Accomodation
Physical Provider Layer
Manufacturing Resources and Capabilities
Components
Knowledge
Machines
Software
Computational Resources
Experiences/Skills
Materials
Personnel

Fig. 2. CMS Hierarchical Architecture

2.3 Global Core Service Layer

In this layer, a global information hub with powerful storage and computation capability aggregates all the information of registered products' life cycle activities and manufacturing units in the cyber system, together with logistics information and transaction log by utilizing big data analytics technique [7]. The main function of this layer is to optimally evaluate and match manufacturing resources and capabilities along the fleet, record manufacturing behaviors and transaction activities in a global scale, where CMS adopts the mechanism of Network Manufacturing and Manufacturing Grid.

2.4 Integrated Connection Layer

Integrated connection layer serves as the local analysis and self-control center. The main activity of this layer is the encapsulation of physical manufacturing units of factory floor into meaningful information. Compared with the fully global control implemented in Cloud Manufacturing, the existence of this layer of hierarchically controlling helps avoiding the unnecessary trivial communication and controlling of the units in factory units over the cyber informational center, which significantly improves the response speed and communication efficiency. By forming a local self-control manufacturing system, manufacturing units' accommodation, job dispatch and quality prediction will become faster and more accurate. Furthermore, supervisory self-control rules and parameters will initially be set by human but will perform self-evolutionarily according to the information learnt by data acquisition from physical provider layer in sequencing system control.

2.5 Physical Provider Layer

Physical provider layer is for all manufacturing components, equipment and personnel in a factory level. The conditions of each manufacturing units might be directly measured by diverse sensors, like presence sensor and RFID, or obtained from controller or enterprise manufacturing systems, such as ERP, MES, SCM and CMM [8, 9]. This advanced sensor deployment is the infrastructure of this layer and control activities are operated by actuators executed by the signal feedback from local data and self-control center.

3 Functions of CMS

A CMS exhibits five important functions that represent all the behaviors and characteristics (Table 2). The numbering sequence is based on the implementation layer where a function is enabled. Starting from 1st to 5th, the function is moving toward core service layer and becomes more accessible to big data analytics and utilizing machine learning algorithm. Real-time acquisition, big data analytics, useful information elicitation, behavior learning, prediction and physical actuation enable all the five functions. These five functions of CMS integrate the manufacturing activities and provide a step-by-step guideline for executing CMS.

Table 2. Main Enabling Techniques, Main Benefits and Main Applications of Five Functions

Functions	Main Enabling Technique	Main Benefits	Main Application
1. Self-monitoring	Monitoring System; Sensor Deployment	Reduce WIP Inventory; Increase Productivity	Machine Failure; Fluctuation in Customer's Demands; Assembly Recipe Missing
2. Self-awareness	Expert-defined Rule; User-defined Rule; Controller Parameter	Save Mode Switching Time	Switch of the Working Modes of the Manufacturing Components
3. Self-prediction	Advanced Sensor Deployment; Adaptive Machine Learning Algorithm	Increase of Product Quality; Decrease of Finish Time; Decrease of Waiting Time	Products with High Quality Requirement; Products in Large Batch Size and of Tool-consuming
4. Self-optimization	Cloud-based Data Analytics	Reduce Finish Time	Products with Requirement on Manufacturing Finish Time
5. Self-configuration	Sensor Deployment; Manufacturing Missions Description Framework	Increase the Utilization of Manufacturing Components in Factory Floor	Machine in Low Occupation but with High Cost in Setup

4 CMS Functions in Life Cycle of Product

The above five CMS functions are implemented in different stages in product life cycle. Self-prediction comes firstly in aggregating resource and allocation of manufacturing jobs. Then self-optimization provides optimal matching of manufacturing units and self-configuration enables waiting missions ready but this function is actually implemented in later manufacturing phase. Self-awareness will be ready for any modification of the working mode of local manufacturing resources and capabilities clusters. Finally, self-monitoring will supervise the functions of all the solution arrangements in the lowest level and latest phase. The working phases of CMS for each function are shown in Figure 3.

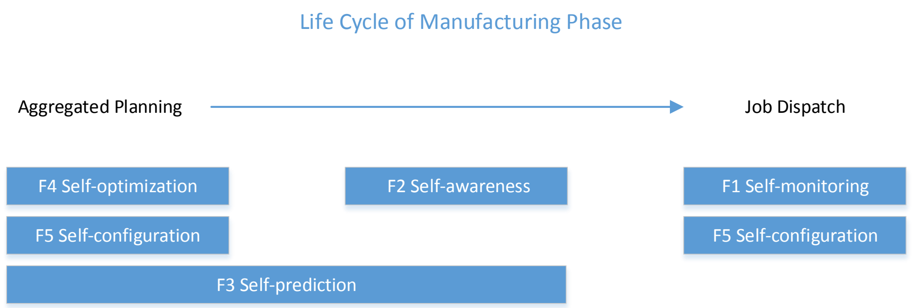


Fig. 3. Working Phase of CMS Function in Product Life Cycle

5 CMS Performance Research

In order to quantitatively and comprehensively evaluate the performance of CMS, performance evaluation and behavior studying of CMS have been conducted.

5.1 Simulation-based Evaluation

Simulation is a powerful tool in studying various complex manufacturing systems by mimicking the real system and exploring scenarios, and thus can be used to evaluate manufacturing system solutions, concepts and scenarios before implementing them in actual world [10, 11]. Various simulation tools can be used to support manufacturing system operation through data-driven decision making. Simulation studies generate data in cycle time, throughput, WIP inventory and bottleneck position. Their results can be used for physical layout design of factory floor, control policies, scheduling and routing strategy, diagnosis and other system configurations of manufacturing systems, and corresponding post what-if analysis for optimization.

Among various simulation methods, Agent-based Modeling and Simulation (ABMS), Discrete-Event Modeling and Simulation (DEMS) and System Dynamics Modeling and Simulation (SDMS) are commonly used. Among them, DEMS provides a dynamic simulation on the servicing time, utilization and bottleneck identification, which provides manufacturing system performance evaluation. Based on that, a combination of DEMS and other analysis tools can provide a broader view, more holistic and comprehensive approach with finer resolution of the results of manufacturing systems' performance. This combination has been applied in the implementation for seeking solution or detecting bottlenecks on current manufacturing systems [12, 13]. Furthermore, CMS is currently only a vision and thus has not been fully realized in industry field yet. Therefore, simulation approach is considered most appropriate and qualified method.

5.2 Examples

In this section, hypothetical examples with different scenarios are used to capture the performance in each phase along manufacturing activities. Simple but representative products, a plastic storage box, a shaft for gear box and a drone, are selected to illustrate the performance of implementation of each function. The manufacturing processes of the storage box are shown in Figure 4. The bill of material of the plastic box, shaft and drone are shown in Tables 3, 4 and 5, respectively. Processing time of manufacturing a drone is given after that, and the information partially from the paper [14]. The processing time is estimated by *WILLIT 3D PRINT* and the transfer time is estimated by *GOOGLE MAP*. Both are open source applications.

Table 3. BOM of the Storage Box

Name	Material	Number	Weight	Total Weight
Lid	PE	1	0.033kg	0.033kg
Box body	PE	1	0.012kg	0.012kg
Bolt	steel	4	0.002kg	0.008kg
Assembly	PE 0.45kg; steel 0.008kg			

Table 4. BOM of the Shaft and Support Information

Name	Material	Batch Size	Roughness requirement	Total Weight
Shaft	Steel	8000	3.6 μm	0.004kg

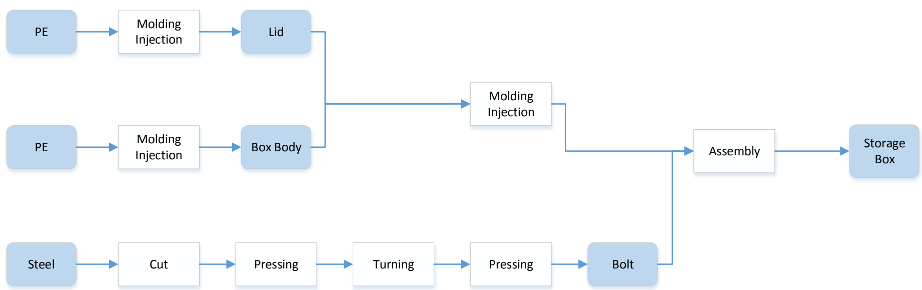


Fig. 4. Manufacturing Processes of Storage Box

Table 5. Bill of Material of Drone

Part	Dimension	Processing Time	Number
Propeller	160×4	20 min	4
Legs	10×4	15 min	4
Arm	90×4	15 min	4
Frame body	35×1	2 h	1
Shield	35×1	20 min	1
Frame body bottom	60×1	15 min	1
Gimbal	-	2 h	1
Outsourced part assembly	Assembly Other Parts	Assembly Time	Number
Motor	12 h	15 min	4
Navigation board	18 h	10 min	1
Main board	18 h	10 min	1
Camera	18 h	10m min	1
Batteries	20 h	6 min	1
Control board	20 h	7.5 min	1

According to [14], the processing time and transportation time are estimated as following table.

Table 6. Processing Time and Transportation Time of Drone

Process	Time or duration	Process	Time or duration
Load Raw Material	5 min	Transport parts to final assembly line	10 min
3D printer failure	30 min	3D printer repair	15 min
Transport assemble to warehouse	15 min	Adjust assembly line	15 min
Switch to assembly other products	15 min	Transport assembly to customer	10 h

Based on the manufacturing information of above three products, 5 scenarios serving for the evaluation of each function are created and summarized in following table.

Table 7. Hypothetical Example Studying Summary

Functions	Examples
Self-monitoring	Example 1 Failure of Tapping in Bolt Manufacturing
Self-awareness	Example 2 Set-up of Threading in Bolt Manufacturing
Self-prediction	Example 3 Turning Tool Remaining Life Prediction in Shaft Manufacturing
Self-optimization	Example 4 Optimization in Selection of Plastic Box Body Inspector Selection
Self-configuration	Example 5 Inspection of the Molding Injection Parts

6 Result and Analysis

Tables 8 shows all the simulation results based on the scenario setting in the previous chapters. Due to the limited space of this paper, the result shows the most critical indicator for measuring and evaluating the performance of each function.

6.1 Self-monitoring

Table 8. Summary of Simulation Result

Example	1	2	3	4	5	
Object	Box Body	Bolt	Finish Time	Box Body	Box Body	Lid
Indicator	Number In Queue	Number Destroyed (Productivity)	Finish Time (/h)	Time in System (/s)	Number Destroyed (Productivity)	
Comparison	CMS – Traditional	CMS – Traditional	CMS – Traditional	CMS – Traditional	CMS – Traditional	
Test	Paired-t	Paired-t	Paired-t	Paired-t	Paired-t	
Length	4 hours	1 min	70 hours	4 hours	1 hour	
Sample Size	100	100	100	100	100	
t-value	-20.845	1.3432	-301.97	-21.552	1.2189	1.42
P-value	2.2e-16	0.1823	2.2e-16	2.2e-16	0.2258	0.1587
C.I.	(-1.15, -0.95)	(-0.19 0.99)	(-27.14, -26.78)	(-20.23, -16.82)	(-5.24, 21.94)	(-4.14, 25.00)
Difference Mean	-1.05	0.4	-27	-18.53	8.35	10.43

In this example, real-time monitoring guarantees the information accurately and quickly conveying among the others components, and the action of starting or stopping of production branch in system is actuated with no delay. In this example, the average number of box body in the production system is selected for showing the performance of the system since the main benefits is to reduce the WIP inventory. Seen from the comparison results, self-monitoring brings significant decrease in waiting items. Even though the absolute storage space saved is less than 2 items, the saving in buffer or storage of the whole system will be significantly accumulated in the networked environment.

6.2 Self-awareness

In this example, the threading machine will not be ready until the arrival of first part from inspection process, from the viewpoint of traditional in-house manufacturing.

Self-awareness function of CMS will save the time on set-up preparation by arousing them in advance upon the detection of coming parts. The benefit mainly shows as the increase of productivity or saving of time. The result shows the difference is not significant since the saving of preparation time or other working mode switching time of one component makes little effect compared with other uncertainties in a production line, such as downtime and stochastic processing time, etc. However, the accumulation of this time saving in production system will greatly shorten the final finishing time.

6.3 Self-prediction

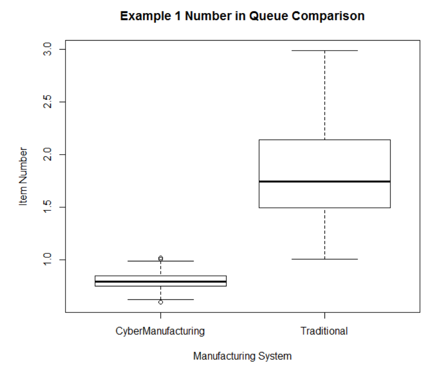
In this example, prediction on tool life and avoidance on possible occurrence of tool breakdown or repair time will significantly save total manufacturing time and the unnecessary loss of tools. Manufacturing time can be used to represent the benefits. Seen from the result, a significant time saving has been achieved.

6.4 Self-optimization

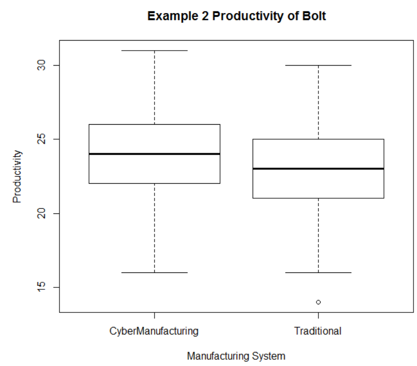
Traditionally, the mission will be more likely to be evenly or randomly assigned to all the available equipment in the factory floor. In CMS, a list of available and favorable manufacturing resources will be ranked and sorted by multi-criteria specified by manufacturing tasks. A smart matching of manufacturing resources may bring either significantly increased productivity output given a fixed manufacturing time or a shorter finishing time given a batch size. Moreover, the variance brought by uncertainties in production system will be greatly reduced by real-time sensor system and dynamic optimization arrangement.

6.5 Self-configuration

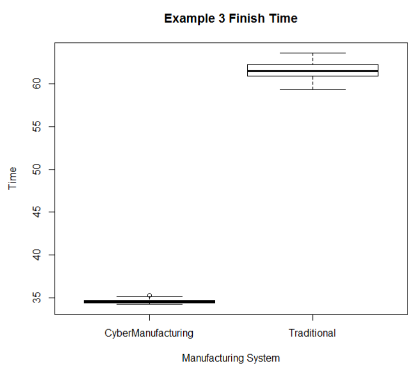
In manufacturing systems, bottleneck processes usually stay in occupied status while the rest processes are always starving. For starving manufacturing components in cyber system, a list of manufacturing missions from the cyber information center are on hold and waiting to be processed, resulting in maximization of these components' utilization. In this example, the inspection worker is overqualified for only coping with inspection mission of box body. The waiting task assigned from cyber center is lid inspection. The result shows a slight increase of productivity of box body, which validates the premise that the current manufacturing mission will not be influenced. In the same time, the production line also makes accomplishment of checking 10 lids by utilizing the idle time of the inspector. The results illustrate that this function not only helps manufacturing units to fully achieve current manufacturing goals, but also makes some extra progresses in on other manufacturing missions.



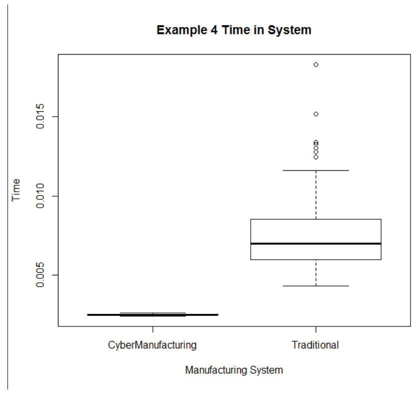
a. Example 1



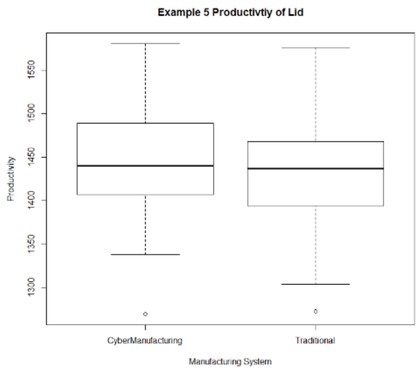
b. Example 2



c. Example 3



d. Example 4



e. Example 5

Fig. 4. Simulation Result Boxplots

In order to quantify the performance change by migrating to CMS, an index system has been developed.

Table 9. Performance Indices Metrics Coefficients Table

	Lid	Box Body	Box Assembly	Bolt	Shaft
Product Revenue ($\$/unit$)	P_{Lid}	$P_{Box\ Body}$	P_{Box}	P_{Bolt}	P_{Shaft}
Time Cost ($\$/(s \cdot unit)$)	TC_{Lid}	$TC_{Box\ Body}$	TC_{Box}	TC_{Bolt}	TC_{Shaft}
Waiting Storage Space Cost ($\$/unit$)	SC_{Lid}	$SC_{Box\ Body}$	SC_{Box}	SC_{Bolt}	SC_{Shaft}

According to the developed coefficients table, the improved performance can be aggregated as in the following table.

Table 10. Summary of Benefits by Implementing CMS Function in Examples

Example	Function	Time Length or Batch Size	Benefits(/$)
Ex. 1	Self-monitoring	4 hours	$1.5 * SC_{Box\ Body}$
Ex. 2	Self-awareness	1 min	$0.4 * P_{Bolt}$
Ex. 3	Self-prediction	8000 units	$27 * TC_{Shaft}$
Ex. 4	Self-optimization	4 hours	$106560 * TC_{Box\ Body}$
Ex. 5	Self-configuration	1 hour	$10.43 * P_{Lid} + 8.35 * P_{Box\ Body}$

From the results, reduction on waiting time, inventory cost, storage space, and increase on productivity and product quality are shown as the main benefits of CMS. Even though not in the same significance level, these key performances indicators measured by evaluation framework shows the change and improvement when migrating to CMS from solely in-house traditional manufacturing system. By rapid communication and adaptive behavior learning in different levels, quick accommodation, better manufacturing mission dispatch, optimal manufacturing component utilization will be achieved.

7 Discussion and Conclusion

CMS is new concept and requires additional work on its definitions and implementation details. This research covers from definition, architecture, uniqueness, functions, performance evaluation and simulation studying, forming a multi-facet, comprehensive learning on CMS. Integrating all the necessary manufacturing information, CMSs give better solution in solving the bottleneck in material & energy consumption, increase of manufacturing efficiency and pricing strategy.

This work provides explorative insights into behavior pattern and characteristics of CMS thus performance assessment with preliminary benefits analysis related with leveraging CMSs. However, more comprehensive models are needed for further studying the working pattern and whole behaviors of CMS. More work and devotion in this area will enable the CyberManufacturing to be quickly developed into a well-defined manufacturing system. This research will convince researchers of the general benefits brought by CMS and enlighten them to further and deeper pursue understanding and application of CMS.

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