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Sustainability Benefits Analysis of CyberManufacturing Systems

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ABSTRACT

Confronted with growing sustainability awareness, mounting environmental pressure, meeting modern customers' demand and the need to develop stronger market competitiveness, the manufacturing industry is striving to address sustainability-related issues in manufacturing. A new manufacturing system called CyberManufacturing System (CMS) has a great potential in addressing sustainability issues by handling manufacturing tasks differently and better than traditional manufacturing systems. CMS is an advanced manufacturing system where physical components are fully integrated and seamlessly networked with computational processes. The recent developments in Internet of Things, Cloud Computing, Fog Computing, Service-Oriented Technologies, etc., all contribute to the development of CMS. Under the context of this new manufacturing paradigm, every manufacturing resource or capability is digitized, registered and shared with all the networked users and stakeholders directly or through the Internet. CMS infrastructure enables intelligent behaviors of manufacturing components and systems such as self-monitoring, self-awareness, self-prediction, self-optimization, self-configuration, self-scalability, self-remediating and self-reusing. Sustainability benefits of CMS are generally mentioned in the existing researches. However, the existing sustainability studies of CMS focus a narrow scope of CMS (e.g., standalone machines and specific industrial domains) or partial aspects of sustainability analysis (e.g., solely from energy consumption or material consumption perspectives), and thus no research has comprehensively addressed the sustainability analysis of CMS. The proposed research intends to address these gaps by developing a comprehensive definition, architecture, functionality study of CMS for sustainability benefits analysis. A sustainability assessment framework based on Distance-to-Target methodology is developed to comprehensively and objectively evaluate manufacturing systems' sustainability performance. Three practical cases are captured as examples for instantiating all CMS functions and analyzing the advancements of CMS in addressing concrete sustainability issues. As a result, CMS has proven to deliver substantial sustainability benefits in terms of (i) the increment of productivity, production quality, profitability & facility utilization and (ii) the reduction in Working-In-Process (WIP) inventory level & material consumption compared with the alternative traditional manufacturing system paradigms.

SUSTAINABILITY BENEFITS ANALYSIS OF CYBERMANUFACTURING SYSTEMS

by

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1 Introduction to CyberManufacturing Systems

1.1 Definition of CyberManufacturing System

CyberManufacturing System (CMS) is an advanced manufacturing system where physical components (e.g., 3D printers and CNC machines) are fully integrated and seamlessly networked with computational processes (Song and Moon 2016a). CMS incorporates the recent advancements in Internet of Things, Cloud Computing, Cyber-Physical System, Fog Computing, Service-Oriented Technologies, Modeling and Simulation, Virtual Reality, Sensor Networks, Machine Learning, Data Analytics, and Advanced Manufacturing Processes, etc. In the context of CMS, manufacturing resources and capabilities are digitized and encapsulated into production services, and then shared with all users and stakeholders in the network. Components in CMS communicate and collaborate with each other through online data handling, intelligent functions and self-management capabilities (Adamson et al. 2016). Therefore, CMS offers on-demand, optimal and sustainable manufacturing solutions (Zhang et al. 2014; Wu et al. 2017). Supported by the development of advanced communication and sensor techniques, CMS incorporates a full range of manufacturing operations & activities and provides advanced features as shown in **Table 1**. CMS shares the vision of Industry 4.0 that attempts to accommodate (i) customers' growing individualized and customized needs and (ii) manufacturers' increasing collaboration requirements. CMS becomes one of the most promising manufacturing paradigms.

Countries around the world are actively developing similar initiatives in practice. In Germany, a continuous march to the informatization, ubiquitous computing, and wirelessly networked microcomputers has helped the formation of "*Industrie 4.0*" (Wang, Törngren, and Onori 2015).

GE created the notion of "*Industrial Internet*," which emphasizes the connection between intelligent machines & people with advanced analytics methods (Posada et al. 2015; Evans and Annunziata 2012). In a similar industrial and technical context, "*Factories of the Future*" was created by the European Union and aims to set up decentralized data pools for collecting and processing all information from production systems (Mavrikios et al. 2013; Herrmann et al. 2014).

Table 1 Supporting Techniques, Incorporated Manufacturing Operations & Activities and Advanced Features of CMS

Supporting Techniques	*Incorporated Operations & Activities*	*Advanced Features*
• Sensor Fusion System • Internet of Thing • Virtual Reality • Modeling and Simulation • Cloud Computing • Fog Computing • Data Mining and Analytics • Machine Learning • Advanced Manufacturing Processes • Service-orientated Technologies	• Product Design/Co-design • Production Plan Generation • Digitalization of Manufacturing Requests • Manufacturing Resource Servitization • Production Progress Monitoring & Clustering • Business Evaluation & Profit Distribution	• Service-orientated Manufacturing • Virtual Manufacturing • Pay-per-use Billing Strategy • Real-time Simulation • Networked Manufacturing System • Proactive and Preventive Maintenance • Fleet Tracking • Supply Optimization • Prediction and Clustering

1.2 Uniqueness of CMS

CMS distinguishes itself from other types of manufacturing systems by its improved manufacturing performance and advanced features. **Figure 1** illustrates an overview regarding the development of different manufacturing systems as well as the comparisons between each manufacturing system type and CMS. The summary comparisons are elucidated as follows.

1.2.1 Computer-integrated Manufacturing and Flexible Manufacturing Cell

Computer-integrated Manufacturing (CIM) utilizes computers and exchangeable &

interoperable databases (i) to bring islands of enabling technologies into an interconnected manufacturing system and (ii) to automate the entire manufacturing processes (Yu, Xu, and Lu 2015). CIM was an early application of information technology in manufacturing with the aim of increasing the productivity and responsiveness of manufacturing enterprises. As an early attempt of CIM, Flexible Manufacturing System (FMS) consists of computer-controlled machines clusters connected by automated material-handling systems to create an integrated system for processing palletized parts across various workstations in the system (Yusuf, Sarhadi, and Gunasekaran 1999). FMS has the flexibility of addressing production within a factory, but FMS cannot fulfill the production requests that require the capabilities that cannot be provided onsite (Kusiak 1986). Furthermore, CIM and FMS execute the control and automation by using predetermined rules, and thus cannot properly respond to dynamic scenarios and new uncertainties.

By contrast, CMS coordinates a pool of potentially unlimited shared, reconfigurable and scalable manufacturing resources, capabilities and techniques residing over off-site geographical locations or regions. Therefore, CMS substantially expands the variety of product types that can be produced, and enables manufacturing requests to be resolved globally. In addition, CMS performs an ever-growing knowledge base, where production plans, operations and accommodations are adjusted to a variety of scenarios and production modes.

1.2.2 Agile Manufacturing and Virtual Enterprise

Agile Manufacturing (AM) is a concept for manufacturing systems that create processes, tools and training as quick responses to the customers' requirements and market changes. AM are mutually compatible with Lean Manufacturing, CIM, etc. (Yusuf, Sarhadi, and Gunasekaran

1999). Virtual Enterprise (VE) is one of the core enablers of AM that facilitate customers to attain the product that they want. VE is a task-based virtual network that links, absorbs (or remove) alliances or strategic partners into a shared network. It rises for the purpose of using the business opportunities that any individual subject is not able to use independently (Januska and Chodúr 2009). VE is the early implementation of sharing manufacturing resources, information and capabilities (Cao and Dowlatshahi 2005). However, the opportunity-driven, context-specific and temporarily-built attributes of VE make it hard to win creditability in the real business setting.

CMS aligns the advanced information technology with the manufacturing capability sharing, customer engineering, skill & knowledge platform—the main drivers of manufacturing agility (Sanchez and Nagi 2001). Furthermore, CMS owns full registrations of all the manufacturers and participators. When responding to manufacturing requests, CMS provides production plans with a declaration of the full production history of all involved manufacturers and participators, which helps CMS win bargaining power, customers' trust and market share (Jiang, Ding, and Leng 2016).

1.2.3 Networked Manufacturing and Manufacturing Grid

Networked Manufacturing (NM) and Manufacturing Grid (MGrid or MfgGrid) utilize network or grid technology to overcome the physical barriers of manufacturing resources and to achieve manufacturing resources sharing and collaborative connections. However, the resource sharing of network-based manufacturing still lies in the network domain, whereas CMS presents the commodity of virtually infinite resources and elastic scalability (Ferreira et al. 2017) supported by well-developed pricing, profit distribution and internet safety strategies (He and Xu 2015).

These main limitations in applying NM and MGrid, including the timeliness of organizing resources, immature technology in the description of resources and lack of supporting techniques, can be properly addressed in CMS (Tao 2007).

1.2.4 Cloud Manufacturing

Cloud Manufacturing owns most overlapping with CMS. Cloud Manufacturing paradigm is a replication of the cloud computing environment using physical manufacturing resources in lieu of computing resources (Argoneto and Renna 2016). Tao et al. (2011), Xu (2012) and Wu et al. (2013) initialized the definition, structure design and operation development, and instantiated Cloud Manufacturing concept through introductory cases. Both Cloud Manufacturing and CMS show sufficient advancements in the realization of full utilization, sharing and circulation of diversified and distributed manufacturing resources and capabilities, which allows customers to access the resources as if they are in a single facility (Tao et al. 2011). What CMS emphasizes is the implementation of Internet of Thing and Cyber-Physical Systems for achieving seamless integration & collaboration and fine-grained monitoring & management. Unlike the centralized controlling manner of Cloud Manufacturing (Bi, Da Xu, and Wang 2014), CMS assigns the trivial, basic control and communication, raw data to be processed at the local level or offline, and thus saving computation power and guaranteeing a higher efficiency than from the central communication and controlling mechanism. Therefore, CMS can be regarded as the latest convergence of the advanced features & visions of previous manufacturing paradigms and has the potential of yielding the greatest competitive advantages.

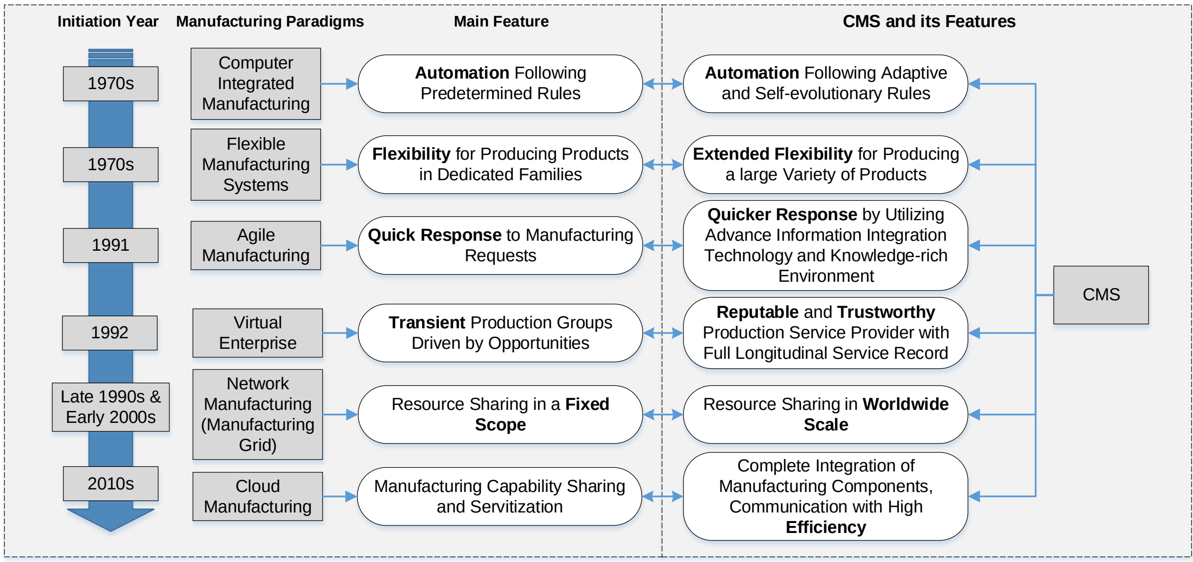


Figure 1 Comparison between Existing Manufacturing System Paradigms and CMS

1.3 Drone Example: An Introductory Example of CMS Operations

In this section, the life cycle manufacturing activities of a drone (shown in **Figure 2**) are selected to illustrate the differences between CMS and traditional manufacturing approaches. The manufacturing operations via traditional and CMS approaches for developing and producing the drone are summarized in **Table 2**.

Table 2 Traditional Manufacturing Operations and CMS Operations Comparison

Manufacturing Activities	*Traditional Manufacturing Operations*	*CMS Operations*
1. Marketing	Survey among Local Customers	Search from *Facebook* and *LinkedIn* by Semantic Web-based Engine
2. Design Generation	**Local** Expert, Engineers and Technician	**Co-design** by Online Community of Designers, Engineers, and Fabricators
3. Access to Software (*CAx*)	**Purchase** Software License	Periodically Subscribe
4. Modeling	Create & Modify 3D Models by **CAD**	Create & Modify 3D Models by **CAD 360**
5. Simulation	Perform FEA & CFD in Local Computer Clusters	Perform FEA & CFD by **Using Amazon EC2**
6. Frame/Propeller Production	**Purchase** 3D Printers, **Print** Frame	**Outsource** to 3D Printing Suppliers in **Quickparts.com**
7. Shield Production	**Purchase** Molding Injection Machines or 3D Printers, **Print**	**Outsource** to 3D Printing Suppliers in **Quickparts.com**

	or **Mold** Parts	
8. Batteries Purchasing	Purchase from **Local** Stores	Purchase from Suppliers in **Thailand**
9. Control Section (Main Board)	Purchase from **Local** Stores	Purchase from Suppliers in **China**

Figure 2 Drone Model

The comparison and discussion of the performance of both manufacturing approaches are described below.

1. During the marketing phase of drone concept development, customer survey is normally conducted in local areas. In CMS, more universal needs and requirements of global customers can be extracted, collected and incorporated, which substantially helps expand the market and increase the potential sale.

2. In the product design phase, traditionally, the concept is limited by the knowledge and experience owned by the local experts, technicians and engineers. In CMS, a broader pool of knowledge, innovative idea as well as specialized expertise will offer a knowledge-intensive platform, where all the functionality requirements could be better resolved.

3. Modeling software is a necessity during the product design and test phases. Traditionally, software licenses are the prerequisite of the accesses to the software, and license purchase is costly for commercial purposes. CMS offers a relatively affordable solution of periodic subscription of software usage, which is a “pay-per-use” purchase strategy.

4. After modeling drone, FEA and CFD simulations for knowing the strength and flying performance are needed for the investigation of its functionality, which imposes heavy computational loads on local computing clusters with limited RAM and CPU power and takes a long time for computing. Unlimited computing and storage resources like *Amazon EC2*, *Google Azure*, etc., could offer sufficient computing capacity, significantly reduce the computing time and avoid the cost of updating IT capitals.

5. In the manufacturing phase, plastic parts could be produced by 3D printing or molding injection. CMS provides a list of qualified suppliers, such as *Saleforce.com* and *3D Hub*, along with online quotes. The best selection can be made by comprehensively considering the cost, product quality and completion time among the candidate options.

6. Batteries and the main board are outsourced parts. Better prices can be provided by the nations or regions which have better accesses to corresponding raw materials and workforce, or specialized technologies of some dedicated parts. This change not only saves economic budgets, but also offers job openness in other labor-intensive countries and regions.

The drone production is a representative example which encapsulates a comprehensive spectrum of general manufacturing activities and initializes a qualitative discussion of a variety of cost drivers. Seen through the discussion, in CMS the drone is designed based on a broader customers base and more solid technical references, which are traditionally unavailable. CMS helps avoid over-purchase of unnecessary infrastructures which will usually stay idle in future manufacturing. For outsourcing parts, CMS refers to more economical strategies. Therefore, the above comparison sufficiently shows the viability and competitiveness of CMS.

2 Literature Review

2.1 Surveys of Main Enabling Techniques

CMS is mainly enabled by technical realization of (i) Cloud Computing, (ii) Internet-of-Thing and (iii) Cyber-Physical System, etc., into the manufacturing context. These main enabling techniques transform the conventional product-oriented manufacturing business model into a service-oriented paradigm.

2.1.1 Cloud Computing

The main thrust of Cloud Computing is to provide on-demand and shared computing services to all computing devices with high reliability, scalability and availability in a distributed environment (Xu 2012). CMS adopts the paradigm of Cloud Computing and utilizes a service-oriented networked product development model and on-demand accesses of manufacturing resources (Wu et al. 2015). Enlightened by Cloud Computing techniques, manufacturing resources in CMS are transformed into an analogous form of computing power. At the same time, Cloud Computing provides adequate computing capability for storing and analyzing manufacturing and production data. "Cyber" in CMS—as well as the "Cloud" in Cloud Computing—describes the place where operational data of all connected products are stored and analyzed (Herterich, Uebernickel, and Brenner 2015).

2.1.2 Internet of Thing (IoT)

IoT can be described as "the network of physical objects or 'things' embedded with electronics, software, sensors and connectivity to enable it to achieve greater value and service by exchanging data with the manufacturers, operators and other connected devices." These entities in IoT are the "things" that are expected to be capable of collaborating with other entities through Internet, leading to innovative services with high efficiency and productivity (Lu and Cecil 2016). IoT shapes CMS by facilitating the coordination of data-driven products design & production and minimizing the role of humans' manipulation (Tao et al. 2011; Yeo, Chian, and Ng 2014). RFID, embedded system, wireless, collaborative robots, sensor devices and electronic products help build up shop-floor infrastructures and manage product life cycle activities in CMS (Zhong et al. 2016; Tao et al. 2014).

2.1.3 Cyber-Physical System (CPS)

Cyber-Physical Systems (CPS) is a meta-concept to CMS and defined as "transformative, coordinated and integrated technologies for managing interconnected systems between its physical assets and computational capabilities" (Lee, Bagheri, and Kao 2015). The adoption of CPS in CMS was driven by the increasing importance of the integration between interconnected computing systems and the physical assets (Wang, Törngren, and Onori 2015). The rapid development of IoT and the affordability of the sensor devices greatly facilitate CPS. CPS and the other enabling technologies are contributing to the complete development of worldwide CMS network (Yue et al. 2015; Wang, Törngren, and Onori 2015).

2.2 Sustainability Benefits and Sustainable Manufacturing

The survival of humanity depends on sustainability; human groups who recognized the significance of sustainability were less vulnerable to resource limitations and showed robustness towards all ecological uncertainties. Sustainability is "the strategic countermeasures for environmental degradation and natural resource depletion" (Michelini and Razzoli 2004). The most widely accepted general definition of sustainable development is provided by the United Nations' Brundtland (1987) Commission: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The sustainability improvement effort must yield benefits at elemental levels involved in (i) reducing environmental impacts, (ii) increasing economic feasibility, and (iii) facilitate societal well-being (Jayal et al. 2010b). The checklist of elemental sustainability benefits is summarized in **Table 3**. Each individual item is a criterion for measuring to what extent sustainability is improved, and serves as an instructional metric for evaluating the sustainability of any industrial practice.

Table 3 Checklist of the Sustainability Benefits

Environmental Benefits	*Economic Benefits*	*Societal Benefits*
• materials saving • energy saving • wastes reduction • emission reduction • land use saving	• incremental productivity • decreased defective rate • cost-effectiveness • efficient transportation • reasonable investments	• satisfaction of customers' requirements • stable employment • good reputation • good prospects

Manufacturing, the driving force of global development, has a profound impact on all three pillars of sustainability: environmental stewardship, economic growth and societal well-being. Consequently, a sustainable manufacturing framework is described as the “creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound” (International Trade Administration 2007; The U.S. Department of Commerce 2010). Rather than driven solely by the profit of productivity, manufacturers are oriented towards the holistic well-being of all stakeholders, which complies with the rising public attention and stricter sustainability provisions (Ocampo, Clark, and Promentilla 2016). Manufacturers begin setting sustainability-oriented goals, deploying sustainably conscious infrastructures and developing or adopting sustainable manufacturing techniques (Haapala et al. 2013). On the demand side, more customers now wish that their products could be created in a sustainable manner (Joung et al. 2013). To make manufacturing sustainable, product designs are studied with regards to the whole life cycle of sustainability performance. Optimal implementation processes are devised to impose the least sustainability burden and efficient coordination among manufacturing systems. Researchers are developing new manufacturing processes and equipment that could reduce ecological footprints. Major sustainability challenges for manufacturing industries include reducing costs and resource consumption, improving production quality, shortening the lead time, and lowering inventory level—all together.

2.3 State-of-the-Art CMS Sustainability Study

CMS owns advanced sustainability-bearing features (e.g., resource sharing, servitization and self-manage capabilities). Therefore, it has attracted academic and industrial efforts in the exploration of CMS sustainability virtues. Xu et al. (2014) proposed the advancement of CMS in energy efficiency. Chen (2014) utilized a SWOT (strength, weakness, opportunity, and threat) framework in analyzing the semiconductor industry in CMS. Wu, Terpenny, and Gentzsch (2015) implemented cost-benefit analysis to investigate CMS paradigm from the perspective of economic feasibility. Wang et al. (2015) developed the extensive application of CMS into the recovery and recycling of Waste Electrical and Electronic Equipment (WEEE). Xie et al. (2015) assessed the performance of cyber-based task scheduling of CNC machine by utilizing sustainability indicators in quality, time, cost, resource consumption and environmental impacts. Watanabe et al. (2016) created a sustainability indicator taxonomy and evaluated the sustainability performance of online reconfiguration functions of CMS. Zhao et al. (2017)

studied the sustainability performance of industrial robots' intelligent applications in CMS mainly from the perspective of energy consumption. The economic feasibility and energy/resource efficiency of cloud-based distributed manufacturing network were respectively investigated by (i) Rauch, Dallasega, and Matt (2017) and (ii) Rauch and Dallasega (2017). Gao and Wang (2017) discussed the sustainability benefits of machining tools along life cycle activities. Seen through these researches, sustainability performance study of CMS starts winning researchers' and practitioners' attention. The increase in resource utilization, energy efficiency, facility utilization, and the increase in profitability & productivity are the identified benefits of CMS. However, the existing works are suffering the limitations of (i) narrowing down the research objects on only subsets of CMS (e.g., standalone machines, implementation technologies and specific industrial domains) and (ii) the incomplete evaluation from certain partial sustainability aspects rather than the comprehensive perspective.

For addressing these limitations and analyzing the sustainability performance of CMS, this dissertation elaborates a comprehensive framework development of CMS and sustainability performance assessment. The layout of the remaining paper is as follows. Chapter 3 introduces the architecture of CMS, which presents the general framework of CMS along with all the constituent components; Chapter 4 elaborates the intelligent functions of CMS; Chapter 5 raises a sustainability assessment framework which could be used to comprehensively benchmark the sustainability advancements of CMS over other types of manufacturing systems; manufacturing scenarios are developed for verifying the effectiveness of CMS functions via simulation studies in Chapter 6; concrete sustainability benefits analysis will be in detailed discussed and analyzed by utilizing three complete and practical case studies in Chapter 7, where all CMS functions are instantiated; finally, the discussion and conclusion about the sustainability viability & benefits of CMS will be provided in Chapter 8 and Chapter 9.

3 Architecture of CMS

Architecture of a system is the graphical presentation of the system's constitution. CMS architectures were developed for introducing CMS paradigm in previous studies (Tao et al. 2011; Adamson et al. 2016). However, the presented architectures only list standalone manufacturing components and don't adequately show the integrations of components along with the emerging properties. These architectures can hardly provide any insight for sustainability performance of CMS. Therefore, this chapter employees a multilayer hierarchical architecture (**Figure 3**) for manifesting functional components, interactions and information/material flows in the CMS network along with the emerging sustainability values. The detailed discussion of each layer is given in the following paragraphs.

3.1 Application/User Layer

CMS end-users, including product developers, designers and normal customers, are the main actors in this layer, where all manufacturing requests are initialized and production services are requested. CMS users will be involved closely with collaborators who specify all essential production details and adjust cyber services according to their needs & preferences through interactive loops (Tzafilkou, Protogeros, and Koumpis 2015). During the design creation phase, consumers could provide the descriptive statements of the required function, volume, price of the expected production and other specificities, the responses will be a list of favorable manufacturing solutions along with the estimate cost, completion time and reputation of each deployed manufacturing component. CMS users further manually filter and confirm their selections. *Application/User Layer* helps CMS better capture the users' requirement details and avoid creating unacceptable productions. The better user-involvement also helps improve the user-perceived service quality and win their trust & confidence.

3.2 Application Interface Layer

Application Interface Layer acts as the buffer of the manufacturing request information processing. A production request will be converted into a sequence of implementable production procedures in this layer. The conversion is enabled by semantic reasoning, pragmatics renderer, text mining, machine learning algorithm and statistical analysis (Jian and Wang 2014; Ferreira et al. 2017). CMS accumulates historical manufacturing records and forms an ever-growing knowledge base, which serves as the training database for solving requests with executable production procedures (Cui, Ren, and Zhang 2016). At the same time, CMS offers user-friendly and graphics-information-based co-design interfaces which help CMS users specify all essential production plan details in a manner of frequent interaction, iterative revision and negotiation (Ren, Cui, et al. 2015). Then, complete production documents that consist of the dimensions, materials, production procedures, workloads and durations will be finalized and parameterized into a digital form of the manufacturing request (Kassim et al. 2017); the working hours for the production procedures specified in the request along with the instant quoting of the project will also be derived (Chen and Chiu 2017). Then the digital packet of the required productions procedures will be uploaded along with the submission of the manufacturing request to *Core Service Layer*.

3.3 Core Service Layer

Core Service Layer acts as a global information hub. Digitized manufacturing requests from *Application Interface Layer* will be aggregated for retrieving and matching with the production services from *Integrated Connection Layer*. The main function of *Core Service Layer* is to

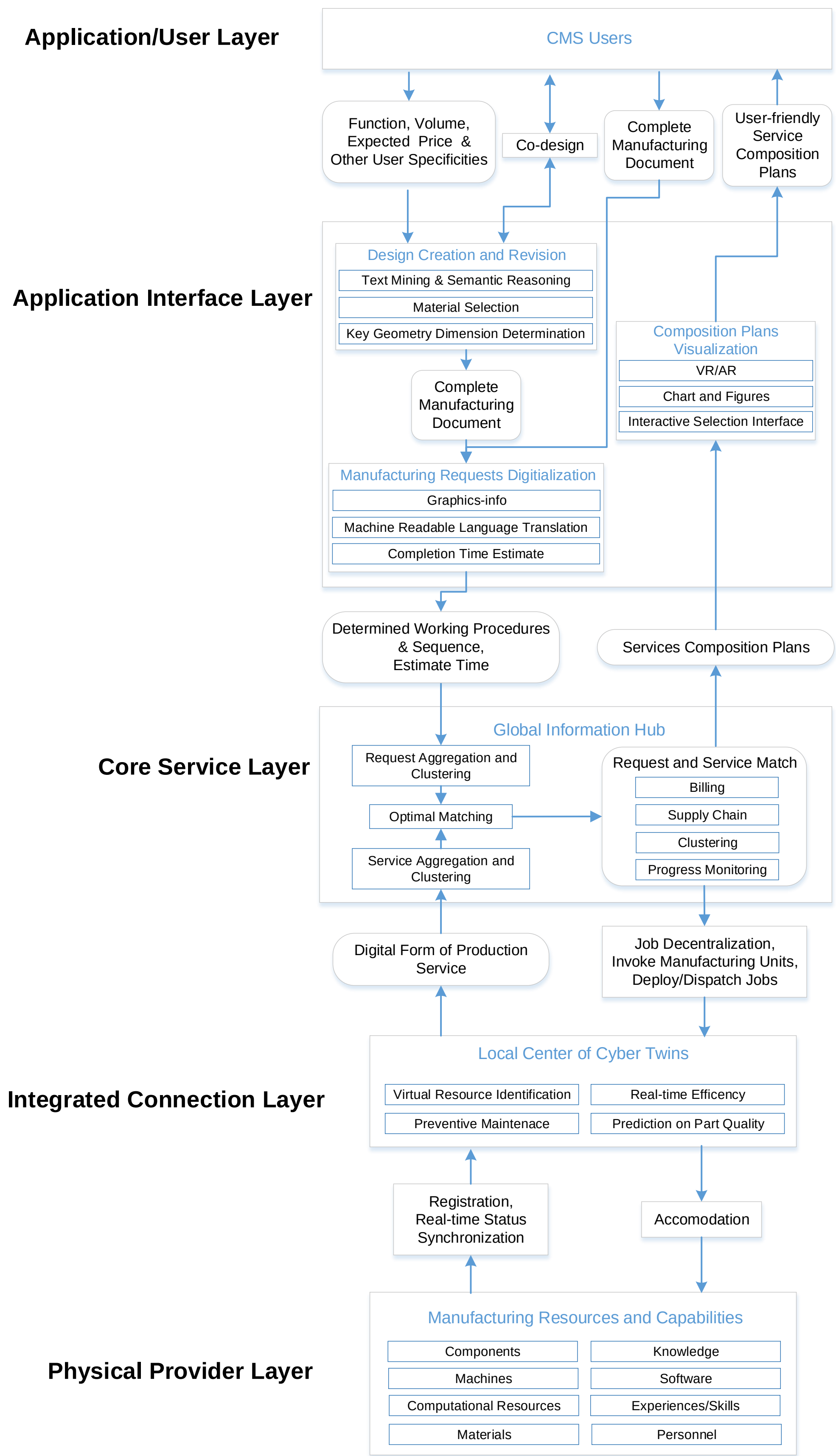


Figure 3 CMS Hierarchical Architecture

enable the optimal matching by utilizing big data analytics technology (Wu et al. 2015; Tao et al. 2011). In *Core Service Layer*, the progress of ongoing productions are real-time monitored and managed (Song and Moon 2017). Taking advantages of the worldwide scope of *Core Service Layer*, complex manufacturing requests will be globally resolved within short response time. *Core Service Layer* also optimizes the production services discovery, selection and composition, and facilitates inter-/intra-organizational workflows and business processes.

3.4 Integrated Connection Layer

Integrated Connection Layer serves as the local analysis and self-control center. *Integrated Connection Layer* coordinates the computing loads between *Core Service Layer* and itself. Specifically, fundamental-level data processing and local optimization could be addressed in the local level, and, consequently, the overall communication efficiency, utilization of bandwidth and response time could be significantly enhanced (Wang et al. 2017). The main function of this layer is to real-time synchronize the working conditions (current availability, manufacturing efficiency, production quality, tool health condition and reputation, etc.) of the physical manufacturing units via Cyber-Physical Interfaces, like Digital Equipment Identifier, RFID and Function Blocks (Chen and Lin 2017; Bao et al. 2012; Feldmann et al. 2013; Ren, Zhang, et al. 2015). CMS utilizes web languages or service descriptive languages to pack the dynamic characteristics of the manufacturing units as production services at different levels of abstraction, and thus facilitates the discovery of manufacturing resources/capabilities (Zhu, Zhao, and Wang 2013; Hu et al. 2017). The visualization techniques, like Virtual Reality, and just-in-time simulation, are also used for simplifying the understanding, interaction, decision-making, onsite or remotely control & supervision for facilities manipulators (Constantinescu, Francalanza, and Matarazzo 2015; Choi et al. 2015; Chen, Wang, and Lin 2017).

3.5 Physical Provider Layer

Physical Provider Layer is colonized by all the manufacturing resources and capabilities in distributed factory floors. Manufacturing resources include the tangible and quantifiable resources, including materials, computation resources and machines. Manufacturing capabilities consist of usage of software, analysis tools, know-how data, standards, knowledge or expertise and professional personnel. The deployment of Cyber-Physical Interfaces is the infrastructure of this layer and enables the synchronization of the working conditions as well as the real-time implementation of intelligent functions and operations (Chen and Lin 2017; Bao et al. 2012; Feldmann et al. 2013; Ren, Zhang, et al. 2015). *Physical Provider Layer* enables flexible production job allocation as well as scalable production capacities. The reusability & responsiveness of each participatory manufacturing resource and capability also increase.

The five-layer CMS architecture interprets the internal mechanism of CMS, where manufacturing requests could be responded and processed by a series of coherent activities and practical solutions. Additional intermediate or supporting components/layers can be added to the structure based on the business needs, user requirements, task specification, or research emphasis, etc. The whole architecture allows manufacturing resources and capability to be efficiently shared, allocated, circulated and arranged, and reflects the agility and responsiveness of CMS. Manufacturers or industrial practitioners could set up their own concrete CMS or migrate to CMS from current manufacturing systems by referring to this architecture.

4 Intelligent Functions of CMS

A total of eight intelligent functions (**Table 4**) have been identified to illustrate the characteristics of CMS (Song and Moon 2017). The name of each function starts with “self,” which emphasizes the automation and intelligence with minimal human interventions (Song and Moon 2016b; Lee, Bagheri, and Jin 2016). Each function is responsible for its respective responsible manufacturing activities and providing strategies for decision-making processes. The following paragraphs will elucidate each function from the perspective of definition, enabling techniques, and benefits.

4.1 Self-monitoring

Self-monitoring is to synchronize the working conditions of the manufacturing components from the physical side to the cyber side via sensor systems. This function mainly takes place in *Physical Provider Layer*. Monitoring data from sensor systems (integrated by image sensor, acoustic sensor, temperature sensor, accelerometer and energy sensor among others) are used to construct cyber twin of the physical counterpart and tell the knowing of the components instead of regular dashboards and human judgments (Xu 2017). Meaningful inferences are drawn from heterogeneous sources of sensor data via information fusion techniques (Mourtzis et al. 2016). Production uncertainties (e.g., “failure,” “defectiveness,” “unavailability of secondary material,” “arrival of urgent demand,” “repetition,” “loss,” “wrong sequence” and “delay”) along with possible root causes will be rapidly recognized. Early knowing of the uncertainties will significantly help reduce time delay and mitigate adverse consequences, making continuous production lines with near-zero downtime.

Table 4 Main Enabling Techniques, Responsibilities, Taken Measures and Benefits of CMS Functions

Functions	*Enabling Techniques*	*Main Responsibilities*	*Main Taken Measures*	*Main Benefits*
Self-monitoring	Sensor Deployment, Monitoring System	Detect Uncertainty	Stop the malfunctioning production line	Save WIP and completion time
Self-awareness	Sensor Deployment	Recognize Changeover	Setup/shut down or switch between normal/peak working modes	Save changeover time or save energy consumption
Self-prediction	Advanced Sensor Deployment, Adaptive Machine Learning	Estimate Tool Health and Production Quality	Offer estimate tool remaining useful lifetime and estimate quality	Prevent tool failure, increase production quality
Self-optimization	Sensor Deployment, Big Data Analytics	Maximize Manufacturing Efficiency	Dynamically revise working plans	Increase manufacturing efficiency
Self-configuration	Sensor Deployment	Maximize Utilization	Dynamically configure scheduling of machines	Increase facilities utilization rate
Self-scalability	Production Capabilities Servitization Framework	Adjust the Production Capacity	Scale up and down the production capacity	Meet requests with different demand volumes
Self-remediating	Progress Monitoring	Make up Production Loss of Time-critical Projects	Take the progress of normal priority production	Reduce time penalty and costly inventory
Self-reusing	Production Information	Reuse the Remaining Values and Functionalities of Afterlife Products	Identify the remaining values/functionalities in four levels	Enrich the resource repository and save the cost of repetitive manufacturing

4.2 Self-awareness

Self-awareness is to assess the potential changes in the production task, and to adjust the machine settings before the actual changeover, thereby driving down machine setup times and increasing quality. This function is implemented in *Integrated Connection Layer*. Demand fluctuations, changes in capacity or other working patterns are the issues to be identified. The corresponding adjustments comprise (i) the preparation of the facilities to be used and (ii) the switch between normal working mode (normal duty) and peak working (heavy duty) mode, etc. Unlike self-monitoring function purely relying on real-time data acquisition, the control program which supervises self-awareness function will be initialized by technicians/experts and consistently updated in a manner of ever-growing knowledge base.

4.3 Self-prediction

Self-prediction is to estimate output productions' quality patterns (e.g., surface roughness, non-defectiveness and reliability) and continuous workability of industrial machines and assets (e.g., availability, health conditions, remaining useful lifetime and functional degradation) in the coming work cycles. Sensor network provides up-to-date data acquisition & information inference. Adaptive prediction techniques (physics-based, data-driven, and model-based) are selected to estimate the quality or workability of interest and predict its future behaviors. Compared with the traditionally periodical prediction independent of a machine's current operation condition, self-prediction helps increase system safety & maintenance effectiveness, improve operational reliability, extend the service life of machines and reduce maintenance costs created by repair-induced failures or unnecessary replacement of components (Gao et al. 2015).

4.4 Self-optimization

Self-optimization is to dynamically and optimally allocate production jobs for best carrying out requested productions. This function is mainly supervised by *Core Service Layer*. CMS provides a repository of theoretically infinite manufacturing resources and capabilities, which lays a solid foundation for optimum matching of the best manufacturing equipment in terms of the task requirements. The optimization strategy is generated based on user-defined criteria or production specificities. The matching mechanism helps avoid (i) underqualified resources and capabilities, which waste opportunities & materials and delay the whole processes, or (ii) overqualified resources and capabilities, which consume more investment and energy usage than necessary (Song and Moon 2016a).

4.5 Self-configuration

Self-configuration is to maximally utilize the capacities of local factory floor. CMS incorporates an online pool of manufacturing requests into the scheduling planning of job shops, open shops and flow shops in the network. The function is operated in *Integrated Connection Layer*. Self-configuration helps shop floors fill the time slots of working schedules with compatible manufacturing requests (no time-conflict) and thus make full use of the manufacturing resources, capabilities & opportunities. At the same time, machinery and assets across different shop floors could collaborate with each other for complementing bottlenecks and absorbing excessive capacities (Chen and Lin 2017; Huang, Li, and Tao 2014). **Figure 4** shows an example of scheduling plans generated for a flexible manufacturing cell by utilizing self-configuration function. Under the umbrella of CMS, the manufacturing components could benefit from the diversity of mission arrangements and the accumulation of operational information of different productions, which are valuable data for future studying and informational analytics.

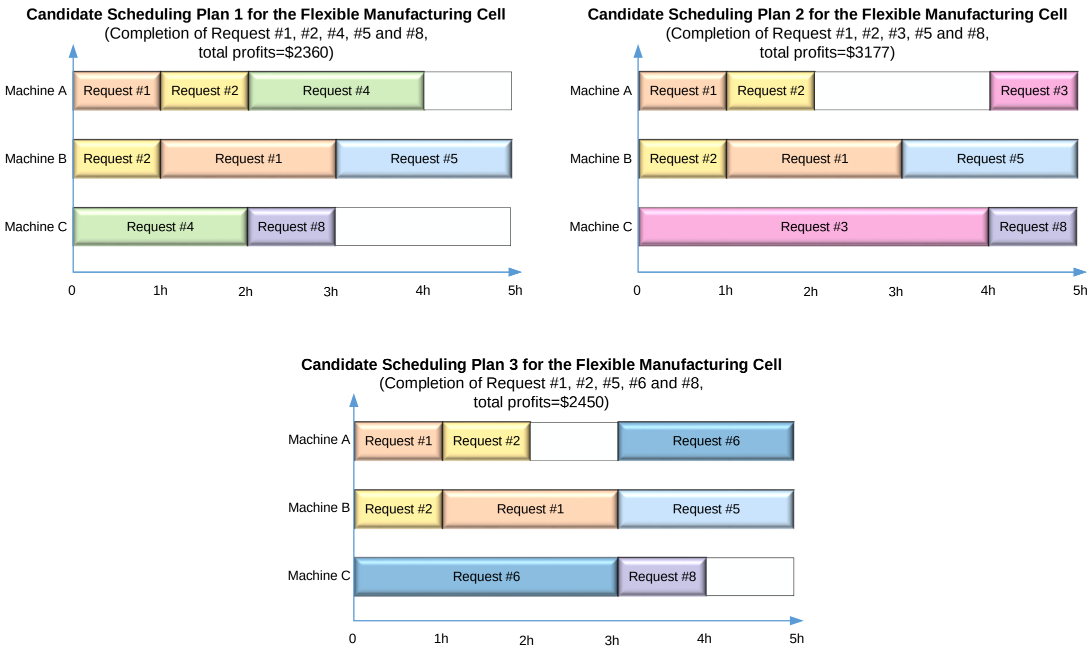
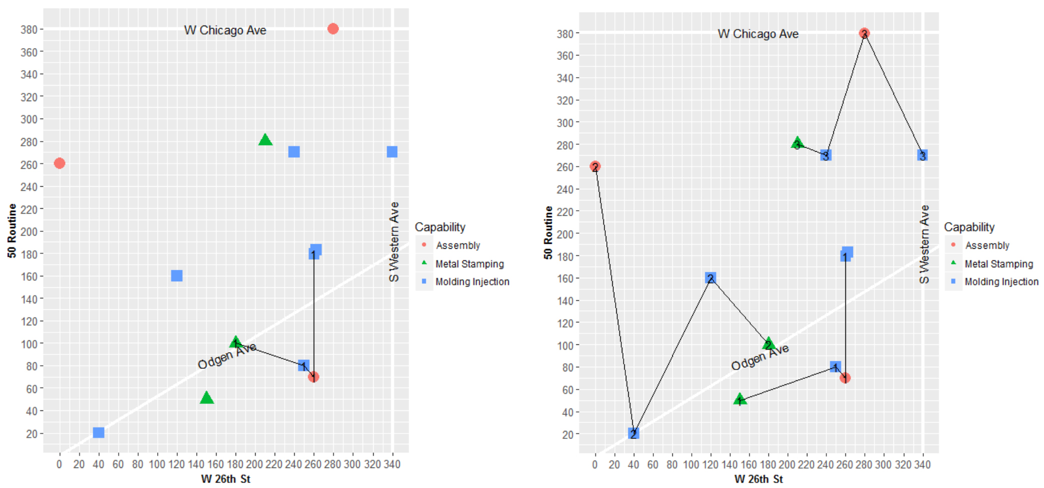


Figure 4 Scheduling Plans of A Flexible Manufacturing Cell

4.6 Self-scalability

Self-scalability is to rapidly scale up and down the production capacity according to the demand volume of the manufacturing request and the provision of production services. The function is enabled in *Core Service Layer* by optimally selecting and compositing production services on the background of the rapidly changing production capabilities information (real-time availability, efficiency, quality and upgrading & maintenance issues) and dynamically changing demand volumes (Juan-Verdejo and Surajbali 2016). The selection and composition strategy could be generated based on the solution space of the optimization problems considering cost, quality, etc., among other key performance factors. The optimization problem can be solved by a diversity of metaheuristic optimization algorithm, linear programming, case-based library or simulation-based approaches (Tao et al. 2013; Tian et al. 2013; Wang, Zhang, and Si 2014; Lartigau et al. 2014; Cheng et al. 2014; Xu et al. 2015; Xiang et al. 2015; Cao et al. 2015; Liu and Zhang 2016; Li, Yao, and Zhou 2016; Cao et al. 2016). The selection of algorithm is determined by (i) the complexity of manufacturing tasks, (ii) performance factors to be considered and (iii) the trade-offs between computation time and optimality of the solutions obtained. **Figure 5** shows an example of production service composition plan generated by utilizing self-scalability function for producing one type of assembly in Chicago urban area. **Figure 6** discloses the correlation between the scaled production capacities and the required transportation expenses.



a. when demand volume is 60 units/hour b. when demand volume is 180 units/hour

Figure 5 An Example of Service Composition Plans

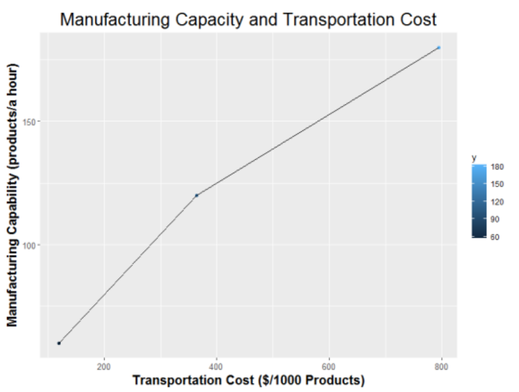


Figure 6 Scaled Production Capacities and Corresponding Transportation Expenses

4.7 Self-remediating

Self-remediating is to make up the production loss caused by failures or other production uncertainties. The central layer of CMS architecture (*Core Service Layer*) supervises the progresses of all ongoing productions projects and also clusters similar production projects (Song and Moon 2017). **Figure 7** shows two production project cluster examples: the manufactured parts in the first cluster example have the same design feature (PLA rounded rectangular base); in the second example, product *A* and product *B* are clustered since both products have part *m* in their assembly recipes.

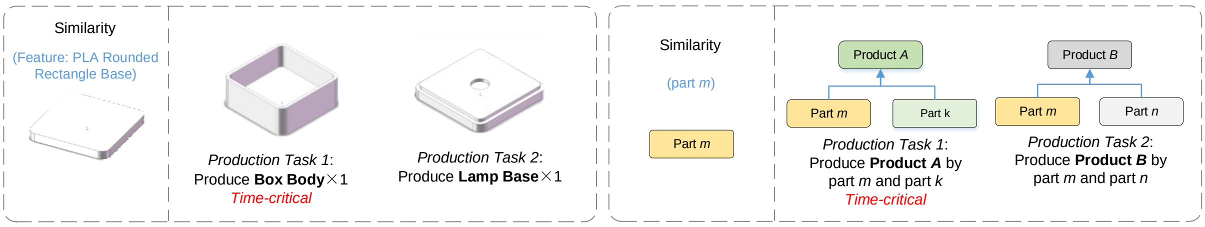


Figure 7 Production Clusters Examples

Time-critical productions in clusters are identified and assigned with high priority, while the rest are in low priority. In the actual production stage, if any uncertainty or failure event occurs to high-priority production facilities, CMS will be immediately informed, and the progresses of other low-priority productions in the same cluster will be taken. **Figure 8** shows the production loss remedy strategy of the productions in **Figure 7**. As shown in **Figure 8**, if any uncertainty occurs to "3D printer 1" (time-critical production) and a nearby "3D printer 2" (is originally assigned to print "lamp base") is currently printing the overlapping feature, this "3D printer 2" will change the printing reference model into the "box body." When finished, the box body will be shipped back to the finished part inventory of "3D printer 1" and thus make up the production loss. Similarly, the part *m* of the product *B* will be taken if the assembly of product *A* (time-critical production) fails. Self-remediating function helps reduce the time delay of the whole project and pricy inventory costs of the remaining parts supply caused by waiting for the recovery of the loss of time-critical production tasks.

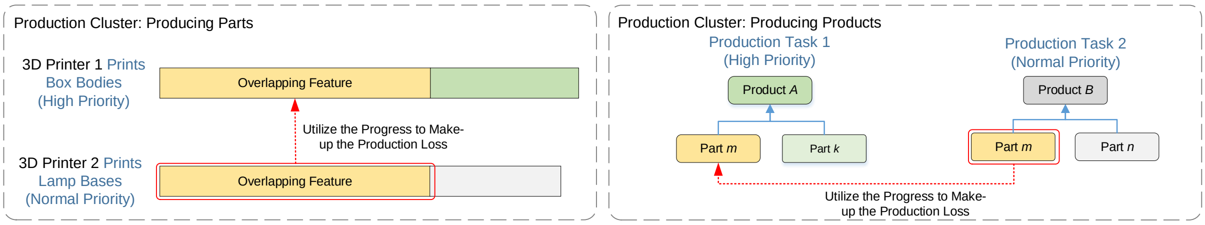


Figure 8 CMS Self-remediating Function

4.8 Self-reusing

Self-reusing is to evaluate, collect and thoroughly reuse products after their lifetime. The remaining values and functionalities of the products will be evaluated by four levels: (i) product level, (ii) component level, (iii) material level, and (iv) waste/restricted substances level. They will be correspondingly processed by (i) recondition/repairing, (ii) remanufacturing, (iii) recycling, and (iv) disposing if the remaining values outweigh the processing costs. The substantial information of products accumulated during production in CMS can facilitate the identification of the remaining values and functionality. The reused resources serve as a portion of the CMS global resource repository and save the cost of repetitive manufacturing.

5 Sustainability Metrics Framework for Manufacturing Systems

Metric—or indicator—is an essential decision-support tool for evaluating a wide range of processes. Different metrics have been created regarding the specificities of different domains along with corresponding criteria rods to evaluate the final index values. For companies' stakeholders, the Global Reporting Initiative proposed sustainability reporting guidelines (Martins et al. 2007); the Institution of Chemical Engineers (IChemE) proposed dozens of elaborate indicators for chemical processes in industrial operations (Sikdar 2003a). However, these indicators don't fit the assessment of manufacturing systems well since most indicators in the list are not directly applicable to manufacturing settings.

A considerable number of indicator sets with quantification methods have been developed for characterizing sustainability of manufacturing systems with different emphases. A comprehensive comparison and discussion about the sustainability assessment methodologies commonly used for manufacturing systems are going to be presented in Chapter 5.1. All selected comparable metrics come from the sustainability metrics summarized by Feng, Joung, and Li (2010) and complemented by the searched articles that have the keywords of "sustainability metrics" and "manufacturing systems." The references in the searched articles are also considered. Although the original intent of some metrics may not have been for manufacturing applications, they are selected as long as they could provide some insights into sustainability patterns from certain perspectives of manufacturing systems.

5.1 Summary and Analysis of Existing Sustainability Metrics

5.1.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a concept and methodology to quantitatively evaluate the environmental impacts of a product or an activity by holistically analyzing the product's life cycle (Klöpffer 1997). LCA is powerful in comprehensive product-focused comparisons between similar products (Kim et al. 2010). LCA essentially involves the compilation of an inventory of relevant environmental exchanges during the life cycle of a product and evaluating the potential environmental impacts associated with those exchanges (Norgate, Jahanshahi, and Rankin 2007). Life cycle inventory (LCI) databases give definite reference values of the ecological impacts regarding the amount of materials and working procedures. However, LCA is not appropriate for benchmarking sustainability patterns regarding different process planning and different production scheduling of manufacturing systems (Haapala et al. 2013; Andersson, Skoogh, and Johansson 2011). When some manufacturing systems have the same output production and cycle time, differences caused by alternative operations—for instance, the adoption of energy-efficient machinery and better inventory control strategies—cannot be captured by LCA (Singh and Madan 2016). These over-generalizations may lead to wildly inaccurate estimates (Mani et al. 2016). Furthermore, LCA is computing intensive and inefficient due to its requirement of excessive details (Rahimifard, Seow, and Childs 2010; Jayal et al. 2010a; Schwarz, Beloff, and Beaver 2002).

5.1.2 Monetary-based Methodology

Several assessment frameworks aggregate different indicators and consolidate them into only one or several sustainability indexes. Monetary-based metrics have been used as one weighing aggregation methodology by mainstream economists (Singh et al. 2009; Jollands 2003). Lee, Kang, and Noh (2014) proposed indicators sets, formulas and coefficients to convert each sustainability indicator of the manufacturing system into economic cost. However, huge gaps between different sustainability domains haven't been resolved effectively. Besides, the validations of the conversions are intensive tasks. Furthermore, after converted into monetary values, environmental/societal impacts cannot preserve their original physical meanings and societal significances. Lastly, some ecological phenomena have long-term effects; therefore, the impact cannot be measured by constant economic costs.

5.1.3 Material Flow Analysis and Dimensional Indicators Metrics

Material Flow Analysis (MFA) quantifies and tracks input flows—energy and materials—within manufacturing systems (Yuan, Zhai, and Dornfeld 2012). This method focuses on the processes and could directly measure the material/energy utilization efficiency in the given cases. The schematic of the steel material flow in a manufacturing system of producing bolts is shown in **Figure 9**. By understanding the internal flows and highlighting the wastes during the process steps, manufacturers can reorient production practices to align with lean thinking and develop plans for future improvement (Brown, Amundson, and Badurdeen 2014). The limitation of this methodology is that the coverage is not comprehensive enough for all the respects of manufacturing systems. For instance, WIP inventory level cannot be encapsulated in this methodology.

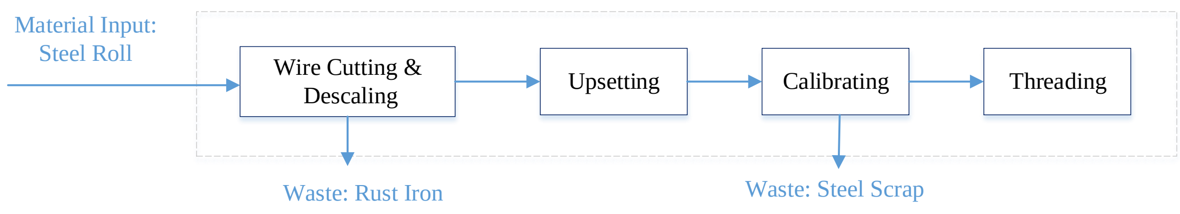


Figure 9 Schematic of the Material Flow in A Bolt Manufacturing System

Sikdar (2003b) and Martins et al. (2007) proposed a typology of indicators with three distinct hierarchical groups, where every indicator is categorized by how many dimensions of sustainability are related to the indicator.

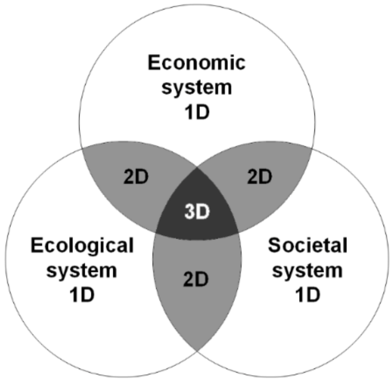


Figure 10 Schematic Depiction of the Three Dimensions of Sustainability

As shown in **Figure 10**, one-dimensional (1D) indicators provide information about one dimension of sustainability: economic, ecological, or societal; two-dimensional (2D) indicators provide information simultaneously about two dimensions of sustainability and use one aggregated index for conveying information related to two dimensions; three-dimensional (3D) indicators involve information about all three dimensions. Although high dimensional indicators could provide more integrated insight, in the majority of situations, high dimensional indicator values provide an ambiguous conclusion and do not allow identification of the impact of any specific sustainability aspect. Therefore, in many cases, this metrics cannot be directly used in decision-making processes.

5.1.4 Ecological Footprint

An ecological footprint is a quantitative measurement depicting the appropriation of natural resources of humans or product function (Čuček, Klemeš, and Kravanja 2012; Barrett and Scott 2001). Ecological footprint metrics are initially created for comparing consumption patterns of the consumer and biologically productivity & absorption of the nature (Wilson, Tyedmers, and Pelot 2007). In this methodology, the sustainability load of production or products' function is usually described by a unit of land. Continuous resource consumption could be measured by continuous productive land areas with a functional unit, where the time dimension doesn't need to be considered. However, this methodology is not easy to use due to the difficulties in making reasonable assumptions, selecting conversion factors, and calculating methodologies & behavioral estimates. Furthermore, the lack of transparency makes it difficult to assess the accuracy and relevance of the calculations (Gaussin et al. 2013).

5.1.5 Embodied Energy

Embodied energy is used for assessing environmental impact and energy efficiency (Kara, Manmek, and Herrmann 2010). Embodied energy in manufacturing aims to represent the amount of energy attributed to production processes (Rahimifard, Seow, and Childs 2010). The evaluation results are in the format of MJ_{eq} and kg CO_{2eq} by referring to available LCI libraries. Although embodied energy methodology could elaborate the manufacturing system performance from the perspective of energy, energy perspective is the unique focus.

5.1.6 Analytic Hierarchy Process and Graph Theory

An Analytic Hierarchy Process (AHP) works for multi-criteria decision-making, which creates the breaking-down structure of the whole system and then measures the priority weight of each end decision-maker (Herva and Roca 2013). Ocampo, Clark, and Promentilla (2016) adopted this methodology to create a four-layered hierarchical framework for identifying each indicator's relative impact on sustainable manufacturing. Graph Theory diagrammatically represents the whole system in terms of subsystems and their interactions. Jayakrishna, Vinodh, and Anish (2015) harnessed Graph Theory to illustrate the inter-relationship between sustainability indicators and then drew separate conclusions on different sustainability pillars to show the awareness and practice of the tested organization. However, indicator and element values of both methodologies are based on subjective human rating or grading, and on how well the organization has practiced sustainable manufacturing. In addition, this takes great effort and expenses during the evaluation procedures.

5.1.7 Distance-to-Target Methodology

Distance-to-Target methodology (Seppälä and Hämäläinen 2001) is a weighing method—comparing the current level in a certain region and time to a target level of the same effect (Brentrup et al. 2004). The "target" in Distance-to-Target methodology represents the tolerable value (background values, standard or norm) according to the impact of the subject that is being measured (Bork et al. 2016). Within the sustainability context, the target could be ecological critical loads, maximum acceptable limits or politically determined standards. The target could also adapt the threshold that marks the limitation of irreversibility or the instability of the given system (Moldan, Janoušková, and Hák 2012). By using Distance-to-Target methodology, a sustainability indicator is assessed by the proximity to its sustainability reference value and classified as good, need for improvement, or alarming (Spangenberg 2002).

Base on the above analysis, a summary of the characteristics of the mentioned assessment methodologies is presented in **Table 5**. Sustainability metrics developed from LCA, monetary-based, MFA & dimensional metrics, ecological footprint, embodied energy, AHP and Graph Theory are suffering from their limitations. They are far from well-defined approaches to characterize sustainability in manufacturing (Fradinho et al. 2015; Lee et al. 2015). However, Distance-to-Target methodology shows adequate potentials to address all mentioned limitations (Song and Moon 2018). The reasons are discussed as follows.

1. While the sustainability impact measurements of the indicators in other methodologies are based on conversions into the unified forms, such as money, energy or ecological footprints, Distance-to-Target methodology measures each indicator with its respective standard. Consequently, Distance-to-Target methodology could comprehensively encapsulate more indicators that are otherwise hard to be converted using other methodologies.
2. The Distance-to-target methodology could capture the differences in sustainability performance regarding alternative manufacturing operations. The sources of data are not subject to subjective evaluations.

Inspired by the above-discussed reasons, Distance-to-Target methodology is adopted for developing an improved sustainability assessment framework for comprehensively and objectively evaluating manufacturing systems in this research.

5.2 Indicator Sets

The indicators should cover all substances that represent the interactions between manufacturing systems and sustainability. The selected indicators are partially adopted from the indicator lists of Sustainable Manufacturing Indicator Repository of National Institute of Standards and Technology (NIST) (Sarkar et al. 2011) and Sustainable Manufacturing Toolkit published (OECD Toolkit 2011). The selected indicators are of adequate sustainability sense and practical, i.e., measurable and effort-effective in terms of data collection. All individual indicators are separate enough from each other to minimize repetitive information. In this framework, all indicators are grouped by three sustainability pillars as shown in **Figures 11**, **12** and **13**. The nomenclatures explaining all indicators are presented in **Table 6**.

Table 5 Summary of the Sustainability Metrics Methodologies

Methodologies	*Extensible Indicator Set*	*Center(x-related)*	*Maximum Scope (Life cycle stage)*	*Final Form*	*Unit*	*Single index or Multiple indices*
LCA	Yes	Product-related; Process-and-product related	Whole life cycle process	Damage or Material Consumption	mPt (eco-indicator 99); kg or *M3*(Material); 1 (Eco-points, EPS)	Impact (many); Goal (1)
Monetary-Based	Yes	Product-related; Process-related	Whole life cycle process	Economic Cost	$ per manufacturing system	1
Material Flow Analysis	No	Process-related	Manufacturing Process	Ratio	Per product, per facility	3
Dimension-Based	No	Process-related	Manufacturing Process	Ratio	Mass, volume or energy per mass or $	Many
Ecological Footprint	No	User's behavior-related	Manufacturing and Use Stage	Mass or Area of Land	Per function, per capita	Many
Embodied Energy	No	Product-related; Process-related	Whole life cycle process	Energy or CO_2 Mass Equivalent	MJ; kg	2
AHP & Graph Theory	Yes	Not related to product or process	Not any phase	Priority Table	1	Many
Distance-to-Target	Yes	Product-related; Process-related	Whole life cycle process	Ratio	1	Many

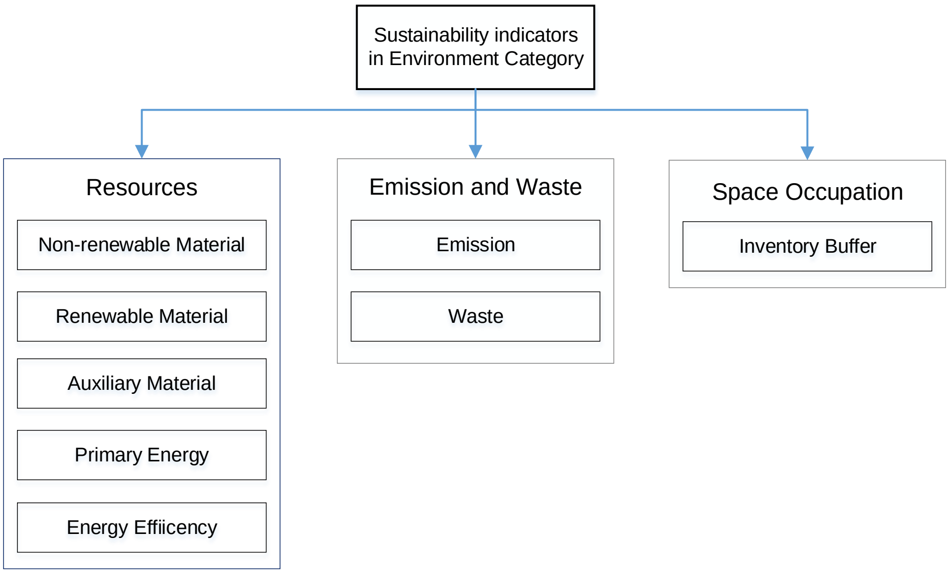


Figure 11 Sustainability Indicators in Environment Category

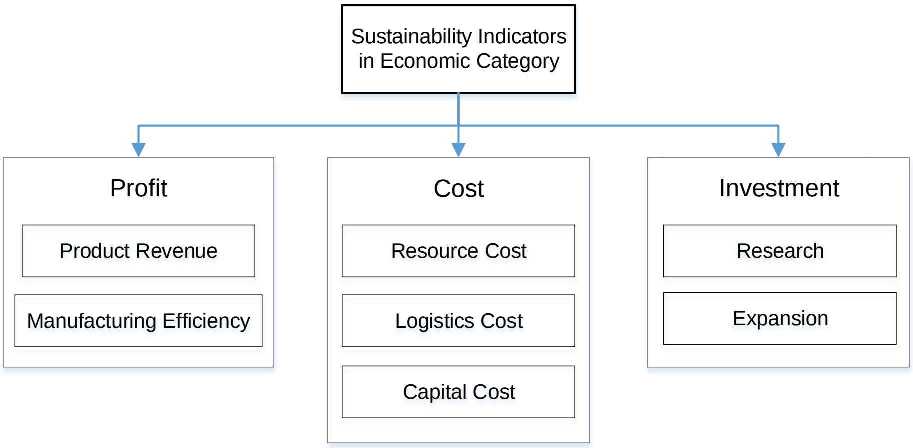


Figure 12 Sustainability Indicators in Economic Category

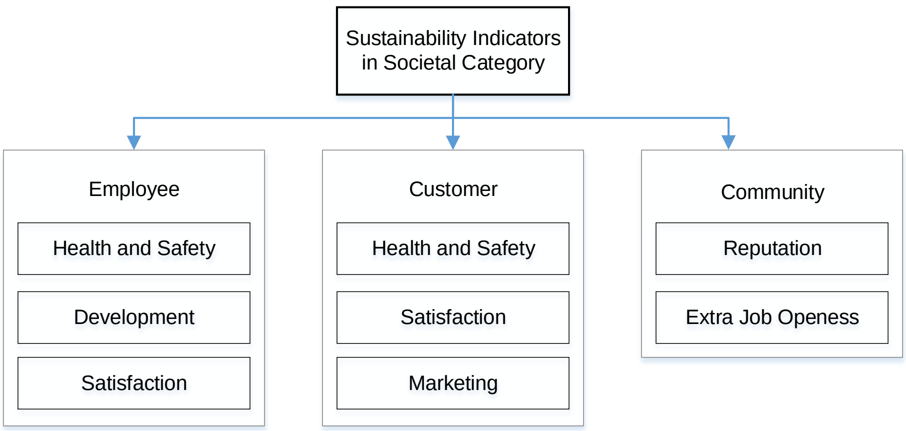


Figure 13 Sustainability Indicators in Societal Category

Table 6 Nomenclature of Each Sustainability Indicator

Nomenclature	*Sustainability Indicator*
I_{NRM}	Non-renewable Material
I_{RM}	Renewable Material
I_{AM}	Auxiliary Material
I_{PE}	Primary Energy
I_{EE}	Energy Efficiency
I_{W}	Waste
I_{E}	Emission
I_{IB}	Inventory Buffer
I_{PR}	Production Revenue
I_{ME}	Manufacturing Efficiency
I_{RC}	Resource Cost
I_{LC}	Logistic Cost
I_{CC}	Capital Cost
I_{RI}	Research Investment
I_{EI}	Expansion Investment
I_{EHS}	Employee Health and Safety
I_{ES}	Employee Satisfaction
I_{ED}	Employee Development
I_{CHS}	Customer Health and Safety
I_{CS}	Customer Satisfaction
I_{M}	Marketing
I_{R}	Reputation
I_{EJO}	Extra Job Openness

Five indicators address resources in environmental category. They indicate the resource consumption patterns of the input side of a manufacturing system:

1) The non-renewable material indicator describes how the tested system relies on scarce non-renewable materials;

2) The renewable material indicator characterizes the degree of input materials' renewability of the tested system;

3) The auxiliary material indicator measures manufacturing consumables wear rates and fluids consumption rates at given productivities;

4) The primary energy indicator describes the profile of manufacturing in how much it

relies on scarce primary energy as energy source;

5) The energy efficiency indicator counts the ratio of energy used for production to the overall input energy.

On the output side, the emission and waste indicators describe the sustainability impacts made by the generated emissions or wastes, respectively. The inventory buffer indicator is used to describe WIP inventory level of the tested manufacturing system.

In economic category, the product revenue indicator presents the profitability of the tested manufacturing system, specifically, the ratio of actual profits to target profits. The manufacturing efficiency indicator measures the productivities of the output productions. The indicators in the cost section of economic category characterize the monetary costs in corresponding perspectives. In investment section, the research investment indicator measures how much investment is attributed to increasing the capability of the manufacturing facilities; whereas the expansion investment indicator indicates how much investment is used for enlarging the scalability of the manufacturing facilities.

In the employee section of societal category, (i) the safety & health indicator measures whether the tested manufacturing system achieves the baseline of normal working conditions; (ii) the satisfaction indicator expresses the extent to which the employees' income is worthy of their efforts; and (iii) the development indicator measures how much the employees benefit from working for the tested manufacturing system, such as the job promotion, certifications and accumulation of expertise & experience. For the customer section in societal category, (i) the safety & health indicator measures whether the products could provide required functions to customers; (ii) the satisfaction indicator expresses the extent to which the products achieve the expected functionalities; and (iii) the marketing indicator describes marketing share changes caused by using the tested manufacturing system. The community section in social category consists of two indicators: (i) the reputation indicator measures people's evaluation of the manufacturing systems, and (ii) the extra job openness indicator measures the number of newly added working positions.

The involved indicators should adapt to the evaluated cases and the level of the scenario study. For instance, it would be unnecessary to involve social reputation indicator when testing the operation of replacing a machine tool, but capital cost is necessary. For some operations, specific indicators could be incorporated for considering more aspects of sustainability (Singh and Madan 2016; Linke and Dornfeld 2012; Priarone 2016; Eastwood and Haapala 2015)

5.3 Computation Formulas

The general mathematical formula of Distance-to-Target based sustainability assessment framework is constructed as follows.

$$I = \frac{1}{s}\sum_{i=1}^{s} e_i \times \frac{DV_i}{TV_i} \quad (1)$$

where I is the sustainability indicator index value;

i is the index of the current indicator's types, representing the ith type of the current indicator;

s is the total number of the current indicator's types;

DV_i is the distance (observed) value of the ith type of the current indicator in the system;

TV_i is the target (reference or destination) value of the ith type of the current indicator;

e_i is the power factor of the ith type of the current indicator (Castellani et al. 2016). $\frac{DV_i}{TV_i}$ is the Distance-to-Target weighting factor (Seppälä and Hämäläinen 2001; Brentrup et al. 2002; Weiss et al. 2007). The calculation process of an indicator's index value is to firstly get the cumulative summation of the multiplications of all Distance-to-Target weighting factors with corresponding power factors and then to make an average by dividing the summation by the type number. The data source accesses of the variables are discussed as follows.

1. DV_i: manufacturing systems inventory data and performance records—such as the input of material/energy and the output of emission/waste—constitute DV_i.

2. TV_i: the target values, TV_i, in this computation formula will not be solely determined by the fixed standard values as discussed in Chapter 5.1.7. The workload and production specificity information—including BOM, estimate energy consumption, estimate operation loads & completion time and estimate revenue—will be incorporated and used to scale the standard values. Since distance values, DV_i, are affected by workloads and production specificities, the form of the Distance-to-Target weighting factor could make the indicator value dimensionless and independent from any specific workload settings.

3. e_i: the power factor, e_i, is used for considering the severity level of the sustainability impacts caused by the ith type of the current indicator (Bork et al. 2016; Brentrup et al. 2001).

This general form can be applied to the computation of index values of the indicators with various types (subcategories), including I_{NRM}, I_{RM}, I_{AM}, I_{PE}, I_W, I_E and I_{IB}. For computing these indicators index values, the data sources of all involved variables are listed in **Table 7**;

the determined values of power factors along with the references are listed in **Table 8**. The power factor of non-renewable material indicator and primary energy indicator are basically determined by the scarcity of the material type, but could vary by the factors such as the discovery of new deposits, technological progress in extraction and exploitation technology, and the development of resource substitutes (Krautkraemer 1998). The power factor of renewable material indicator is primarily determined by the reuse rate—or recycle rate—of the material type. For auxiliary material indicator, the major determinant of the power factor's value is the sustainability impacts of the disposable consumable materials or the fluids. For waste indicator and emission indicator, the determinants are ecological damage points of the waste type and marginal equivalent cost of the emission type, respectively. The power factor value of inventory buffer indicator depends on the inventory cost of the intermediate part or product.

Table 7 Data Source of the Variables of the Indicators with Subcategories

Indicator	*Variable*	*Data Source of the Variables (Exact Value or Measurement Approach)*
Non-renewable Material	DV	Manufacturing system inventory data of non-renewable materials input
	TV	Estimated by the preview function of CAD/CAM packages
Renewable Materials	DV	Manufacturing system inventory data of renewable materials input
	TV	Estimated by the preview function of CAD/CAM packages
Auxiliary Material	DV	Inventory data of actual lifetime of the consumable or the consumption rate of the fluid
	TV	The estimated lifetime of the consumable or the estimate consumption rate of the fluid
Primary Energy	DV	Manufacturing system inventory data of the primary energy substance usage
	TV	The estimate primary energy substances usage
Waste	DV	The observed waste generated by manufacturing system
	TV	Estimated by CAD/CAM packages preview of the given workpiece and procedure; chemical reaction analysis
Emission	DV	For airborne emissions, the value is the observed emission generated by manufacturing system; for noise, the value is the detected time-averaged noise level.

	TV	For airborne emissions, the value is the summation of the multiplication of emission factors (EMEP/EEA air pollutant emission inventory guidebook 2016) with mass or energy of the corresponding used energy substances; for noise, the value is the referenced time-averaged noise level.
Inventory Buffer	DV	Actual manufacturing system WIP sizes
	TV	Safety stock sizes

Table 8 Determined Values or the Main Determinants of the Power Factors

Indicator	*Determined Values and the References of the Power Factors*
Non-renewable Material	50 for very scarce resources (bauxite, cement, natural gas, crude oil); 10 for moderately scarce material (coal, iron ore); 2 for marginally scare resource, (platinum group, metal). (2000-2008 Global Non-renewable Natural Resource Summary)
Renewable Materials	0.65-0.6 for aluminum (National Minerals Information Center Aluminum Commodity Summaries 2012-2017); 0.96 for rubber, 0.65 for paper (Institute of Scrap Recycling Industries 2002a, b); 0.75 for plastics (Hopewell, Dvorak, and Kosior 2009); 0.36 for Iron and Steel (Steel Recycling Institute 2002); 0.4 for Copper (Gloser, Soulier, and Tercero Espinoza 2013)
Auxiliary Material	depends on the composition of each disposable material type and the ecological impact of each material for manufacturing consumables; or depends on the percentage of each fluid composition and the toxicity of each fluid type for cooling, lubricant or cleaning fluid
Primary Energy	50 for very scarce resources (natural gas, crude oil); 10 for moderately scarce material (coal); (2000-2008 Global Non-renewable Natural Resource Summary) 1 for renewable resources, (solar energy and wind power).
Waste	2 for metals; 7 for plastics; 8 for paper (eco-indicator 99 landfill waste treatment databases).
Emission	2 for cooling water effluent or CO_2; 20 for NO_X; 280 NH_3; 100 for SO_2; 33 for VOC. (Muller and Mendelsohn 2007; Lackner 2003); 1 by default for noise but could vary by situations.
Inventory Buffer	inventory cost of each intermediate part or product (determined in cases).

The energy efficiency, resource cost, logistic cost, capital cost, research investment and expansion investment indicators are uniformly measured by energy value or money. Therefore, they don't need power factors to aggregate the impacts levels caused by different subcategories. These indicators' values are computed by using a simplified mathematical formula shown as follows. The data sources of all involved variables are listed in **Table 9**.

$$I = \frac{DV}{TV} \quad (2)$$

where I is the sustainability indicator index value;

DV is the distance (observed) value of the current indicator in the system;

TV is the target (reference or destination) value of the current indicator.

Table 9 Data Source of the Variables of the Indicators without Subcategories

Indicator	*Variable*	*Data Source of the Variables (Exact Value or Measurement Approach)*
Energy Efficiency	DV	The summation of the estimated energy consumption of all the involved machines
	TV	The summation of input chemical exergy values (maximum useful work) contained in the used energy substances
Product Revenue	DV	Actual profit from the sale of all parts or products
	TV	Estimated by benchmarked products in the market and production volume
Manufacturing Efficiency	DV	The actual productivity or the inverse of the actual completion time
	TV	The estimated productivity or the inverse of the planned finishing time
Resource Cost	DV	Total resource cost
	TV	Actual profit from the sale of all parts or products
Logistic Cost	DV	Actual manufacturing system logistic cost
	TV	10% of the production sale
Capital Cost	DV	Total actual capital values of all the involved machines
	TV	The estimate total capital values of the involved machines
Research Investment	DV	The actual marginal investment in research development
	TV	The planned marginal investment in research development
Expansion Investment	DV	The actual marginal investment in expansion of production scale
	TV	The planned marginal investment in expansion of production scale

Overall, all distance variable values come from the observed values in inventory or performance data. All target variable values are determined by workloads and production information, which could be determined offline. The inventory data and performance data are determined by both manufacturing system sustainability patterns and current production workloads with some related production information. By making distance variables (inventory data and performance data) over target variable (workload data and production information data), the influence or the scale caused by workload or production specificity could be eliminated to the maximum extent. The power factors could be roughly categorized into two groups: (a) indicating the potential to deplete resources, and (b) indicating the damage to sustainability. The power factors of non-renewable, renewable materials, primary materials are in group (a) while the rest power factors are in group (b).

The computation of the societal indicators values will not be included in this framework, since the subcategories involved in a societal indicator are usually uncertain and depend on societal contexts. Furthermore, it is difficult to directly find the reference values and power factor values for each subcategory of the societal indicators. Lastly, some social indicators reflecting long-term phenomena, like reputation and new job openness, could not be studied without time dimension (Sutherland et al. 2016). Therefore, the research on such indicators will require separate research work.

The interpretation guideline for different indicator index value scales is shown in **Table 10**. The sustainability performance could be interpreted as moderate if the indicator index value is around one. Manufacturers could get the knowledge of all the concerned sustainability issues and the weak respects by referring to the interpretations; by making comparisons of performance before and after alternative operations, manufacturers could know what practices result in the greatest value-added performance.

Table 10 Interpretation Guidelines and Corresponding Index Value Scales

Indicator Value Range		*Textual Descriptive Evaluation*
$I_{NRM}, I_{RN}, I_{AM}, I_{PE}, I_W, I_E$ $I_{IB}, I_{RC}, I_{LC}, I_{CC}, I_{RI}, I_{EI}$	I_{EE}, I_{PR}, I_{ME}	
> 0 & <= 0.1	> 10	Sustainably excellent
> 0.1 & <= 0.5	> 2 & <= 10	Sustainably good
> 0.5 & <= 2	> 0.5 & <= 2	Sustainably moderate
> 2 & <= 10	> 0.1 & <= 0.5	Need improvement
> 10	> 0 & <= 0.1	Urgently need improvement

5.4 Assessment Framework Validation: A Case Study

In order to test the validity of the proposed sustainability assessment framework, a real case of Pusavec, Krajnik, and Kopac (2010) is utilized and analyzed. The case is to compare the sustainability performances of machining with (i) conventional cooling/lubricant fluid, (ii) high-pressure jet assisted machining (HPJAM), and (iii) liquid nitrogen (LN). In the aforementioned reference paper, the sustainability assessment of case was conducted by LCA. Although LCA has the limitation in evaluating the sustainability performance of different process planning and scheduling activities, this case doesn’t involve such activities. Therefore, the LCA report can reflect the appropriate sustainability performances and serve as the benchmark for validation.

The validation process consists of comparing the values generated by the proposed framework presented in this paper with those reported in the LCA case study. The sustainability indicators in the proposed framework have wider coverage than the LCA report. Therefore, only the overlapping sustainability aspects are compared. Then, the indicator value interpretations are compared with the research contents of the referenced paper. Equivalent data and consistent conclusions from these two methodologies would lead to the validation of the proposed framework. All variable values used during validation and discussion are provided in **Table**

11—drawn from the references (Pusavec, Krajnik, and Kopac 2010; Pusavec et al. 2010; Bhaskar et al. 2004; El-Fadel, Findikakis, and Leckie 1997), publicly available data, and reasonable assumptions.

Table 11 All Variable Values of the Cooling/Lubricant Fluid Example

Indicators	*Variable*	*Conventional*	*HPJAM*	*Liquid Nitrogen*
Non-renewable Material	DV	Crude oil 1121.37L	Crude oil 836.84L	0
	TV	Crude oil 1100L	Crude oil 1100L	NA
Renewable Material	DV	Water 1009.2kg	Water 1007kg	Air
	TV	Water 1000kg	Water 1000kg	Air
Auxiliary Material	DV	Tool Lifetime 200h	Tool Lifetime 500h	Tool Lifetime 450h Cooling Water
	TV	Estimate Tool Lifetime 200h	Estimate Tool Lifetime 200h	Estimate Tool Lifetime 200h Cooling Water
Energy Efficiency	DV	Estimate value 821.9MJ	Estimate value 821.9MJ	Estimate value 821.9MJ
	TV	Electricity 821.9MJ	Electricity 613.6MJ	Electricity 136857.6MJ
Waste	DV	Solid Waste 576.65kg	Solid Waste 431.07kg	0
	TV	Estimate Solid Waste 7.5kg	Estimate Solid Waste 7.5kg	Estimate Solid Waste 7.5kg
Emission	DV	CO_{2eq} 93.58kg	CO_{2eq} 70.312kg	CO_{2eq} 0
		SO_{2eq} 280.05g	SO_{2eq} 209.18g	SO_{2eq} 0
	TV	CO_{2eq} 42.08kg	CO_{2eq} 42.08kg	CO_{2eq} 42.08kg
		SO_{2eq}	SO_{2eq}	SO_{2eq}
Production Revenue	DV	€46834.5	€65518.3	Main production €63923.44 By-product Liquid Oxygen €9670.75 By-product Liquid Argon €614.83
	TV	€50000	€50000	€50000
Manufacturing Efficiency	DV	25.666 units/hour	35.905 units/hour	35.031 units/hour
	TV	25 units/hour	25 units/hour	25 units/hour
Capital Cost	DV	€157500	€167500	€177500
	TV	€157500	€157500	€157500

Figure 14 shows the comparisons result between indicator values determined by the proposed framework and values of the referenced LCA report. The calculation procedures are presented

in **Table 12**. The following conclusions can be drawn from comparing the results from the two methodologies.

1) For each sustainability aspect, the indicator index values exhibit the same trend as the LCA report's values. The relative performance of the (i) conventional approach, (ii) HPJAM approach and (iii) LN approach are similarly presented by the indicator index values and the LCA report.

2) The indicator values of the SO_2 emission and the solid waste are very large when the machine approach is conventional or HPJAM. Therefore, SO_2 emission and solid waste are identified as serious sustainability burdens for conventional and HPJAM approaches, which require immediate improvement or solutions. By contrast, LN approach has no SO_2 emission or solid waste generation, but requires a very large amount of energy input. These are consistent with the discussion presented in the source references.

3) There are differences between the proposed framework and the LCA methodology. One difference is the scales of the values. The LCA report provides misleading absolute values. For instance, the absolute value of SO_2 emission of the conventional approach looks low, but in fact, the emission performance of the conventional approach is sustainably poor since the entire production process only uses a very small amount of input material. In order to avoid being misled by the absolute values, decision makers should investigate the cases and refer to the relevant standards before drawing valid conclusions. However, the indicators of the proposed framework give standard-integrated and dimensionless values, directly indicating the performance of corresponding sustainability aspects. In addition, through the background colors scale of the bar plots as shown in **Figure 14**, the

sustainability performance of the corresponding indicator could be quickly interpreted.

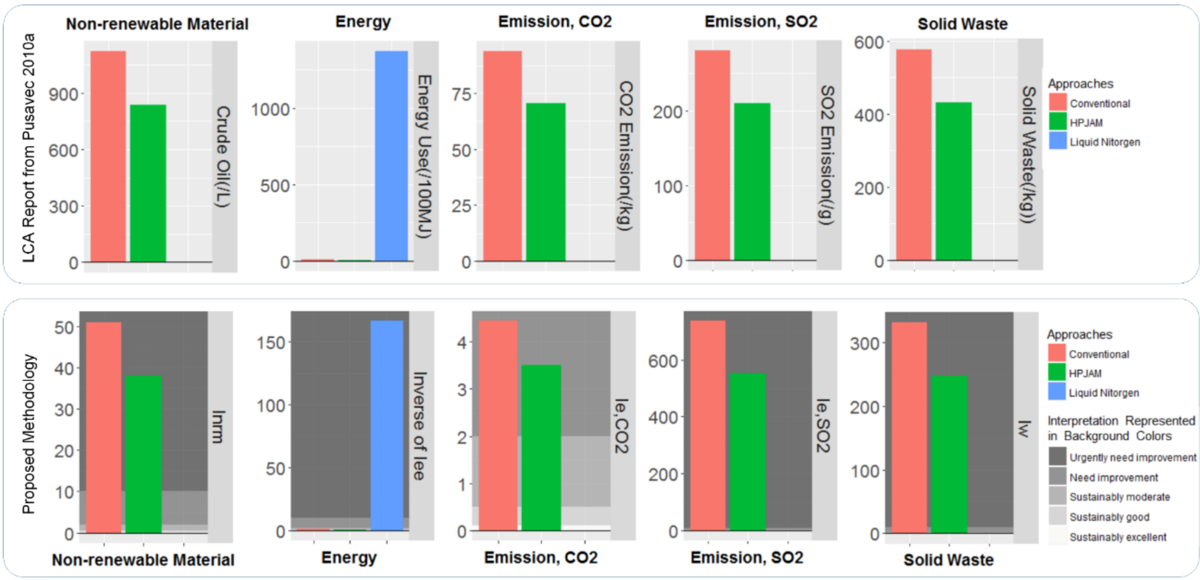


Figure 14 Sustainability Metrics Framework Comparisons

Table 12 Indicator Index Value Computation of the Machining Fluid Example

Indicator	*Conventional*	*HPJAM*	*Liquid Nitrogen*
I_{NRM}	$I_{NRM} = 50 \times \frac{1121.37kg}{1100kg} = 51$	$I_{NRM} = 50 \times \frac{836.4kg}{1100kg} = 38$	$I_{NRM} = 50 \times \frac{0}{1100kg} = 0$
I_{EE}	$I_{EE} = \frac{821.9MJ}{821.9MJ} = 1$	$I_{EE} = \frac{821.9MJ}{613.6MJ} = 1.34$	$I_{EE} = \frac{821.9MJ}{136857.6MJ} = 6 \times 10^{-3}$
I_E	$I_{E,CO_2} = \frac{93.58kg}{42.08kg} = 2.22$	$I_{E,CO_2} = \frac{70.312kg}{42.08kg} = 1.67$	$I_{E,CO_2} = \frac{0}{42.08kg} = 0$
	$I_{E,SO_2} = \frac{280.05kg}{38g} = 7.37$	$I_{E,SO_2} = \frac{209.18kg}{38g} = 5.5$	$I_{E,SO_2} = \frac{0}{38g} = 0$
	$I_E = \frac{1}{2}(2 \times 2.22 + 100 \times 7.37) = 370.72$	$I_E = \frac{1}{2}(2 \times 1.67 + 100 \times 5.5) = 276.91$	$I_E = \frac{1}{2}(2 \times 0 + 100 \times 0) = 0$
I_W	$I_W = 4.315 \times \frac{576.65kg}{7.5kg} = 331.77$	$I_W = 4.315 \times \frac{431.01kg}{7.5kg} = 331.77$	$I_W = 4.315 \times \frac{0}{7.5kg} = 0$

All indicator values are presented together in **Figure 15**. I_{AM}, I_{PR}, I_{ME} and I_{RC} indicate the sustainability assessment from the perspectives of auxiliary material consumption, profitability, productivity and cost-effectiveness, respectively. These sustainability aspects were thoroughly analyzed and discussed through the source references and regarded as important sustainability aspects. However, they are not encapsulated in the LCA reports, which makes the LCA report incomplete if sustainability evaluation from a comprehensive perspective is required.

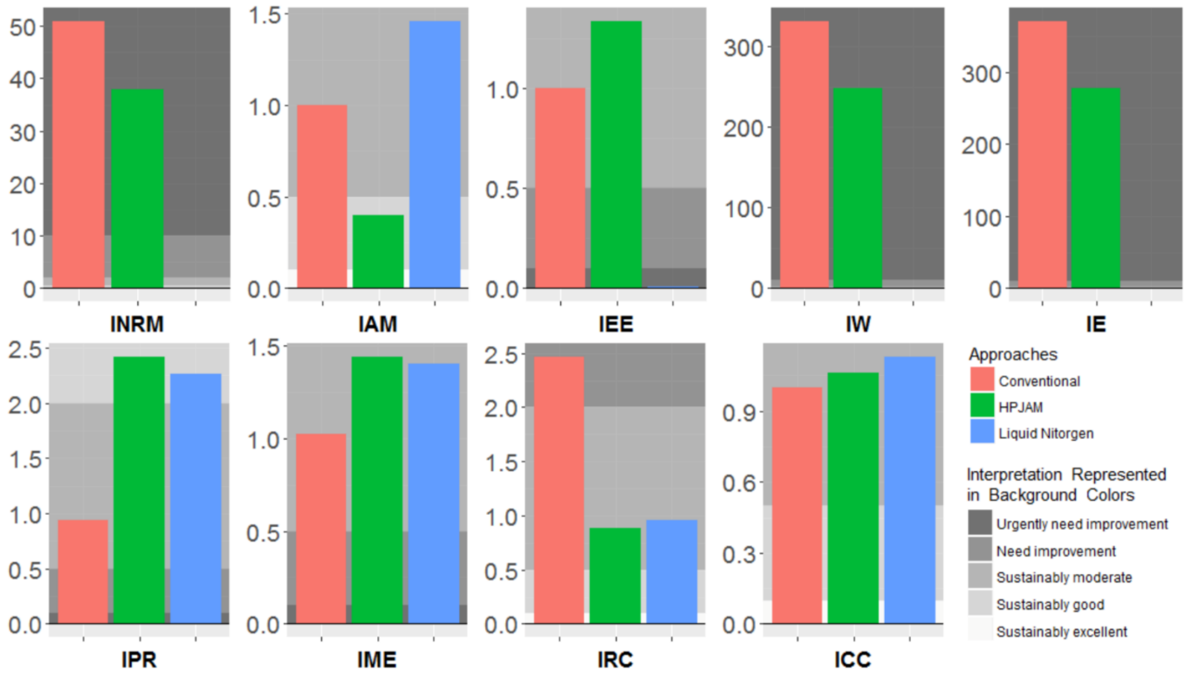


Figure 15 Complete Sustainability Performance Comparison of the Machining Fluid Example

Based on the above analysis, the proposed framework is proved to be capable of sufficiently reproducing the sustainability assessment results and getting consistent evaluation conclusion. Moreover, the proposed framework provides more comprehensive standard-integrated indicators and self-interpretative figure presentation, which could navigate the decision-making processes more effectively and enhance sustainability assessment result presentations.

6 Simulation Study and Verification of CMS Functions

This chapter is designed to test and verify CMS functions through simulation studies. All the performance data will be assessed by the sustainability assessment framework proposed in Chapter 5 and the sustainability performance will be interpreted.

A total number of 16 scenarios are derived from partial or whole manufacturing processes of (i) a plastic storage box, (ii) a drone and (iii) a holder. The Bill of Materials (BOM) and production procedures of the plastic storage box, drone and holder are shown in **Figures 16, 17 and 18.** The detailed production information of the three products is presented in **Tables 13-16**, respectively. Among them, the processing time of the drone was adopted from Wu, Rosen, and Schaefer (2015); the processing time was estimated by *WILLIT 3D PRINT* and the transfer time was determined by *GOOGLE MAP* according to product information and location information.

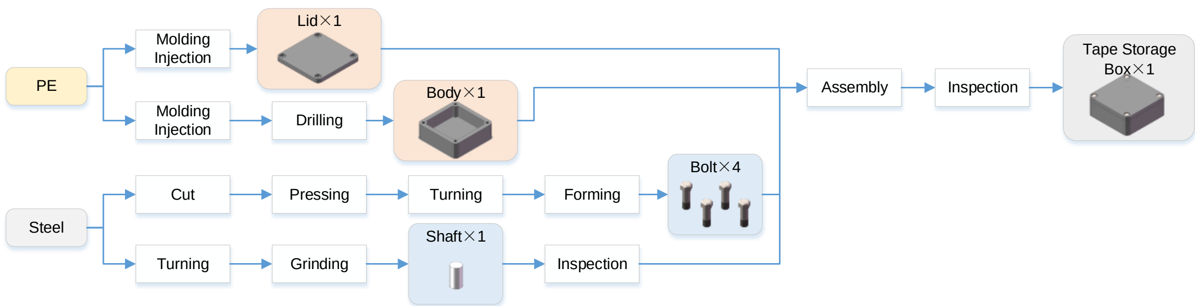


Figure 16 BOM and Sequential Diagram of the Storage Box Production

Table 13 Information of the Storage Box's BOM

Part	*Material*	*Number*	*Weight per piece*	*Other Information*
Lid	PE	1	0.033kg	-
Box body	PE	1	0.012kg	-
Bolt	steel	4	0.002kg	-
Shaft	steel	1	0.013kg	Surface roughness $R_a 3.6\mu m$

Table 14 BOM and Production Information of the Drone

Part	*Dimension(/mm)*	*Processing Time*	*Number*
Propeller	1604	1/3 h	4
Legs	104	1/4 h	4
Arm	904	1/4 h	4
Frame body	351	2 h	1
Shield	351	1/3 h	1
Frame body bottom	601	1/4 h	1
Gimbal	-	2 h	1
Outsourced part assembly	*Assembly Other Parts*	*Assembly Time*	*Number*
Motor	12 h	1/4 h	4
Navigation board	18 h	1/6 h	1
Main board	18 h	1/6 h	1
Camera	18 h	1/6 h	1
Batteries	20 h	1/10 h	1
Control board	20 h	1/8 h	1

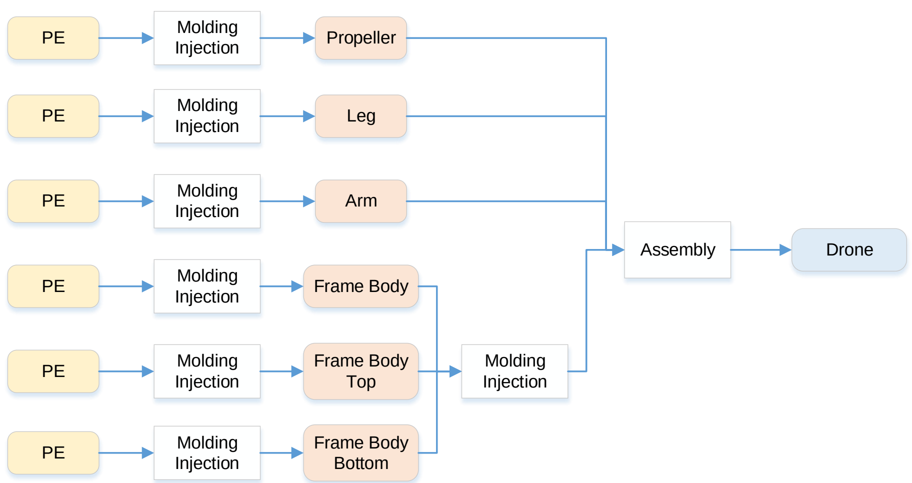


Figure 17 Sequential Diagram of the Drone Production

Table 15 Time Duration of Manufacturing Events in the Drone Production

Manufacturing Events	*Time Duration*
Load Raw Material	1/12 h
3D printer failure	1/2 h
Transport assemble to warehouse	1/4 h
Switch to assembly other products	1/4 h
Transport parts to final assembly line	1/6 h
3D printer repair	1/4 h
Adjust assembly line	1/4 h
Transport assembly to customer	10 h

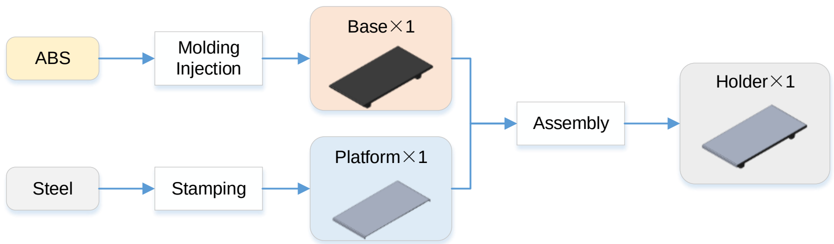


Figure 18 Sequential Diagram of the Holder Production

Table 16 Information of the Holder's BOM

Part	*Material*	*Number*	*Weight per piece*	*Other Information*
Base	Steel	1	0.017kg	-
Platform	PE	1	0.021kg	-

All developed production scenarios for simulation studies are summarized in **Table 17**. Under each scenario, traditional manufacturing operating models and models with CMS function will be separately built. Traditional manufacturing model is in the vision of high-volume, dedicated tool & routine setting, static scheduling & accommodation, human operation & supervision and technicians' judgment, whereas CMS models are equipped with the corresponding CMS functions.

Table 17 Summary of the Scenarios Studies

Functions	*Scenarios*
Self-monitoring	Scenario 1-1 Failure of the Steel Forming Machine
	Scenario 1-2 Part Supply Shortage for Storage Box Assembly
Self-awareness	Scenario 2-1 Warmup of the Steel Forming Machine
	Scenario 2-2 Work Mode Switch of the Subassembly Machine
Self-prediction	Scenario 3-1 Varying Tool Lives
	Scenario 3-2 Surface Roughness Quality Control of Shaft Production
Self-optimization	Scenario 4-1 Selection of Plastic Box Body Inspectors
	Scenario 4-2 Drone Assembly Production Lines Selection
Self-configuration	Scenario 5-1 Inspection of Injection Molded Parts
	Scenario 5-2 Inspecting and Packaging Plastic Parts
Self-scalability	Scenario 6-1 Production Planning for Massively Producing Holders
	Scenario 6-2 Storage Box Production Planning in Chicago Urban Area
Self-remediating	Scenario 7-1 Production Losses Makeup for Drilling Box Body
	Scenario 7-2 Compensating Platform Loss Caused by Assembly Failures
Self-reusing	Scenario 8-1 Remanufacturing of Defective Box Bodies

	Scenario 8-2 Reconditioning the Material of Afterlife Platforms

Simulation is a powerful tool in analyzing real manufacturing systems and conducting manufacturing scenarios analysis (Boulonne et al. 2010; Heilala et al. 2008; Moon 2017). Among all kinds of simulation approaches, Agent-based Modeling and Simulation (ABMS), Discrete-Event Modeling and Simulation (DEMS) and System Dynamics Modeling and Simulation (SDMS) are widely used (Jahangirian et al. 2010; Baines and Harrison 1999; Monostori, Váncza, and Kumara 2006). Among them, DEMS gives a dynamic simulation on the energy consumption and can be used for calculating servicing time, utilization and bottleneck identification (Widok et al. 2012; Mani et al. 2013). DEMS is the appropriate technique for the sustainability performance analysis since it directly provides the DVs that are required by indicators index computations. Therefore, simulation models for studying these scenarios are constructed in a DEMS package, *Simio* (Pegden 2008).

No real data could be used for directly validating the established models since CMS has not been realized in the real world yet. The validation work of CMS is similar to the validation of any upcoming manufacturing system, where the model of each production procedure and the coherency between production procedures could be individually validated. Then the whole model could be step-by-step validated. A further way to validate the models is to validate between the CMS model and the traditional manufacturing operation model: after the CMS function strategies and scheduling difference are removed, the simulation results should be identical. The verification of simulation models will be performed based on the animation and real-time parameter display built within the simulation package. In the remaining paragraphs of Chapter 6, each scenario will be in detail discussed and CMS operations will be provided.

The sustainability aspect which could reflect the effectiveness of CMS functions is captured to compare performance between CMS approach and the traditional approach under each scenario. The comparison result is presented in **Figure 19** in the form of indicator index values.

6.1 Scenario 1-1 Failure of the Steel Forming Machine

Under the umbrella of CMS, working condition of every individual component is real-time communicated among the others, and quick response & reaction could be guaranteed. However, working components are traditionally isolated from each other, and failures used to be manually detected. The delay of detecting and communication of the failure information leads to the accumulation of WIP inventories or even results in congestions. Seen from the comparison, we can conclude that self-monitoring function helps avoid unnecessary increment of WIP inventory level.

6.2 Scenario 1-2 Part Supply Shortage for Storage Box Assembly

The part recipes for the storage box assembly is the box body and the lid. When supply is in shortage or even unavailable, the traditional remedy is to passively wait for the recovery of that supply source, which leads to the WIP inventory accumulations of the rest recipe parts and the delay of the overall progress. Whereas in CMS, make-up inventories source will be retrieved and triggered to compensate the missing sources. In the comparison between CMS and the traditional approach, CMS performs well in controlling I_{IB} and maintaining I_{ME}, i.e., reducing the overall inventory level and increasing the productivity.

6.3 Scenario 2-1 Warmup of the Steel Forming Machine

In this scenario, steel forming machine requires a five-minute warmup phase before being ready. The traditional operation is to trigger the production procedure in a compartmentalized, linear, consecutive way in sequence, and, therefore, the warmup (or setup) of a working component begins right after all its prerequisite processes are completed. CMS utilizes an integrative strategy and saves the preparation time by getting awareness of the changeovers in advance according to the data acquisition and user-defined rules. The sustainability performance result shows that the manufacturing efficiency in the first hour could increase by 5% if the system can perceive the coming job assignment and make a pre-setup.

6.4 Scenario 2-2 Work Modes Switch of the Subassembly Machine

In this scenario, an extra supply of plastic lids is utilized. However, the arrival schedule of the extra supply is unknown. In traditional manufacturing vision, visual examination and human judgment from experienced workers or experts determine the switch between peak load working mode and normal working mode. The machine manipulators may delay the switch considering the tolerance of false alarms. By contrast, CMS could use expert rules to accurately and immediately identify the requirements of changing. In the given scenario, there is a slight increase in CMS operation. Better performance can be achieved when the switch rule is refined.

6.5 Scenario 3-1 Varying Tool Lives

In this scenario, a pool of tools with different tool lifetime are available for turning. Some tools may break down in the coming working period, leading to the loss of tools and machine downtime. Traditionally, the most efficient units are dedicatedly arranged for shortening completion time, and the schedules of manufacturing facilities are fixed. The job will not be reallocated to other facilities until the current occupied ones fail down. In CMS, lifetimes of each manufacturing unit or agent will be real-time estimated. The efficiency and the tool degradation will be comprehensively considered, and the optimal schedule is made with the objective of maximizing the overall productivity. Taylor's Equation is used to predict the remaining tool lives in this scenario. By avoiding the downtime caused by tool failures, CMS has the manufacturing efficiency which approaches the expected efficiency.

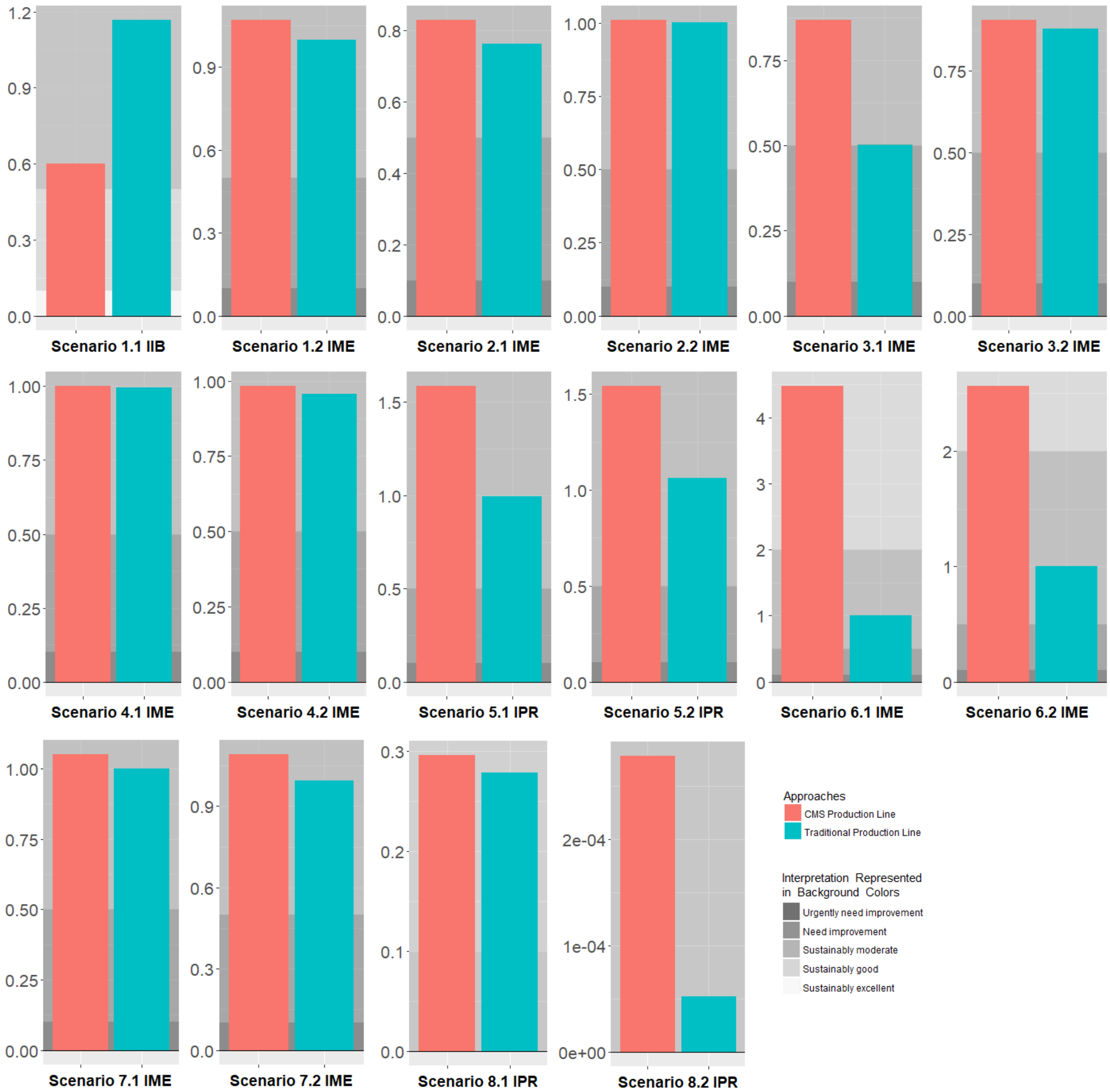


Figure 19 Simulation Results of the Scenario Studies

6.6 Scenario 3-2 Surface Roughness Quality Control of Shaft Production

In this scenario, if the surface quality, i.e., the roughness, of an output shaft doesn't meet the quality requirement, it won't be accepted. Traditionally, the product quality in the future generation is estimated by the past finished products. Without a dynamic prediction, the products' quality will be roughly regarded as being unchanged to the last batch, which is not practical in real manufacturing, especially in tool-consuming cases. The static scheduling plan leads to a higher probability of unacceptable batches. In CMS, the product quality will be learned by real-time data acquisition, and the accommodation strategy will be made in order to maximize the overall product quality. Seen from the simulation result, I_{ME} increases by 2% if self-prediction function is implemented.

6.7 Scenario 4-1 Selection of Plastic Box Body Inspectors

A total of three inspectors are assigned for the inspection process, and they have a dynamic work efficiency based on their current fatigue levels. Traditionally, the mission is more likely to be evenly or randomly assigned to all the available inspectors in the factory floor. In CMS vision, each new-arrival job will be assigned to the manufacturing resources which is estimated to have more favorable performance regarding the efficiency. Seen from the simulation result, the overall productivity of CMS is increased by 0.5% compared with the traditional approach.

6.8 Scenario 4-2 Drone Assembly Production Lines Selection

In this scenario, production lines are the manufacturing resource for selection. CMS selects the best production line considering logistic cost, processing time and current WIP inventory size, whereas dedicated schedules will be used in traditional operations. In this scenario, self-optimization could improve the productivity by 2.5% compared with the traditional approach.

6.9 Scenario 5-1 Inspection of Injection Molded Parts

In this scenario, self-configuration is utilized for addressing bottleneck processes. In this example, the inspector has surplus capacity if only handling with inspection process of the box body. In CMS production lines, self-configuration function is used to utilize the surplus capacities of the non-bottleneck process components by assigning other manufacturing jobs to them. In this scenario, a batch of lids will be fed to be inspected when CMS detects a lid inspection mission will not intervene the ongoing main job—the plastic part inspection. The extra inspection assignment brings a great increase (around 60%) in profitability.

6.10 Scenario 5-2 Inspecting and Packaging Plastic Parts

The scenario is to study the performance of the inspection and packaging processes of the drone in traditional and CMS production lines. The bottleneck of both production lines is the upstream supply of drone assembly. In this scenario, CMS assigns (i) "ship assembly inspection" job to the inspection machine and (ii) "plastic dice packaging" job to the packaging machine. This configuration won't intervene in the production of the primary job (inspection and packaging of the drone). The I_{PR} of CMS production line shows that CMS production line has substantially better performance (around 50% increment) in economic profitability compared with the traditional production line. The extra profits come from the extra assignments (inspection of "ship model" and packaging of "plastic dice").

6.11 Scenario 6-1 Production Planning for Massively Producing Holders

This scenario is used to create the production plan for massively producing holders. After the holders are completed, the consumers will pick up the finished products themselves from the production sites and thus the delivery doesn't need to be considered. Only facilities within the 3miles×3miles region are taken into consideration in order to avoid high transportation expenses. The productivities and manufacturing cost of the retrieved local available facilities for the three production procedures are listed in **Table 18**. The transportation of shipping intermediate parts recipe is enabled by road networks, which consist of vertical and horizontal roads. Shipping cost rate is $500 per mile every 1000 items.

Table 18 Production Facilities Information in Scenario 6-1

	Molding Injection Facilities	*Steel Stamping Facilities*	*Assembly Facilities*
Productivity	Base: 30 units/hour	Platform: 60 units/hour	60 outputs/hour
Manufacturing Cost	$0.5 per output	$2 per output	$1 per output

One example of CMS production services composition plan by using self-scalability function is presented in **Figure 20**. In 100-replication simulation experiment, 4.47 production lines could be composited and assigned to work parallelly, leading to an output productivity of 268.2 units per hour. When availability changes, CMS could rapidly initialize another round of service composition and create the optimal plan based on current manufacturing units' availabilities. By contrast, traditionally, the information of available facilities for scaling production capacity is limited and the completion time will be delayed upon availability changing.

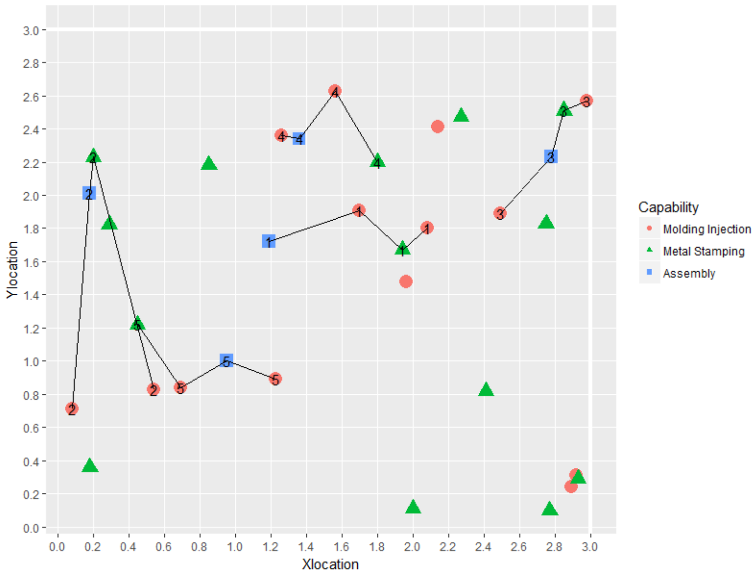
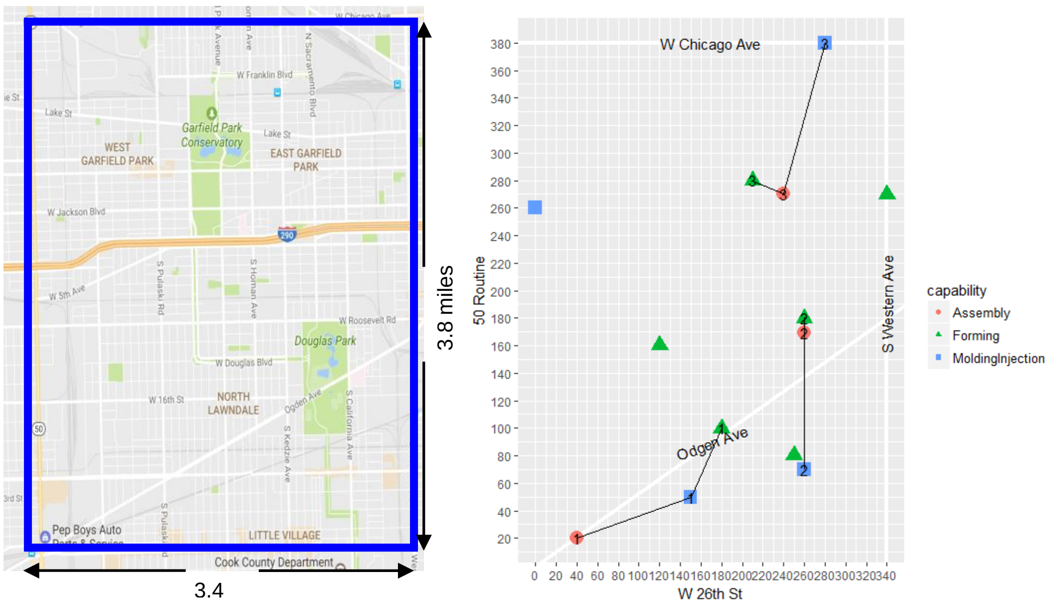


Figure 20 Service Composition Plan (A Single Simulation Run in Scenario 6-1)

6.12 Scenario 6-2 Storage Box Production Planning in Chicago Urban Area

In this scenario, the storage box production request with high demand volume is published in a portion of Chicago urban area as shown within the blue boundaries in **Figure 21**. In this region, a total of 13 production facilities are assumed to be available and distributed in this region. Their geographical locations come from the industry spaces information provided by the website *cityfeet.com*. For simplification, all the facilities are assumed to have the same productivity. The result from a 100-replication simulation shows that, averagely, up to averagely 2.56 with a standard deviation of 0.83 parallel production lines could be constructed. The logistics cost per unit of output product is \$0.65 with a standard deviation of \$0.28. In both Scenarios 6-1 and 6-2, the logistics cost is increased as the trade-off of the productivity increase. However, the transportation is a worthwhile investment since it brings the considerable increments in productivity and profitability as returns.



a. Chicago Urban Area b. CMS Production Services Composition Plan

Figure 21 Composition of the Production Services Locating in A Region of Chicago Urban Area

6.13 Scenario 7-1 Production Losses Makeup for Drilling Box Body

This scenario is created based on the condition that the failures of drilling tools disqualify the box body that is being processing. Another rigid box body is in the same production series with the box body and has the same geometrical dimensions, materials and undergoing the same molding injection procedure. The difference is that the production of rigid box skips drilling. In CMS vision, when a failure occurs to the drilling process, the inventory of finished rigid box body will be utilized as the immediate supply of drilling in order to guarantee the in-time supply of the box body. As a result, in a 24-hour simulation experiment, the box body has an output volume of 149.39±0.49 (the number coming after "±" is the half-width of the variable for the whole paper) compared with 136.13±0.5 via the traditional approach, which means self-remediating function is an effective solution to address uncertain incidents in the real production settings.

6.14 Scenario 7-2 Compensating Platform Loss Caused by Assembly Failures

The holder production is assumed to be time-critical since it lies in the critical path of its meta-project. However, it is vulnerable to assembly failures (defective rate 10%). In defective parts, bases could be recovered whereas the platforms cannot. The platform lies in a product family along with two similar platforms, which require grinding after CNC machining. In CMS context, if a failure occurs, the productions progress of the other platforms will be utilized for compensating the loss. Specifically, CMS will find the platform that is being CNC machined and has made more progress. After finishing CNC machining, the platform is shipped back to the site where the holders are assembled. In a simulation duration of 24 working hours, the

CMS model accomplishes 1436.12±0.4 output acceptable parts, whereas the traditional manufacturing approach can only provide 1369.01±1.78 output acceptable products.

6.15 Scenario 8-1 Remanufacturing Defective Box Bodies

Under the same context setting of Scenario 7-1, this scenario is created to test the effectiveness of self-reusing in coping with the defective box bodies. The defective box bodies will be fed to a remanufacturing process (machining), where the defective feature (threaded holes) will be removed. The remanufactured box bodies will be the resource for one type of lamp base's production. The remanufacturing task will be taken by the CNC machines which are mainly responsible for other productions but with surplus working capacity. Traditionally, information of the ongoing production and real-time supply/demand is not fully available, and, therefore, manufacturers choose a conservative way to process defective parts—directly recycle the materials of the defective parts. As a result, in a 24-hour simulation experiment, 7.26±0.54 defective products can be remanufactured.

6.16 Scenario 8-2 Reconditioning the Materials of Defective Platforms

In the same context of Scenario 7-2, the reusing strategy of defective platforms is reconditioning. A reconditioned platform will return as a full-value item. By contrast, the traditional approach is to recycle the steel material and to obtain some income as the return of selling waste steel. In a simulation duration of 24 working hours, the CMS model could recondition 70.99±1.78 defective platforms and make a slight increase in production revenue.

This chapter utilizes 16 scenarios for discussing, analyzing and verifying the effectiveness of CMS functions. However, the significance of the improvement brought by CMS functions is constrained by short-term working hour duration and limited scope of the tested scenarios &

contexts since the improvement of consequent downstream and the meta-projects cannot be reflected. Therefore, the case studies, where the complete production procedures and manufacturing activities are defined, will be presented in Chapter 7, and the well-being of CMS functions' integration and overall sustainability benefits will be tested and studied.

7 Case Study

In this section, three practical cases are captured for instantiating and testing the effectiveness of CMS operations. For study approach, this paper utilizes a hybrid of *R-studio* and *Simio* for modeling & simulating all manufacturing operations and generating the manufacturing performance data of interest. Starting from *R-studio*, Monte Carlo simulation is used for conducting the production facilities selections and generating master-level production plans. Then, *Simio* is utilized to carry out the production plans, generate manufacturing events and implement the configurations and controlling contained in different manufacturing systems. The generated data by Monte Carlo simulation and DEMS will be both fed to the sustainability metrics developed in Chapter 5. Finally, the indicators index values will be presented, and the sustainability performance of all comparative manufacturing systems will be interpreted and discussed.

7.1 Case 1: Storage Box Production

In this case, the entire manufacturing processes of the storage box are selected, and all the CMS functions are incorporated in the CMS operation model. **Figure 22** shows the diagram of CMS model operations and material flows. Self-monitoring function is implemented for monitoring failures of the turning process, and for monitoring the assembly process in location 1. The applications of self-awareness function are (i) the setup awareness of the forming process and (ii) the working mode switch awareness of the molding injection process in location 1. The instantiations of self-prediction function are (i) the prediction on the remaining useful life of drilling tools and (ii) the prediction of the milled shafts' quality. Optimal selection among PE sources suppliers is the implementation of self-optimization function. For the implementation of self-configuration function, a drone assembly inspection mission from cyber center is waiting to be triggered on the condition that inspection machine at location 4 is temporarily unused. For comparison, the traditional manufacturing solution, where dedicated schedules and fixed machines are used, is shown in **Figure 23**.

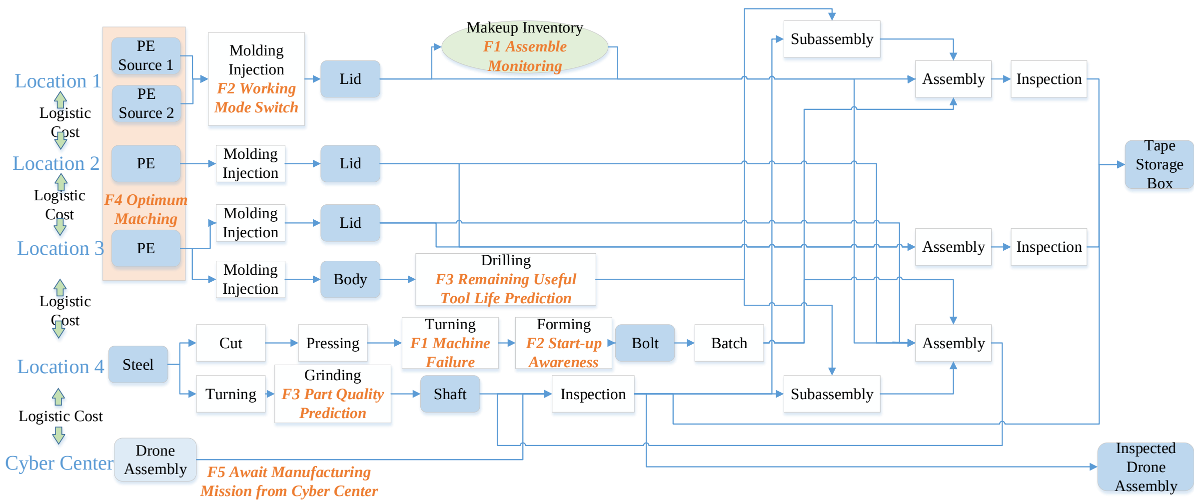


Figure 22 Diagram of the CMS Solution

The validation of the constructed simulation models in whole Chapter 7 was conducted by removing the (i) differences of the operations, arrangement and schedules contained in different manufacturing solutions and (ii) the uncertainties that occur, and then checking whether the simulation results are identical or not. CMS functions/operations as well as the operations of the comparative approaches were verified by the visualization & animation of the simulation package and real-time display of the internal control parameter values.

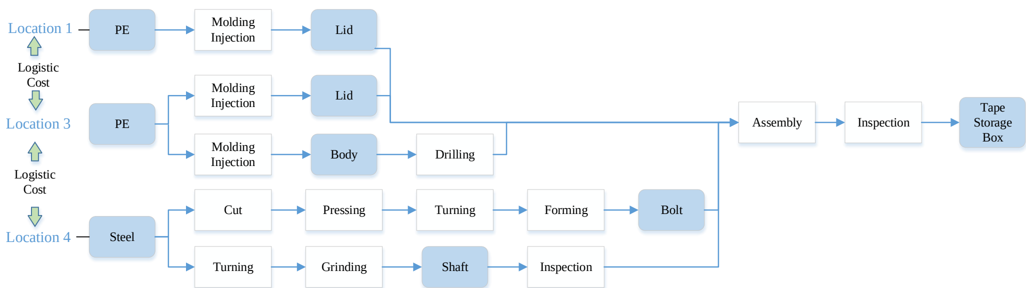


Figure 23 Diagram of the Traditional Manufacturing Solution

Manufacturing performance on a time duration of 24 hours is simulated. The simulation animation shows CMS functions cooperate in harmony way with mutual gain effects. In *Simio*, the random number generation for part arrivals and manufacturing events are identical across different manufacturing scenarios. Therefore, *Paired t-Test* is used for comparing manufacturing performance between two manufacturing solutions (Romeu 1986; Walpole et al. 1993). The comparison result is shown in **Table 19.** The data generated by the simulation are implemented into the proposed sustainability assessment framework. The indicators index values are shown in **Figure 24**.

Table 19 Paired T-Test Result of Case 1

Indicator	*t-Value*	*P-value*	*95% Confidence Interval (CMS-TMS)*	*Mean Difference*
Renewable Material	165.96	<2.2e-16	(0.168, 1.72)	0.17
Energy Efficiency	-19.622	<2.2e-16	(-0.019, -0.015)	-0.017
Inventory Buffer	-208.48	<2.2e-16	(-2.668, -2.618)	-2.642
Product Revenue	397.25	<2.2e-16	(0.655, 0.661)	0.659
Manufacturing Efficiency	362.05	<2.2e-16	(0.603, 0.609)	0.606
Resource Cost	-21.074	<2.2e-16	(-0.034, 0.028)	-0.031
Logistic Cost	-341.14	<2.2e-16	(-0.204, -0.201)	-0.202

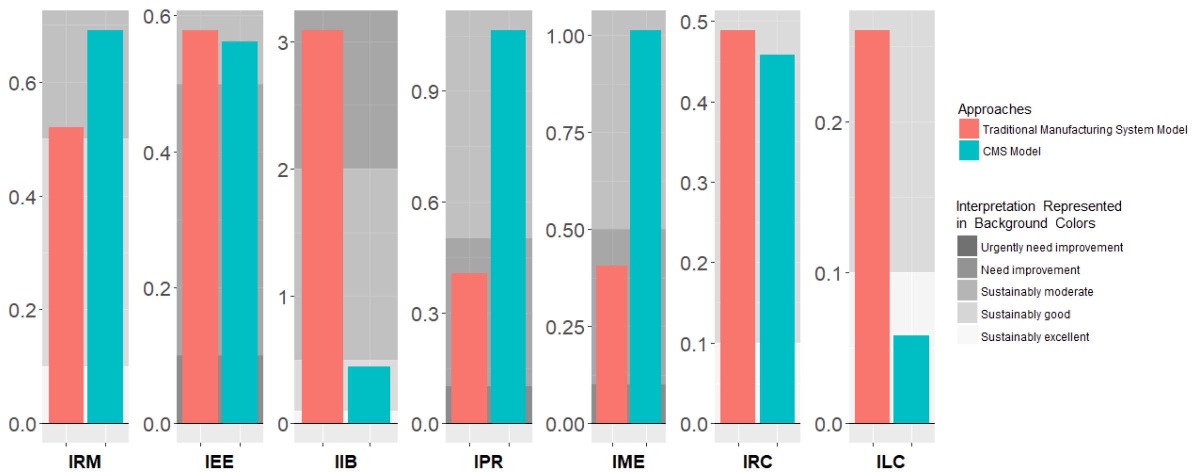


Figure 24 Manufacturing Sustainability Performance Comparison of Case 1

Seen from the indicators result illustration, the performance of CMS is substantially different from that of the traditional approach. The specific discussions on every aspect of sustainability are as follows.

1. I_{RM}: The I_{RM} of manufacturing systems with CMS functions is higher than that of the traditional manufacturing system since a make-up inventory is used as an extra lid supply for assembly, which makes the overall renewable materials consumption slightly higher. I_{RM} of both CMS and the traditional approach are smaller than 1, i.e., smaller than the standard value, mainly due to the fluctuations in part supplies.

2. I_{EE}: CMS has a lower overall energy efficiency since CMS incorporates more facilities to be used and two of them have a below 50% utilization rate. The production task scheduling and arrangement allocation need to be further refined & improved, and more facilities need to be incorporated for consideration.

3. I_{IB}: One of most significant benefits of CMS is the reduction of WIP inventory buffer levels.

4. I_{PR}: The extra profits of CMS are brought by the increased productivity and the additional assignment—the drone inspection. By contrast, the production revenue of the traditional vision suffers from influence of production uncertainties. Therefore, the revenue cannot meet the expected economic profits.

5. I_{ME}: The manufacturing efficiency of both CMS and traditional manufacturing system don't reach the desired level. The reason is that the warm-up phase of the simulation is intentionally included for testing its influence to the performance of both approaches and the effectiveness of self-awareness function. The result shows self-awareness function helps better address warm-up issues and slightly improve the efficiency.

6. I_{RC} and I_{LC}: Even though the absolute values of the resource cost and logistic cost of CMS model are higher than those of the traditional model, CMS model shows better sustainability performance in logistic and resource aspects since CMS has more output production and sale income as return. The results also prove that the indicator index values of the proposed sustainability assessment framework can provide unbiased conclusions when comparing different workload cases.

Compared with the benefits analysis of individual scenario studies in Chapter 6, the sustainability benefits of the whole storage box production turn out to be much more significant. The intelligent functions are leveraged to enhance the downstream manufacturing activities and thus the initial improvements can be magnified to more substantial improvements.

7.2 Case 2: Additive Manufacturing Productions

In this case, two specific productions tasks—(i) task A: producing part *P1* and (ii) task B: producing part *P2*—are the missions to be completed. Part *P1* and part *P2* have one overlapping feature (same dimension, material and production requirement)—PLA rounded rectangular base (L100mm, W100mm, H5mm). One type of Additive Manufacturing, specifically, 3D printing is selected as the production procedure (Berman 2012). Processing time & timeliness requirements of both parts and the processing time of the common feature are shown in **Table 20**. The uncertainty that occurs during the printing is natural printing defectiveness. An empirically estimated 20% defective rate is assumed. The working period for this case is 24 hours. Four 3D printers in location 1 are scheduled to produce part *P1* for production task A; one printer in location 2 is working for part *P2*. The distance between locations is 15 miles and accounts for 15 minutes of transportation.

Table 20 Production Task Information in Case 2

Production Task	Production Task A	Production Task B
Produced Item and Timeliness	produce Part *P1* Time-critical (need 4 unit 55 minutes)	produce Part *P2* No requirement in term of Timeliness
Printing Time	50 min	40 min
Production Similarity	Part Design: PLA Rounded Rectangular (In both productions, this feature will be produced in the first 30 min)	

In CMS operation, the four printers in location 1 and the other printer in location 2 are closely cooperated. If a failure occurs on any of the four printers that are responsible for part *P1*, the defective plastic part will be fed to recycling pool, and the printer won't start working until the next work cycle. At this moment, if the printer in location 2 is currently printing the overlapping feature, the current progress will be utilized, i.e., this printer will immediately change the printing reference model into the CAD file of part *P1*. If the printer in location 2 has already finished the common feature and continued printing part *P2*'s unique feature, the printer will firstly finish current job and then go for printing part *P1*. The finished part *P1* in location 2 is shipped back to location 1. Self-monitoring function takes charge of failure detection by utilizing advanced sensor network.

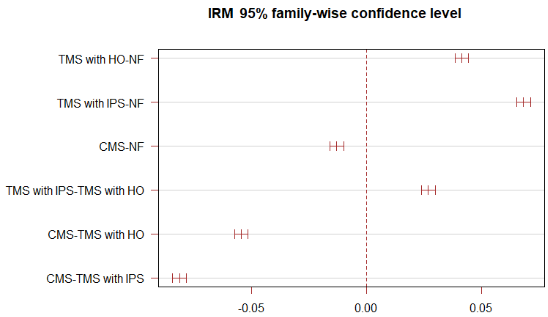
Traditionally, the printers in location 1 and location 2 are isolated and working for their own tasks. Any defectiveness in production can only be detected by regular human inspection (5-minute regular check is assumed in this case). The remedy for defectiveness is to reprint another one to compensate the production loss.

In this case, four scenarios/approaches are implemented for comparison: Scenario 1: *No Failure* scenario, which means no failure (pure ideal scenario) occurs during the production period; Scenario 2: *TMS with HO*, which means a traditional manufacturing system with the human observation detection method; Scenario 3: *TMS with IDS*, which means a traditional manufacturing system with image detection system; and Scenario 4: *CMS*, where CMS functions are implemented. **Table 21** shows the numeric results of 100 simulation experiments for each scenario/approach.

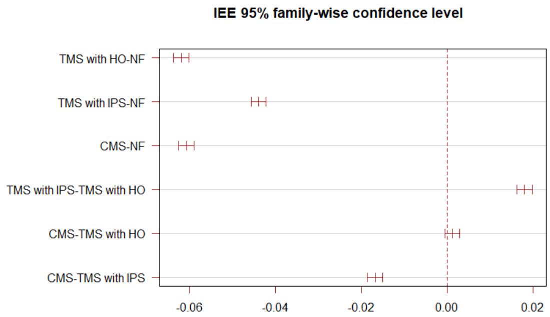
Table 21 Numeric Simulation Result of Case 2

Value of Interests		No Failure	TMS with HO	TMS with IDS	CMS
Total Number of Machine Occupied		4	4	4	5
Production Number	*Acceptable Part P1*	520	431 ± 1.35	445.41 ± 1.6	518.35 ± 0.43
	Defective Part P1	0	108.52 ± 1.94	110.33 ± 2.2	105.69 ± 1.76
	Acceptable Part P2	178	102 ± 1.78	102 ± 1.78	32.55 ± 2.11
	Defective Parts in Location 2	0	41.15 ± 1.27	41.15 ± 1.27	33.65 ± 1.17

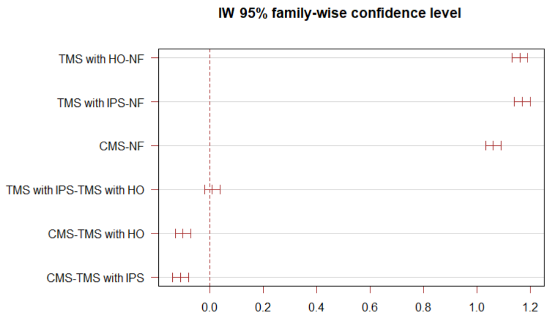
The results show that the CMS (Scenario 4) provides timely output supply with a small variance as if no failure occurs (Scenario 1). This performance guarantees the in-time property which is the core virtue of Just-in-Time approach. The simulation result of Scenario 2 shows the substantial loss caused by the defectiveness. The traditional manufacturing system with human observation, Scenario 2, can hardly provide enough number of items for the time-sensitive demand. In Scenario 3, the utilization of Image Detection System cannot thoroughly solve this dilemma. Besides above scenarios, another alternative solution is to add one additional printer, i.e., using five printers in location 1. However, this strategy cannot compete with the CMS operation since the capital cost along with the extra personnel and materials & energy investment turns out to be far more expensive than adopting CMS. The Tukey's Test (Walpole et al. 1993) of sustainability indicators' index values across different scenarios (Scenarios 1 to 4) is presented in **Figure 25**. When framed into the sustainability metrics, the sustainability performance comparison among scenarios is presented in **Figure 26**. The detailed discussion of different scenarios is as follows.



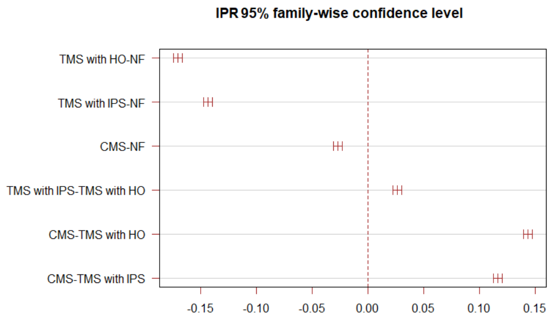
a: Renewable Material



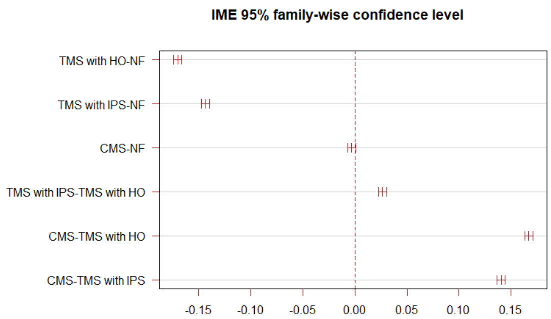
b: Energy Efficiency



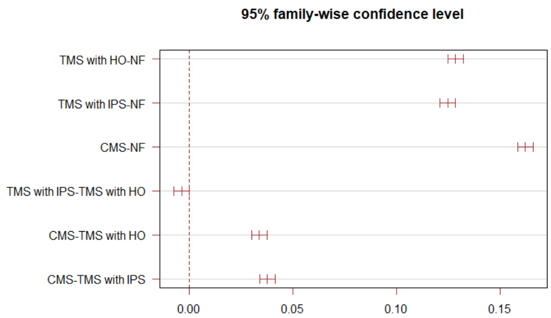
c: Waste



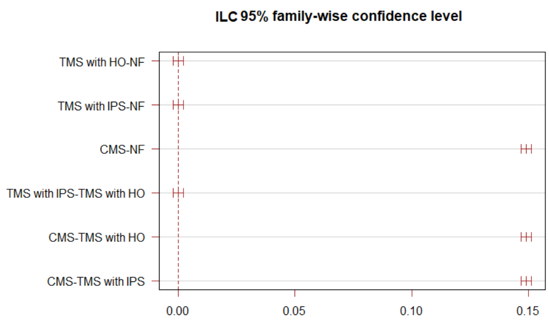
d: Production Revenue



e: Manufacturing Efficiency



f: Resource Cost



g: Logistic Cost

Figure 25 Sustainability Performance Tukey's Test of Case 2

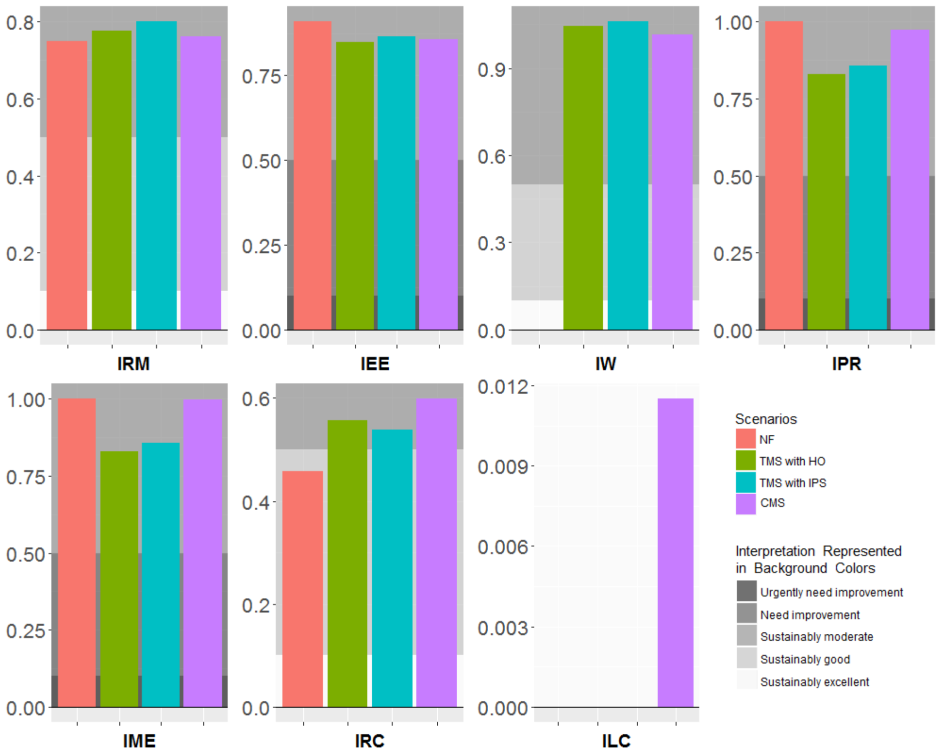


Figure 26 Manufacturing Sustainability Performance Comparison of Case 2

1. I_{PR} and I_{ME}: In these two indicators, CMS shows the greatest advancements. By utilizing the manufacturing progress of normal-priority productions—part *P2*, the time for making up the loss production could be substantially reduced. The production task *A* can keep its timeliness-related values.

2. I_{RC}: CMS has a higher resource consumption compared with other operations. The main reason is that producing part *P2* is less profitable than producing part *P1*. In the CMS, 5 printers—four printers printing part *P1* and one printer printing *P2*—are counted, whereas the rest scenario or approaches, only the four printers (printing part *P1*) are counted.

3. I_{LC}: Only CMS leverages transportation for compensating production loss and thus triggers transportation cost whereas other scenario or approaches don't. Seen from the index value, the transportation cost is negligible compared with the whole sale and thus acceptable.

4. There are no practical differences among different scenario/approaches in I_{RM} (renewable material consumption pattern), I_{EE} (energy efficiency pattern) and I_W (waste generate pattern) aspects.

The main achievement of the CMS is the in-time supply of the time-critical production. Within the context of progress allocation, CMS could further allow customers to modify their requested product even after the corresponding production has begun, and to trade the production progress based on their own needs.

7.3 Case 3: Sealed Box Production

A group of consumers continuously demand a specific sealed box in very high volume. The BOM and involved production procedures are graphically presented in **Figure 27**. The sealed box and the part recipes are shown in **Figure 28**. After the boxes are finished, the consumers will pick up the finished products themselves from the production sites.

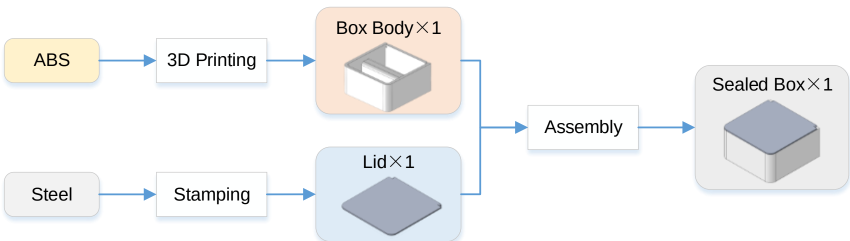
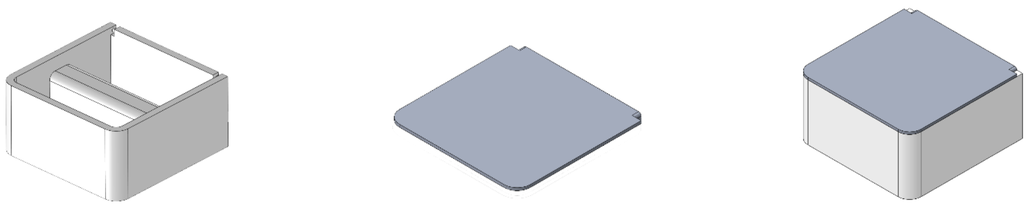


Figure 27 BOM and Sequential Diagram of the Sealed Box Production



a: Box Body b: Lid c: Sealed Box

Figure 28 Sealed Box and Recipe Parts

To avoid high transportation cost, only the production facilities in local area (3miles×3miles region) are considered. The numbers of available facilities, the productivities, production quality, maintenance cycle and other manufacturing information are listed in **Table 22**. The transportation of shipping intermediate parts is enabled by road networks, and the shipping distance between two facilities could be approximated by the Manhattan distance between the locations of the facilities. Shipping cost rate is assumed to be $500 per mile for every 1000 items.

Table 22 Production Facilities Information in Case 3

	3D Printers	Steel Stamping Facilities	Assembly Facilities
Available Units No.	>=20 & <= 25	>=6 & <= 10	4 or 5
Productivity	10 units/hour	20 units/hour	20 units/hour; setup 0.5 hour
Production Quality	Non-defectiveness: 80%	-	-
Maintenance Cycle	-	15-minute cleanup every 120 minutes	-
Energy Consumption	0.5 kw	5 kw	1 kw
Resources Cost	$3 per unit	$2 per unit	$1 per unit
Estimated Profit	Sealed Box: $10 per output unit		

In this case study, three manufacturing systems—VE, Cloud Manufacturing and CMS—are tasked to accomplish the requested production, and the performance of all three manufacturing systems will be analyzed and discussed after being framed in the sustainability assessment framework.

The productivities of (i) printing body, (ii) stamping lid and (iii) assembly are 1:2:2. A complete production line requires two 3D printers, one steel stamping machine and one assembly machine capable of continuously working with full capacity. The production line—consists of two 3D printers, one steel stamping machine and one assembly machine—is the basic production unit for the manufacturing systems to carry out the requested production. A general overview of the manufacturing solutions of VE, Cloud Manufacturing and CMS are shown in **Table 23**. The details of the unique operations of each manufacturing system and the simulation results are discussed in the following paragraphs.

Table 23 Manufacturing Solutions of the Comparative Manufacturing Systems

Manufacturing System Paradigms	*Manufacturing Solutions*
Virtual Enterprise	utilize companies' networking to form manufacturing groups which could provide all required production capabilities
Cloud Manufacturing	composite the production services from the distributed available production facilities; dynamically configure and modify the plan if availability changes; production uncertainties could be rapidly detected
CMS	scale up the production capacity and create the service composition plan according to the (i) availability, (ii) quality and (iii) manufacturing cost and (iv) transportation cost of the production facilities in the location (**self-scalability function**) monitor working conditions and workpiece quality (**self-monitoring function**) advance the setup of assembly machinery (**self-awareness functions**) estimate the workability of stamping machines in the next work cycle and select the best piece of machinery (**self-prediction** and **self-optimization functions**) make up the production loss (caused by defective printed parts) by incorporating extra 3D printers (working for similar productions) (**self-remediating function**)

VE manufacturers coordinate their production resources with the resources of the other partners, aiming to provide all the capabilities required by the manufacturing request. However, traditional data & information manager, time-consuming negotiation, and constraints of formally defined contracts & service agreements significantly limit the VE's scalability (Karageorgos et al. 2003; Tao et al. 2010). Moreover, these external factors make it hard to directly simulate the final size of the VE production lines' integrated production capacity. Therefore, in this case study, the capacity size of VE production lines is assumed to be 40 output units per hours (i.e., two production lines).

By contrast, Cloud Manufacturing and CMS take the advantages of full shared and circulated manufacturing capabilities and thus could fully utilize all the available resources to scale up the production capacity. Linear Programming is adopted as the algorithm to find the optimal service composition plan in this case. **Figure 29** shows one example of service composition plan (a single simulation run), where four simultaneously working production lines are formed. Each "point" distributed in **Figure 29** represents a machine, and the number in the middle of the point indicates which production line the machine belongs to. Cloud Manufacturing has the equivalent operations on production service discovery and composition to CMS and, therefore, generates the same production service composition plan.

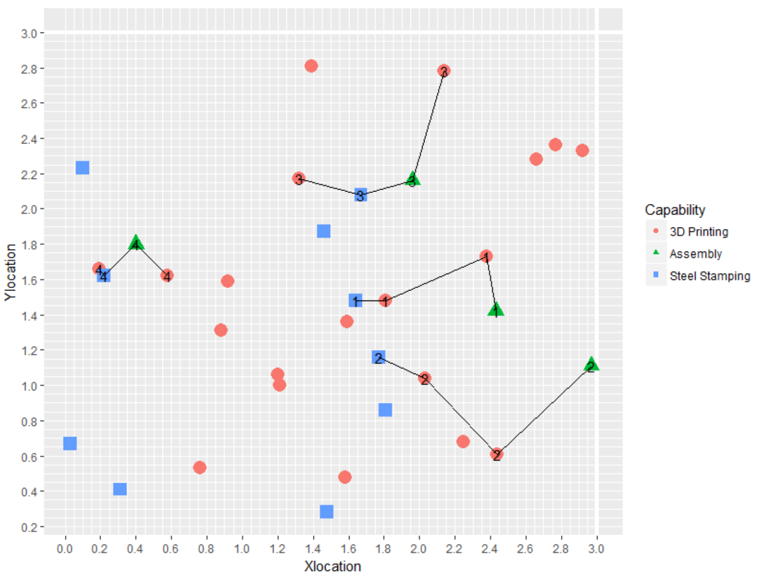


Figure 29 CMS Production Services Composition Plan

Simulation results of the production capacities and manufacturing costs of VE, Cloud Manufacturing and CMS in the planning phase are presented in **Table 24**. CMS and Cloud Manufacturing are capable of maximally constructing production lines and enlarging the production capacity. Then Discrete-event Simulation Models use all data generated from

Monte Carlo simulation and finish the simulation of actual production implementation.

Table 24 Monte Carlo Simulation Results of CMS, Cloud Manufacturing and VE's Production Plans

CMS and Cloud Manufacturing		VE	
Production Capacity	*Manufacturing Cost*	*Production Capacity*	*Manufacturing Cost*
85.6±10.04 units/h (4.28±0.5 constructed production lines)	Resource Cost $9/unit; Transportation Cost $0.93±0.2/unit	40 units/h (two production lines)	Resource Cost $9/unit; Transportation Cost $2.95±0.73/unit

Figure 30 shows the layout of the manufacturing facilities network and functions deployment of the CMS manufacturing solution. Self-monitoring function is deployed on 3D printers for knowing the qualities of ongoing workpieces. Self-awareness is formulated into the scheduling of assembly machines for saving the setup time. Self-prediction and self-optimization functions are utilized for assisting the decision-making on when to use the alternative steel stamping machine. Two extra 3D printers are assigned to print a type of plastic part that is similar to box body, and always ready to make up the production loss of the box body. The models of VE and Cloud Manufacturing are separately constructed. Simulation duration time is set to be 24 hours and replication time is set at 100.

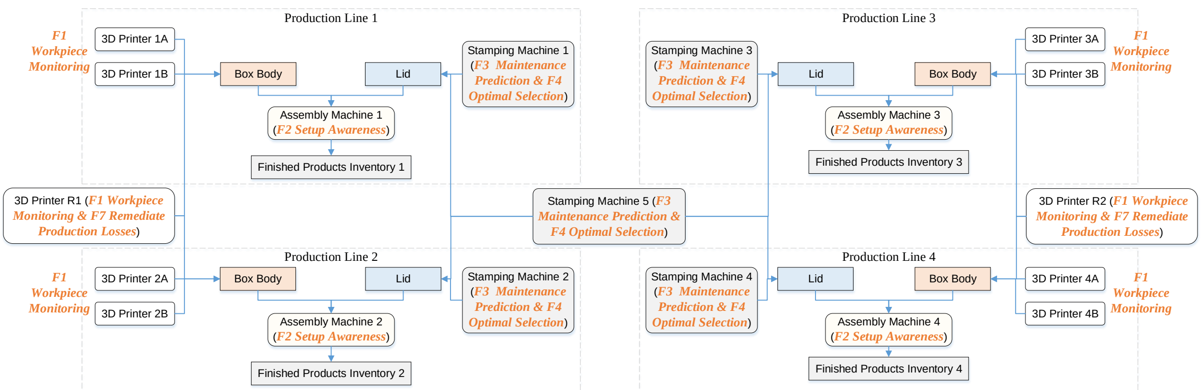
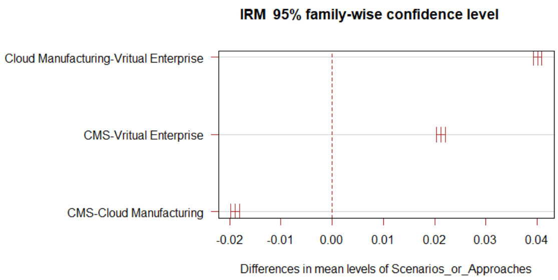
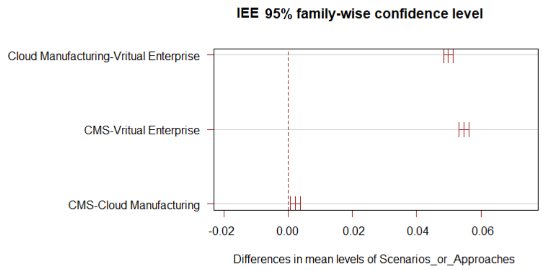


Figure 30 Diagram of CMS Solution and CMS Functions Deployment

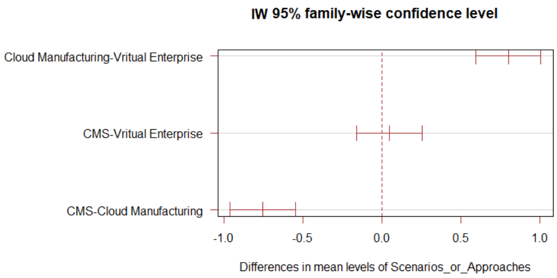
The Tukey's Test of sustainability indicators' index values across all candidate comparative manufacturing systems is presented in **Figure 31**. The complete sustainability performance comparison is shown in **Figure 32**. The sustainability performance of all candidate manufacturing systems is discussed in the following paragraphs.



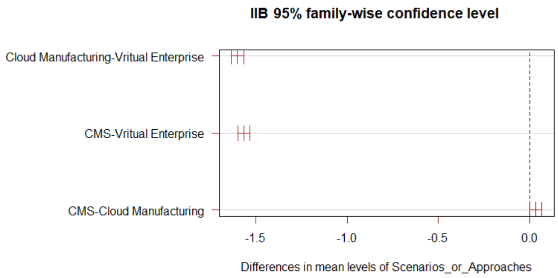
a: Renewable Material



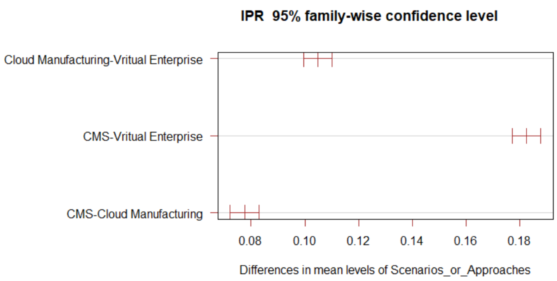
b: Energy Efficiency



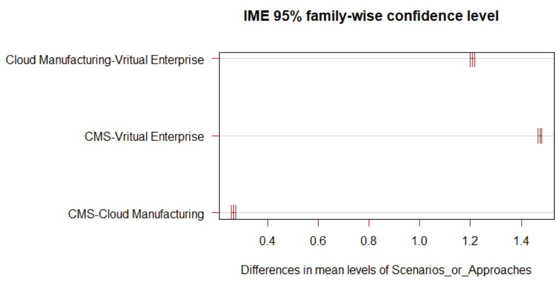
c: Waste



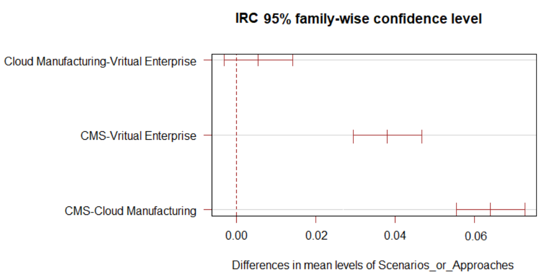
d: Inventory Buffer



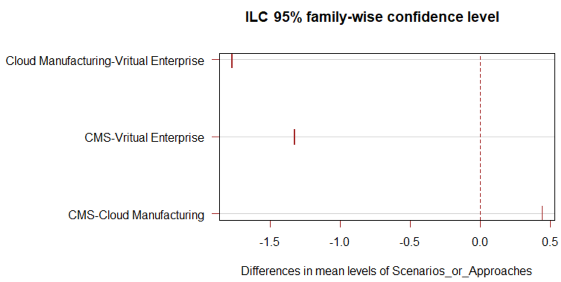
e: Production Revenue



f: Manufacturing Efficiency



g: Resource Cost



h: Logistic Cost

Figure 31 Sustainability Performance Tukey's Test of Case 3

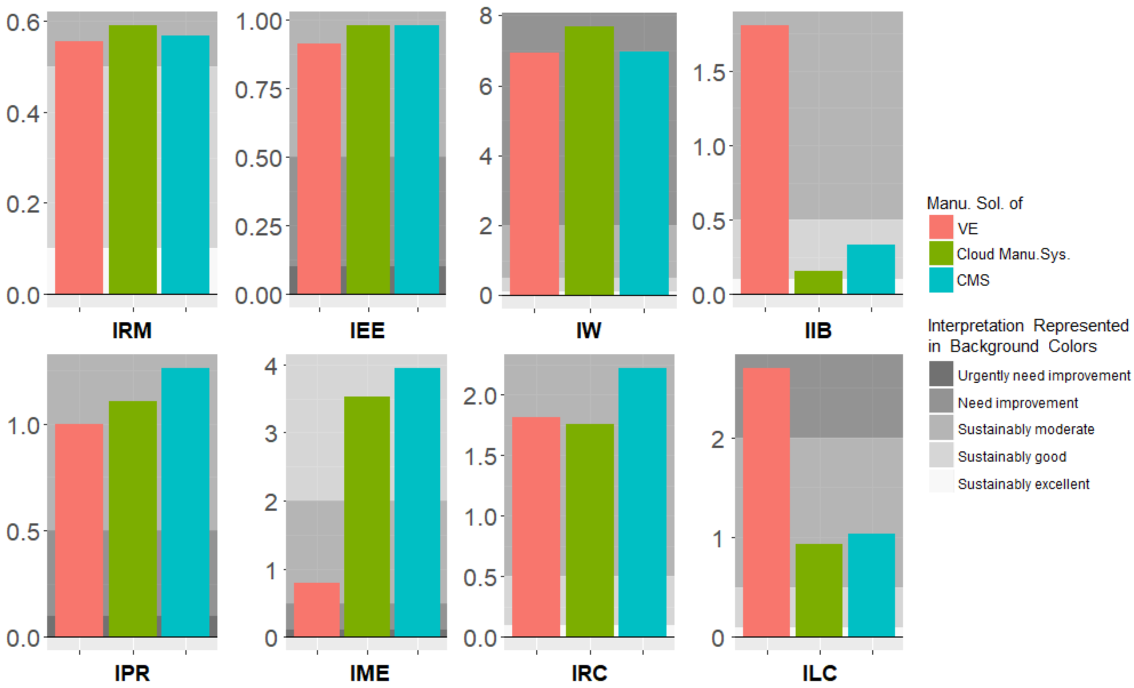


Figure 32 Manufacturing Sustainability Performance Comparison of Case 3

1. I_{RM}: The renewable material consumption patterns of all candidate manufacturing systems are close to each other since all manufacturing systems are working for the same production. The index value of Cloud Manufacturing is slightly higher over the indices of the other two manufacturing approaches since the 3D printers in Cloud Manufacturing system immediately starts another new printing task when the current workpiece is detected as defective. Therefore, Cloud Manufacturing solution results in a higher amount of material input.

2. I_{EE}: The maintenance issue of the stamping machine will influence the progress and energy utilization of the downstream assembly machine in VE production lines since the assembly machine will stay idle if the lid supply is inadequate. By contrast, Cloud Manufacturing could retrieve another machine when the current machine needs maintenance, while CMS has self-prediction and self-optimization functions to address this issue.

3. I_W: For all three manufacturing approaches, the plastic of the defective box body is the only source of waste. The reason of having a higher I_W value for Cloud Manufacturing is the higher amount of material input.

4. I_{IB}: VE has dedicated scheduling plan and thus is more likely to accumulate WIP inventories. Both Cloud Manufacturing and CMS have excellent performance in controlling WIP inventory level.

5. I_{PR}: Cloud Manufacturing has a substantial improvement in profitability compared with VE. The increment results from the improved productivity. CMS has an even higher index, which reflects that CMS is more robust towards the failures and maintenance issues occurring during production.

6. I_{ME}: The limitation in scalability and production uncertainties both influence the production efficiency of VE, making VE have the lowest performance. Cloud Manufacturing and CMS have the same planned production capacity, but CMS is more powerful in managing the production uncertainties and thus has a higher actual productivity than Cloud Manufacturing.

7. I_{RC}: Cloud Manufacturing has the best performance from the perspective of resource cost-effectiveness. Then follows by VE. The reason why CMS has a low resource cost-effectiveness performance is that for enabling self-remediating function, another two 3D printers are retrieved and assigned to print lower-value items while being prepared for making up the possible production losses of the box body. The overall cost-effectiveness of the CMS is thus diluted by the portion of lower-value productions.

8. I_{LC}: The transportation cost of VE production line is based on the contracts and can hardly reach the optimal setting, whereas CMS and Cloud Manufacturing have production plans based on the protocol of shared resources and the solutions of mathematical optimization problems. CMS has a higher I_{LC} than Cloud Manufacturing since extra transportation arrangement is needed for production-loss compensation activities.

Seen from the sustainability index values comparison and the discussion above, CMS manufacturing solution provides compelling improvements in profitability (shown in I_{PR}) and manufacturing efficiency (shown in I_{ME}) at the expense of an affordable increase in resource cost (shown in I_{RC}) and reduction in energy efficiency (shown in I_{EE}). Cloud Manufacturing provide moderate increase in I_{PR} and I_{ME} with tradeoffs on the increment of material and energy input. Both Cloud Manufacturing and CMS generate considerable sustainability benefits but CMS has even more sustainability improvement with the help of seamless integration between computational processes, information integration and production procedures.

8 Main Contributions

This research is to introduce a multi-facet, comprehensive description of an emerging manufacturing system, CMS, from the perspective of definition, uniqueness, architecture, functions and practical case studies. A sustainability assessment tool is developed for holistically analyzing manufacturing performance of CMS and the other manufacturing systems for benchmarking. The major contributions of this research will be discussed in detail as shown in the following paragraphs.

8.1 Development of the CMS Architecture

Even though previous researches have made several attempts to establish CMS architecture, the constructed structures are too conceptual to offer practical guidance. This research proposed a five-layer architecture for elaborating the constitution of CMS, interactions between internal components, material/information flows between layers along with the emerging sustainability properties. The architecture shows how manufacturing requests can be resolved by a sequence of coherent manufacturing activities. Stakeholders and industrial practitioners could build their own CMS according to their requirements and specifications by referring to the developed architecture template.

8.2 Exploration of CMS Intelligent Functions

In this research, a total number of eight functions, (1) self-monitoring, (2) self-awareness, (3) self-prediction, (4) self-optimization, (5) self-configuration, (6) self-scalability, (7) self-remediating and (8) self-reusing, are defined. The functions encompass a complete range of manufacturing life cycle activities and provide well-information & well-focus decision-making references. The functionality and effectiveness of each CMS function are verified by scenarios and simulation studies. CMS functions are proven to be capable of working in harmony and making much more benefits than single individual function. Therefore, CMS functions are summarized for qualitatively characterizing the advancements of CMS.

8.3 Development of Sustainability Assessment Framework for Manufacturing Systems

The sustainability metrics framework provided in Chapter 5 tailors Distance-to-Target methodology to address the limitations of the existing assessment methodologies in evaluating sustainability patterns of manufacturing systems. The sustainability indicator set in the framework can comprehensively cover all the respects of manufacturing systems that have impacts on sustainability pillars. The mathematical formulas set for computing each indicator value are based on measurable or available data. In Distance-to-Target weighting factor, taking the ratio of distance values (inventory or performance data) to target values (workload and production data) can eliminate the influence of workload and production specificity. The interpretations of the indicator index values are thus independently from the specific manufacturing scenario.

Through case studies, Distance-to-Target methodology is proved to be capable of offering an all-inclusive, consistent, unbiased, transparent, “easy-to-implement” and efficient way for developing a comprehensive insight into the sustainability patterns of manufacturing systems. In addition, this assessment framework is a data-based approach rather than case-specific approach. The data-based evaluation is in line with the trend of digital manufacturing and the implementation of big data analytics techniques in manufacturing. Also, the indicator index values are visualized in bar plots with color-scaled backgrounds, entailing the interpretation of the corresponding sustainability performance. Therefore, interpretation of single indicator and comparison among different indicators among all the aspects become extremely immediate.

8.4 Summary of CMS Sustainability Benefits

Summarized from all generic manufacturing case and scenario studies, CMS is proved to have the capability of providing better manufacturing solutions and addressing the sustainability issues. Reduction of the scarce or ecological harmfully material consumption, decreasing WIP inventories level, shortening production completion time and increasing profitability & economic cost-effectiveness are identified as main sustainability benefits of CMS. Sustainability benefits of CMS are practically proved and concretely analyzed rather than conceptually discussed and theoretically reasoned. The benefits types and degree of benefits vary with the defined scope and boundary of the CMS that is being studied. Sustainability benefits of CMS serve as the solid foundation for stakeholders and industrial practitioners to adopt CMS or migrate to CMS.

9 Conclusions and Future Work

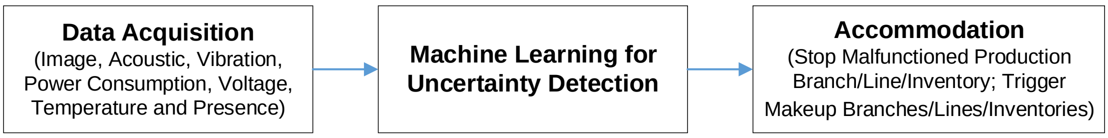
Despite an early stage, the investigation provided in this paper promises that CMS can develop into an intelligent, productive and sustainable manufacturing system, which can improve industrial manufacturing and even revolutionize the global industry in coming years. This work provides comprehensive insights into sustainability performance assessment & benefits analysis of CMS, and serves as a solid foundation for its sustainable viability and motivation for the further research on each aspect of CMS. At the same time, CMS shows promising potentials in completing the expectations of *Industry 4.0* (or *Industrie 4.0*) as illustrated in the results shown in this article.

However, in order to make CMS from a conceptual manufacturing system to a fully implementable reality, more works with other focused specificities need to be placed in the future research agenda. Information & Communication Technology and infrastructure design, including the deployment and fusion of the sensors system, and the enabling technologies for CMS intelligent functions deployment and system integration approaches deserve high-level emphases and research attention. The encapsulation of physical manufacturing facilities has obstacles in timeliness and efficiency that are required to be considered and solved: informational infrastructures are not easy to be practically implemented on legacy equipment; the transition or migrating from traditional manufacturing systems into CMS are also limited due to the economic budgets. CMS is vulnerable to cyber-attacks since CMS could be regarded as a fully data-driven system that provides many interfaces which hackers could intrude on. For further refining the sustainability assessment framework, the values of power factors still need to be normalized and standardized. In order to get a complete sustainability view of CMS, the integration of the societal performance study into current methodology is an essential work. When more Information and Communication Technologies, IoT and CPS are incorporated into CMS for realizing the next level's integration, new intelligent functions need to be explored and emerging sustainability benefits need to be analyzed.

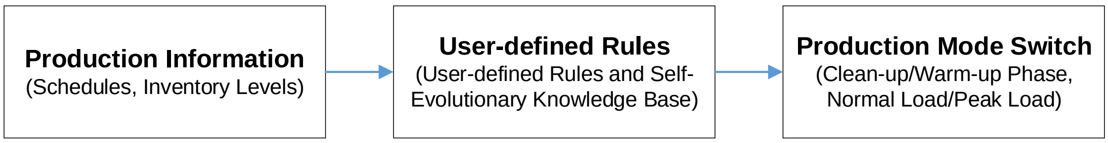
10 Appendices

Appendix A: Framework of CMS Functions

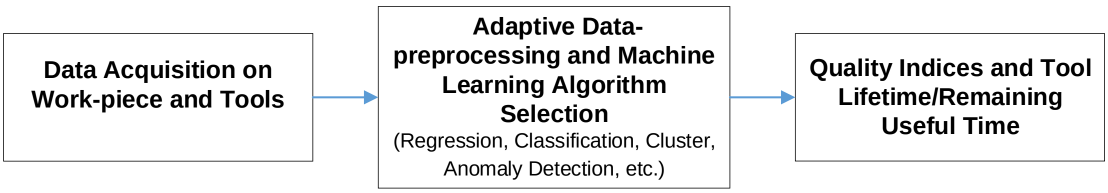
Self-monitoring Function



Self-awareness Function



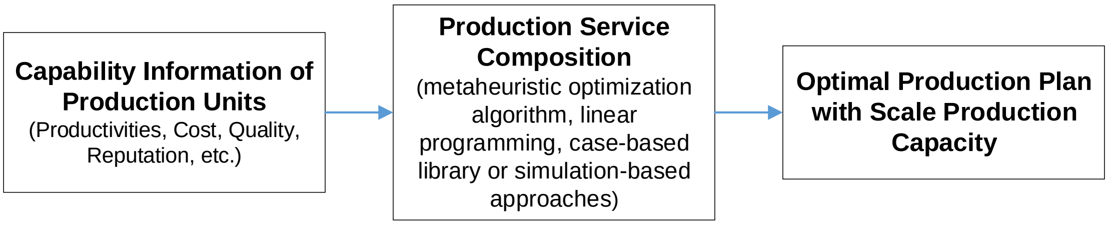
Self-prediction Function



Self-optimization Function

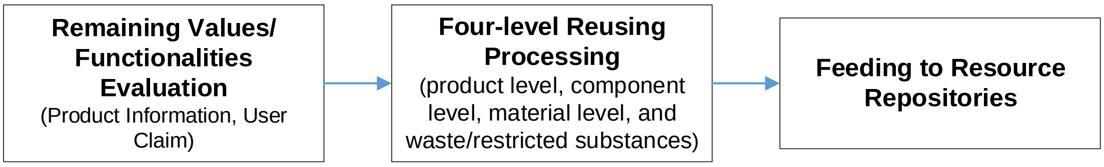
Self-configuration Function

Self-scalability Function



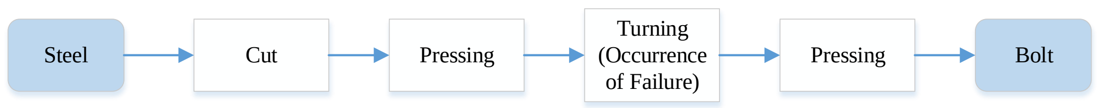
Self-remediating Function

Self-reusing Function

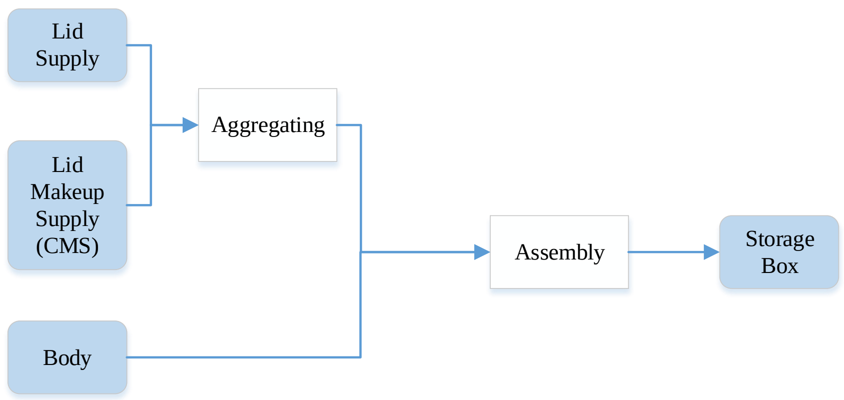


Appendix B: Sequential Diagram of Scenario Studies in Chapter 6

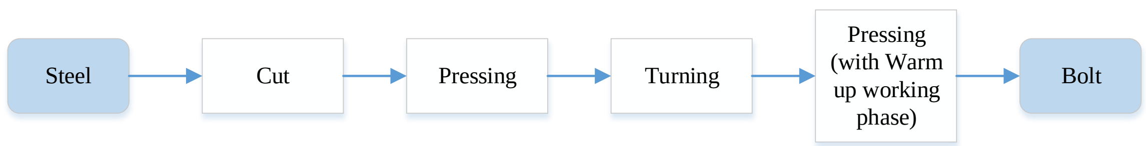
Scenario 1-1



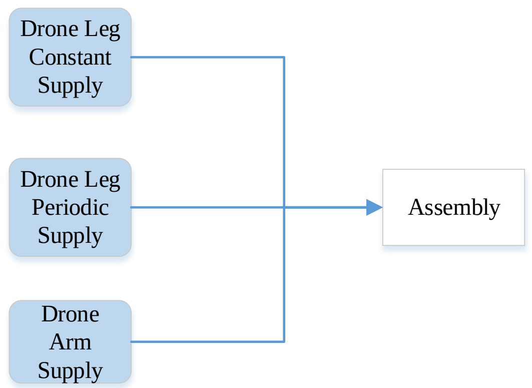
Scenario 1-2



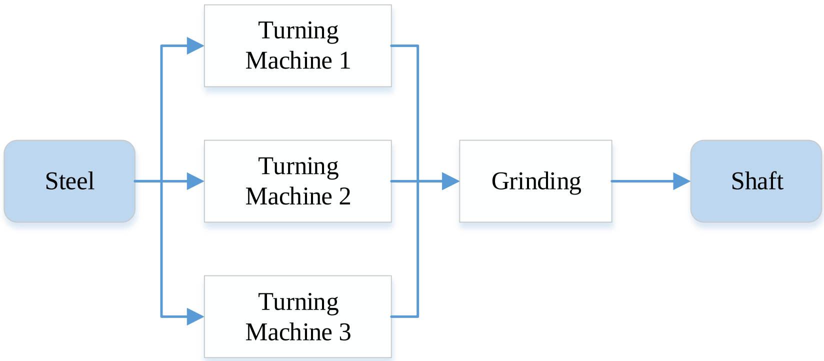
Scenario 2-1



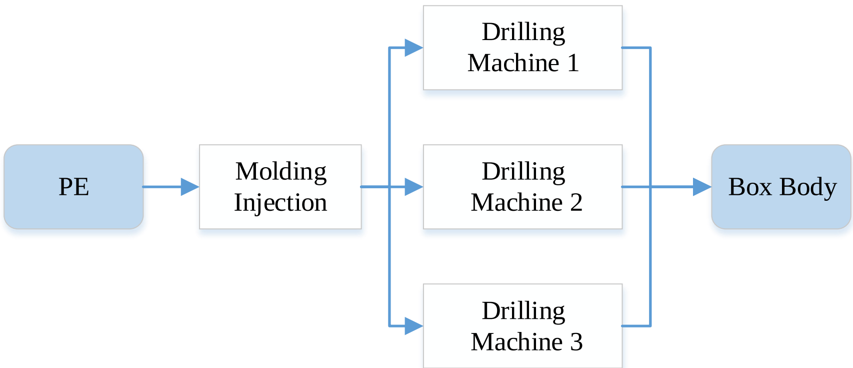
Scenario 2-2



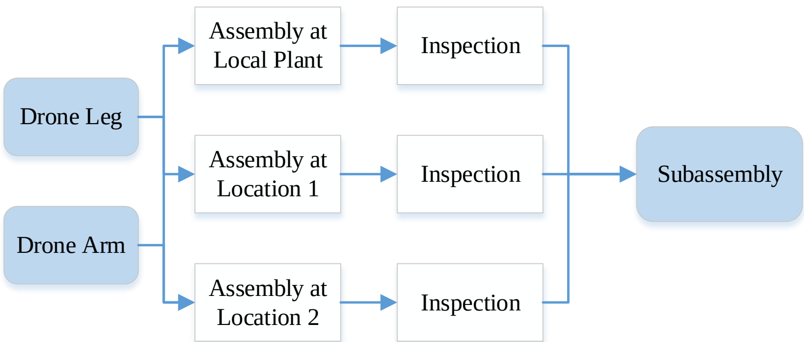
Scenario 3-1 and Scenario 3-2



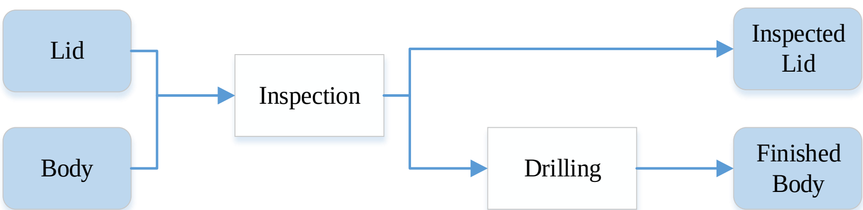
Scenario 4-1



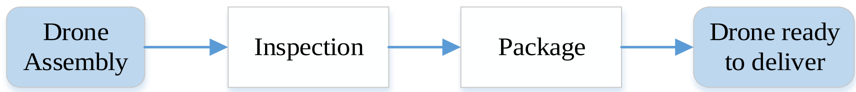
Scenario 4-2



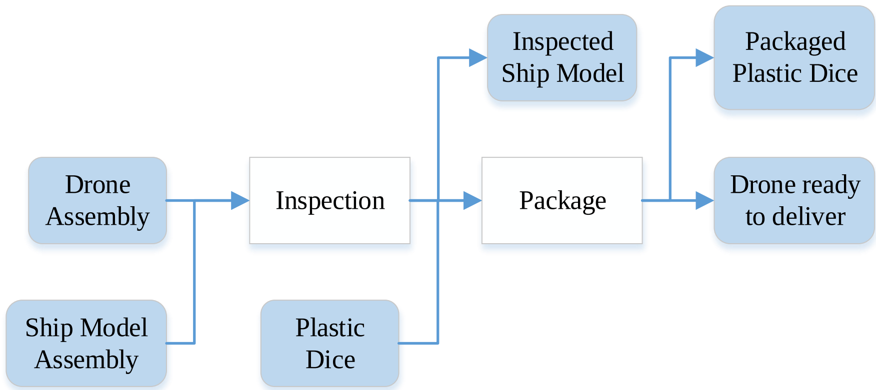
Scenario 5-1



Scenario 5-2

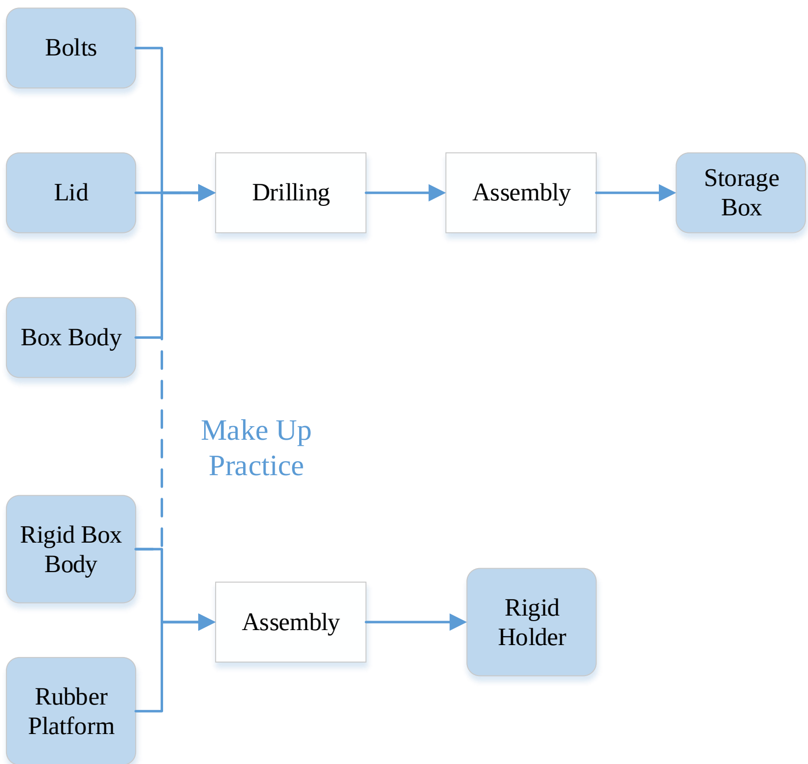


(a) Traditional Manufacturing Operation

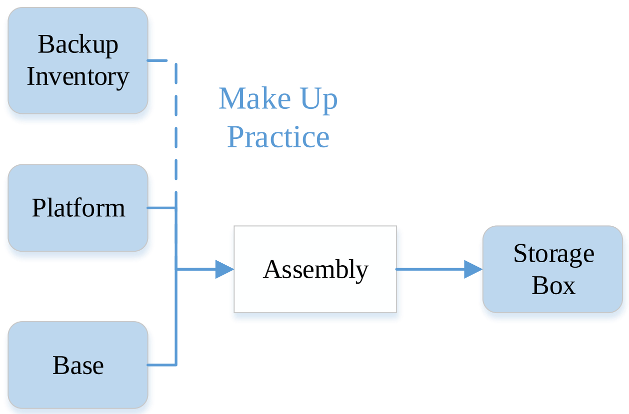


(b) CMS Operation

Scenario 7-1



Scenario 7-2


Backup Inventory
Make Up Practice
Platform
Assembly
Storage Box
Base

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Curriculum Vitae

Publication

Song, Zhengyi, and Young Moon. 2018. "CyberManufacturing System: An Emerging Solution for Sustainable Manufacturing." 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE), Pittsburgh, PA, USA

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Wu, Mingtao, Heguang Zhou, Longwang Lucas Lin, Bruno Silva, **Zhengyi Song**, Jackie Cheung, and Young Moon. 2017. "Detecting Attacks in CyberManufacturing Systems: Additive Manufacturing Example." MATEC Web of Conferences.

Song, Zhengyi, and Young Moon. 2016. "Assessing Sustainability Benefits of CyberManufacturing Systems." *The International Journal of Advanced Manufacturing Technology* 90 (5-8):1365-1382. doi: 10.1007/s00170-016-9428-0.

Song, Zhengyi, and Young B Moon. 2016. "Performance Analysis of CyberManufacturing Systems: A Simulation Study." *IFIP International Conference on Product Lifecycle Management*.

Research Interests

Sustainable Manufacturing, Operations Research, Data Analytics, Machine Learning, Intelligent Manufacturing, Sustainability Metrics, Modeling and Simulation, Optimization

Research Projects

Micro-environmental Control System (μX) (DOE: DE-AR0000526) 02/2018 – 04/2018

Development and Construction of CyberManufacturing Systems (CMS) Testbed

06/2017 – 01/2018

Wegmans Food Pharmacy Checkout Counter Layout Design and Process Optimization

09/2015 – 12/2015

Adaptive Automobile Headlights Control Systems Development 02/2012 – 06/2012

Teaching Experience

Graduate Teaching Assistant

ECS	526	Statistics for Engineers	2014 Fall, 2015 Fall, 2016 Fall & 2017 Fall
MAE	184	Engineering Graphics/Computer-Aided Design	2015 Spring
MAE	300	Engineering Data Analysis	2016 Spring & 2018 Spring
MAE	630	Simulation and Data Analytics	2017 Spring

Awards

3rd Place Award in 6th International Forum on Sustainable Manufacturing Student Poster Competition, Institute for Sustainable Manufacturing (ISM) 12/2017

3rd Place Award in Syracuse University Mechanical and Aerospace Engineering Advisory Board Poster Competition, Syracuse University 05/2017

Merit Student & First-class Scholarship, USTB, Beijing 10/2012

1st Prize of 3rd "Higher Education Cup" National Contest in Integrated Mapping Technology and Product Information, China 09/2010

2nd Prize of 5th "Beijing Automobile Cup" Capital Undergraduate Mechanical Designing and Innovation Competition, Beijing, China 06/2010

Professional Service

Journal Reviewer of *Production and Manufacturing Research*

Production and Manufacturing Research is an Open Access Journal which provides a high-quality platform for the research on manufacturing engineering and technology, operations research and management, supply chain performance management, lean manufacturing, etc.

Invited Author of *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*

The *Journal of Engineering Manufacture* is peer-reviewed and is a member of the Committee on Publication Ethics (COPE). It provides a focus for developments in engineering manufacture, covering technological and scientific research, developments and management implementation in manufacturing.

Programming Languages and Software

Programming Language	Python, MATLAB, C++, SQL and R
Software	Tableau, Minitab, Arena, Simio, Qlik Sense, Abaqus, ANSYS, SolidWorks, Inventor, AutoCAD and MS Office Suites

Professional Association

The International Council on Systems Engineering (INCOSE) Student Member

American Society of Mechanical Engineers (ASME) Student Member