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ORIGINAL ARTICLE

Integration of design and manufacturing data to support personal manufacturing based on 3D printing services

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Abstract This paper suggests an extended product data model that integrates product design and manufacturing data to support personal manufacturing based on 3D printing services. To produce highly customized products with limited resources, personal manufacturers require data management tools for integrated product design and manufacturing. However, the current separated and dedicated design and manufacturing information systems for mass production cannot satisfy the requirements of personal manufacturing. To solve this problem, this study introduces an extended product data model that has data objects for bills of processes (BOP), customer orders and manufacturing operation linked to 3D printing services through Internet of things (IOTs) technologies. The extended product data model can support product design, process planning, production planning, and execution of manufacturing operation in a unified single user environment. To demonstrate the applicability of the model, this study implemented it as a prototype product data management (PDM) system and applied the system to an example product development.

Keywords Personal manufacturing · Additive manufacturing · 3D printing services · Product data management (PDM) · Product lifecycle management (PLM) · Bill of process (BOP)

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1 Introduction

3D printers are a type of additive manufacturing (AM) facility that can produce three-dimensional shapes by laying a layer of plastic or metal powder on top of another [1]. Additive manufacturing is comparable to subtractive manufacturing, which cuts or carves material using cutting tools or laser beams to shape products. While existing subtractive manufacturing for mass production requires multi-phased manufacturing steps with dedicated tools and fixtures, additive manufacturing can produce products directly from their 3D CAD models without additional tools or fixtures [2].

Consumer 3D printers are affordable 3D printers that individuals can purchase. The market for consumer 3D printers expanded by 200–400% annually between 2007 and 2011, and makes up the largest portion of the whole 3D printer market [3]. Decreases in prices due to innovations in 3D printing technologies and open-source hardware and software [4] have increased the market for consumer 3D printers and their distribution. Consumer 3D printers are adequate tools for those who want to create simple personalized goods such as toys, accessories, shoes or simple gear.

Due to the widespread availability of consumer 3D printers, Internet-based 3D printing services are considered an emerging manufacturing platform for personal manufacturing or customized production [2]. These provide online 3D printing services or link personal manufacturers requiring 3D printing services to individuals who own 3D printers. Current 3D printing services provide upload-to-make printing services, where users cannot control 3D printers directly through the Internet. They need to upload their 3D model files on web sites provided by service providers, and then service providers print the products and send them to users through delivery services.

Personal manufacturing allows an individual to produce and sell small amounts of personalized products by using additive manufacturing facilities, laser cutters and open-source hardware and software [5]. Additive manufacturing features allow personal manufacturers to produce small amounts of highly customized products without dedicated manufacturing facilities and resources. This new manufacturing approach is based not only on improved machines, software and controls for manufacturing, but also on the spread of Internet and social media (SM) as collaboration and communication tools with outside advisors for marketing, design, manufacturing and customer services. The Internet also allows individuals to easily deliver capital and reach markets for their product development and manufacturing.

However, the current personal manufacturing individuals have no design and manufacturing support for their integrated and consistent data management needs. Even though they have to manage product data and processes from design to manufacturing with limited resources, they can only use isolated CAD/CAM software systems, general-purpose email systems, office applications and file servers to manage various customer orders of relatively small lot sizes. They have difficulty managing design and manufacturing data along with customer orders spread among heterogeneous information tools and data storages.

To solve the current problems of data management for personal manufacturing, the author proposed a framework to integrate design and manufacturing data that can support personal manufacturing based on 3D printing services [6]. The framework consists of three features: the application range of product design and manufacturing, product data management (PDM) centered-integration, and enabling information technologies for the integration.

In order to realize the framework, this study enhanced the framework and proposed an extended product data model that can integrate product data including bills of processes (BOP), customer order and manufacturing operation with existing product design objects. The product data model allows personal manufacturers to manage product design, process planning, production planning and manufacturing execution data in a unified user environment of an extended PDM system. It supports the unified user environment through applications of SM, AM and Internet of things (IoT) technologies based on 3D printing services.

To demonstrate the feasibility of the product data model, this study implemented it as an extended PDM system for personal manufacturing. In addition, to illustrate the supporting functions of the implemented PDM system, four representative application examples of the prototype system for each design and manufacturing process are presented.

The remainder of this paper is organized as follows: in Section 2, this study reviews related work. Section 3 introduces a framework for integrating design and manufacturing data for personal manufacturing. Section 4 proposes a product data model for an extended PDM system that integrates data objects for BOP and manufacturing operation with existing product design objects. Section 5 describes the implementation of the model as an extended PDM system with application examples of product design and manufacturing. Section 6 concludes the study with further research topics.

2 Related work and research contributions

The main theme of this study is to integrate design and manufacturing data using emerging information and communication technologies (ICTs), including 3D printing services, in order to support personal manufacturing. Therefore, this section describes different approaches to design and manufacturing integration based on ICTs for personal and customized production. Since the result of this study will be a computer-based information system, the reviews focus on information management tools and methods.

2.1 Integration of design and manufacturing

To support personal manufacturers with integrated information systems, the proposed framework and product data model integrate design and manufacturing processes and their associated data. In order to integrate enterprise information systems including design and manufacturing supporting systems, Xu et al. [7] proposed industrial information integration engineering (IIIE), and Chen [8] reviewed related studies. IIIE is a set of fundamental concepts and techniques that facilitate the industrial information integration process [8].

The proposed framework and data model can be a subset or instance of IIIE, since it allows interactions with multiple disciplines in separate areas as IIIE suggested. For example, it allows the integration of online hardware facilities and information systems. The proposed framework attempts to integrate not only separate data management functions for design, planning and manufacturing processes, but also manufacturing hardware facilities (3D printers) with a supporting information system as a function of an extended PDM system. In addition, the framework applies social science to enhance information systems and product design processes. It applies social media for collaboration with outside experts during product design and manufacturing processes.

To integrate emerging IoT technologies into manufacturing industries, Cai et al. [9], Tao et al. [10] and Tao et al. [11] use the product lifecycle management (PLM) concept, which covers product lifecycle stages from product conceptualization to disposal. The proposed framework in this study also uses extended PDM to cover processes from product design to manufacturing execution, in order to integrate IoT technologies for remote operation of 3D printers. Just as Tao et al. [10]

use bill of material (BOM) as the basis of the integration and application of IoT technologies through the product life cycle, the proposed framework also uses BOM (product structures) to integrate product design, process planning, material resource planning and manufacturing execution in an extended PDM system. It also integrates 3D printing services with its product data management through IoT technologies. However, while previous studies use IoT to identify products during different stages of the product life cycle, the proposed framework uses it to allow personal manufacturers to monitor and control dispersed 3D printers through the Internet.

As another integration framework based on an emerging information technology, Wu et al. [12, 13] suggested cloud-based design and manufacturing (CBDM), which consists of cloud computing infrastructures, computer-aided design and manufacturing software, hardware, information management and supply chain management services. Figure 1a shows the CBDM framework and its six component services, along with its supporting design and manufacturing processes. This paper compares the components of the proposed PDM system with CBDM services to clarify the relationship between the two approaches (see Fig. 1a, b).

The extended PDM system follows a subset of CBDM architecture. While CBDM has no limitations to its application domain, the proposed approach specifies personal manufacturing as its application domain. CBDM also considers general product development processes from conceptualization to manufacturing, but the proposed approach limits its processes from product design to manufacturing execution (see the four product design and manufacturing processes in Fig. 1b). The proposed approach also limits its production methods to 3D printing services. However, the generalized conceptual model in CBDM prohibits the provision of concrete descriptions or examples of the approach. Even the scenario in a study [12] lists available technologies and services without concrete data or instantiation examples. This study implemented the extended product data model as a prototype PDM system and applies it to product development and manufacturing processes for a personalized product.

While CBDM considers information management as a service, the proposed approach uses information management as a unified user interface to integrate services for product design and manufacturing processes (see the extended PDM system in Fig. 1b). To integrate the services, the proposed approach supports both product data objects and extended PDM functions (see product data objects). In the case of CBDM, there are no specifications for integrators or containers that integrate necessary services for specific applications. It may be difficult for personal manufacturers to integrate or interface necessary services, since the services cover whole product design and manufacturing processes and have heterogeneous operation and interface environments.

The 3D printing services with the product data objects in the proposed PDM system correspond to the hardware as a service and supply chain management in the CBDM architecture. Selecting a specific 3D printing service determines a supplier (3D printing service provider) and the supplied part. Through product data objects, the supplier and associated part data are tightly integrated to other product data that can be applied to various kinds of design and manufacturing data management. For example, an item object that represents hardware-as-a-services maintains an operation object that links connections of the part supplier (see the assembly, part and operation objects in Fig. 1b). In addition, the item object maintains its 3D model file as its associated document object. As a manufacturing application, it can provide the 3D model file to the 3D printing service managed by its operation object. The item, document and operation objects are integrated with other design and manufacturing data objects in the product data model. They can provide integrated and comprehensive product data for different product design and manufacturing applications.

As a result, the proposed extended product data model for personal manufacturing allows personal manufacturers to manage comprehensive and integrated design and manufacturing data in one place, allowing external services for computer-aided tools and online 3D printing services (see Fig. 1b).

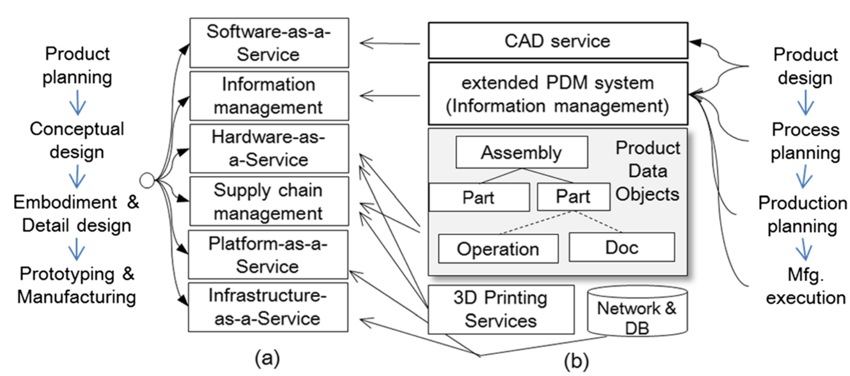


Fig. 1 Comparisons with CBDM architecture

2.2 3D printing services in cloud manufacturing

There have been many reports on different 3D printing services [2, 12, 14]. This paper is interested in online 3D printing services and classifies them into four groups: online 3D printing services, distributed 3D printing services, online design tool services, and online 3D printer cluster services.

Online 3D printing services provide upload-to-make services to individuals who want to print their customized products. Shapeways [15] and Ponoko [16] provide online 3D printing services. They use their own 3D printing facilities to produce ordered designs.

Distributed 3D printing services match individuals who want to print their products to owners of personal 3D printers, allowing the individuals to search locations, 3D printing conditions and available materials of service providers. 3D hubs [17] provides distributed 3D printing services.

Online design tool services aim to provide online software tools such as 3D modelers and 3D scanners for 3D printing. 123Dapps [18] provides different online software tools for 3D printing. They provide a cloud computing-based 3D CAD modeler, smartphone-based 3D scanning service and online design tool for electronic circuits. They link the results of some design tools to other distributed 3D printing services in order to streamline customer design and manufacturing processes.

Some 3D printing services use a farm of 3D printers with centralized control systems [19] and provide application programming interfaces (APIs) for customers to use the service from their application programs. This clustering approach aims to overcome the long fabrication time of 3D printers with efficient allocation of resources for printing tasks. Centralized control systems are applied to their own 3D printer farms and the APIs allow users to add their printing job to the schedule managed by the control systems.

Our approach allows personal manufacturers to access and control dispersed 3D printers as their local 3D printer, allowing users to upload 3D files, start 3D printing, adjust printing parameters and monitor progress through web cameras. The 3D printers are connected to an extended PDM system through the Internet using small computer boards [20] with Linux operating systems and open-source control software [21]. Our approach also allows users to manage online and distributed 3D printing services as manufacturing execution data associated with item objects from the view of an integrated product data object for design and manufacturing.

Mai et al. [2] suggested a framework of 3D printing services in cloud computing-based manufacturing. Figure 2a shows the framework, which consists of five different layers from the physical device to the application layers. Through the physical device, adapter and servilisation layers, it can provide basic 3D printing services that connect networked 3D printers. Based on the services, the service and 3D model management layer allows users to connect to proper 3D printing services and manage 3D models for 3D printing. The application layer can build planning or scheduling systems for 3D printing based on the management layer.

To illustrate the differences of the proposed system to existing approaches, this paper compares components of the proposed system with those of the existing framework in Fig. 2a. Figure 2b shows components of the proposed system that can be built using the proposed framework and product data model described in Sections 3 and 4.

The physical device and adapter layers in Fig. 2b are the same as the existing framework. However, the proposed system has poor servilisation functions, since it uses 3D printing services connected to each 3D printer without service publication or query functions. It also uses the online or distributed 3D printing services described in the previous section.

To manage connections to 3D printing services and 3D models, the proposed system uses an integrated product data model. The document objects (see Doc in Fig. 2b) manage 3D models as part of the product design specifications, and the operation objects maintain connections to selected 3D printing services as attribute values of their manufacturing execution data. The document and operation objects are elements of product data objects that represent comprehensive product design and manufacturing data including parts, document, product structures, manufacturing processes and operation objects.

The extended PDM system based on the product data model supports basic procedures to connect 3D printing services and upload 3D models to 3D printing services using the integrated document and operation objects. The extended PDM system also provides more comprehensive applications with integrated product data objects. For example, the proposed system plans production of a product with the items, product structures and operation objects. Then, the associated document and operation objects support 3D printing services based on the production schedule. As a result, the proposed system supports the management and application layers of the existing framework with more comprehensive and integrated product design and manufacturing data and extended PDM functions.

2.3 Research contributions

To support integrated design and manufacturing information systems for personal manufacturers using online 3D printing services, this study proposed a framework, product data model and prototype PDM system with illustrative application examples.

The framework is a subset of previous frameworks such as IIIE or CBDM that include integration of design and manufacturing. The proposed framework is different from previous studies in that it provides a product data model that can implement specific application systems based on the proposed framework. This is because the framework limits its integration area to design

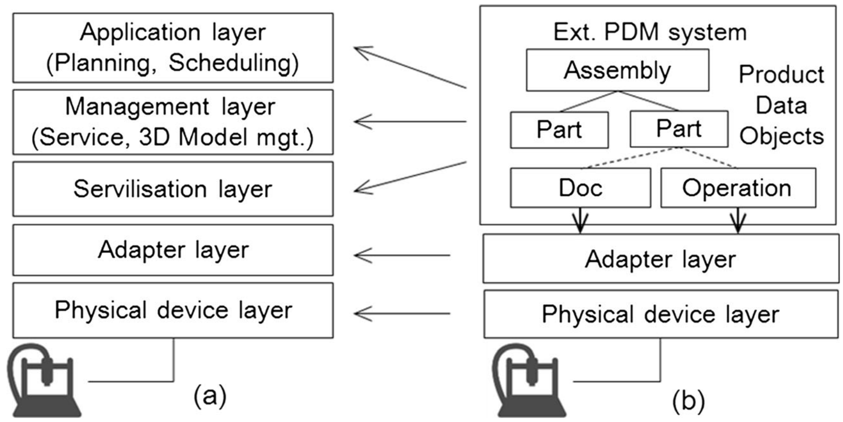


Fig. 2 Comparisons with the framework of a 3D printing service [2]

and manufacturing and its application area to personal manufacturing based on 3D printing services.

The other difference is that it provides a PDM-centered integration framework, which extends PDM systems to integrate or contain different services required during product design and manufacturing. The PDM system extends its data structures to support customer orders, operation and manufacturing execution to support different services for manufacturing and remote 3D printing operations.

Based on the framework, this study developed a product data model that can support the integration of design and manufacturing for personal manufacturers based on 3D printing services. The model enables personal manufacturers to link existing online 3D printing services to its comprehensive product data model, which covers product design, process planning, production planning and manufacturing execution. This is different from the existing approach that concentrates on 3D printing centered services with limited integration of design and manufacturing processes such as the management of 3D models or scheduling of 3D printing sequences.

Implementation of the framework and data model employs current state-of-the-art 3D printing and associated IoT technologies. Different from the existing product identification-oriented IoT application, implementation focuses on the application of IoT to integrate remote 3D printers into integrated design and manufacturing information systems where users can monitor and control remote 3D printers through the Internet. This comprehensive and integrated information system allows personal manufacturers to develop and manufacture their products in a unified supporting information system based on online 3D printing services.

3 A framework for integrated design and manufacturing data management

This section describes a framework for integrated design and manufacturing data management for personal manufacturing based on 3D printing services. It enhances the existing framework [6] with the data object layer, and provides a basic framework for the extended product data model and its implementation in Sections 4 and 5. Figure 3 presents features of the framework.

3.1 Integrated processes from product design to manufacturing execution

As shown in Fig. 3, the framework covers four design and manufacturing phases, including the product design, process planning, production planning and manufacturing execution processes (see the production processes in Fig. 3). Product design specifies properties of target products such as their shapes or dimensions. Process planning defines how to make products by using manufacturing technologies and their sequences. The framework assumes that personal manufacturers prepare product configurations that have both common modules for groups of products and personalized modules for each customer. To prepare the product configurations before customer orders, the design and manufacturing process goes through the production design and process planning phases before the customer order events. Production planning calculates the amount of products and their production time based on customer orders and process planning. Manufacturing execution monitors and controls the progress of manufacturing processes.

3.2 PDM-centered integration

There are existing information systems for target design and manufacturing processes (see the supporting information systems in Fig. 3). PDM, computer-aided process planning (CAPP), material resource planning (MRP) and manufacturing execution system (MES) are supporting information systems for product design, process planning, production planning and manufacturing execution, respectively.

The proposed framework tries to integrate all supporting functions for design and manufacturing into an extended PDM system. Extension of the PDM system considers the

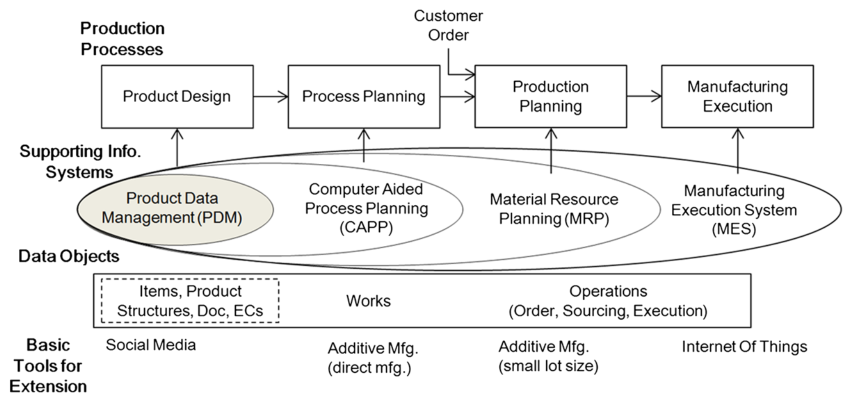


Fig. 3 A framework for integrated design and manufacturing data management for personal manufacturing based on 3D printing services

following characteristics of personal manufacturing based on 3D printing services.

First, SM functions in a PDM system are an essential tool for personal manufacturers to collaborate with outside experts for product design and manufacturing. There have been studies on SM in PDM [13, 22, 23] and the implementation of SM in commercial PDM systems [24–26]. In addition, there are many outlooks for social PDM systems that employ SM as their main communication and knowledge management tool as a future PDM system [27–29]. Therefore, the framework selects SM as a tool for the PDM extension in Fig. 3.

Second, personal manufacturing requires version control and change management to efficiently produce customized products using existing product design [5]. Since personal manufacturing should keep different product specifications for customized products and maximize their reuse, efficient management of the design specifications is a critical function for supporting information systems. Since the main functions of the PDM system include version control and engineering change management, the framework employs PDM as a main information tool for supporting personal manufacturing.

Third, low-volume production in personal manufacturing decreases the importance of CAPP. In addition, 3D printing services also decrease the importance of MRP. In mass production, CAPP can effectively improve the efficiency of the manufacturing process, since small improvements in the manufacturing process can be magnified by large production numbers. In personal manufacturing, CAPP cannot improve the efficiency as much as the mass production since the lot size is often one or a relatively small number. In addition, online 3D printing services through the Internet serve as flexible and unlimited supply chains or inventory networks. Since the low volume production and 3D printing service is a flexible supply chain, the integrated system requires only primitive CAPP and MRP functions.

Fourth, direct manufacturing through 3D printing services simplifies the function of CAPP. As additive manufacturing can produce final products from 3D CAD models without dedicated tools or fixtures, CAPP in 3D printing services has a limited role. It allows an extended PDM system to integrate CAPP functions into a unified user environment.

To merge the functions and processes of other supporting information tools into an extended PDM system, the framework uses an extended product data model that can support all phases of design and manufacturing. The data objects in Fig. 3 show the original product data objects for PDM (see items, product structures, document and engineering changes objects in Fig. 3) and extended objects (see the work and operation objects). To integrate CAPP functions, the data model provides the work object that represents a manufacturing process unit. It also supports BOP concepts that integrate product structures of parts with manufacturing processes. The operation object contains the order, sourcing and execution objects that can represent basic data for the production planning and manufacturing execution (Objects will be introduced in Section 4).

3.3 IoT and online 3D printing services

The technologies for the extension in Fig. 3 list SM, AM and IoT as emerging technologies that enable new supporting information tools for personal manufacturing. Since the previous section describes the roles of SM and AM, this section introduces IoT as an enabling technology that integrates control of remotely connected 3D printers to the extended PDM environment as MES functions.

Internet of things (IoT) is a set of information and communication technologies that connects dispersed sensors or actuators thorough the Internet [30]. It allows users to collect information from sensors and actively control connected machines or facilities through embedded actuators. This study introduces Octo Print technology [21], which enables remote users to monitor and control Internet-connected 3D printers. It supports open hardware and software for 3D printers [4]. Through IoT technology, users can upload 3D printing files, start printing their products, and monitor and control the 3D printers as MES functions for their production.

4 A product data model for integrating product structures, routings, and operation

The proposed product data model describes data objects and their behavior, which enable PDM systems to support integration of design and manufacturing data for personal manufacturing. This section describes the overall data structure for the extended PDM system and then illustrates the extended manufacturing data objects, BOP and operation objects.

Figure 4 displays a class diagram for the proposed product data model. The diagram shows three main objects: the object, item, and operation with related objects. The item group, the item object and its associated objects represent product design data that existing PDM systems manage. The operation group consists of objects representing manufacturing data that will be integrated with design data. The object group integrates the item and operation groups and provides common objects that support access control, documentation, social media and workflow.

4.1 Product data model for design data management

This section shows the item group that manages product design data. Item represents a general object for design data, and contains the part, material and work subclasses. Part represents physical components, assemblies or end products that consist of part lists. Material represents general material resources used to fabricate products. Work represents specifications of operation to produce its parent part by using sibling parts or materials in product structures. It will be described further in Section 4.2.

Rel, an abbreviation of relationship, represents relationships between two items through the relating and related attributes. It usually represents a constituent relationship between the relating and related items when the related item serves as a component of the relating item. By using a set of linked rel objects, the model can represent product structures of participating items.

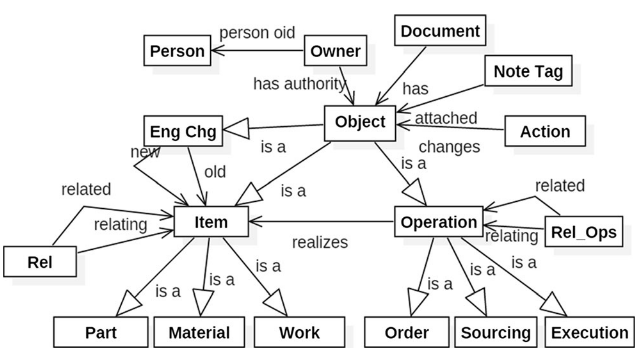


Fig. 4 A class diagram showing all participating product design, routing, and operation classes and their relationships

Object is a generic object of the item and operation objects. Thought the object, the model can share the person, owner, document, note tag and action objects by inheriting associations with the objects to the three subclasses: the item, engineering changes, and operation objects. The person and owner objects manage access of users to specific data objects. The document object contains engineering documents including CAD models or 3D printing files and associates them with specific objects. The note tag is a simple text-based SM that engineers can attach to item or engineering change objects to communicate during product development. The action object is a simple workflow that allows stages of review or approval by other participants. All these associated product data can be shared through the generic object.

As a subclass of the object, the engineering change object (the eng chg object in Fig. 4) represents changes in product designs through the two link attributes, the input and output, to the item objects. It also shares the owner, document, note tag and action objects through its parent object.

Figures 5 and 6 show how to represent real products using the proposed product data model. Figure 5 shows a product, 17001 lamp, and its product structures with component parts and materials. The 07001 and 030 base asm are components of 17001. The lines between 17001 and the two parts represent constituent relationships. The 07001 part is made from M010 PLA material through a W020 3D printing process. The 030 part is an assembly and has 010 LED as a purchased part and 020 base through the W010 3D printing process using M010 material.

Figure 6 shows the example 17001, 030, 020 and 010 parts and M010 material and their product structures instantiated with the product data model in Fig. 4. Each instance uses object identifiers from their part or material numbers or system generated identifiers (e.g., the rel and rel_ops objects).

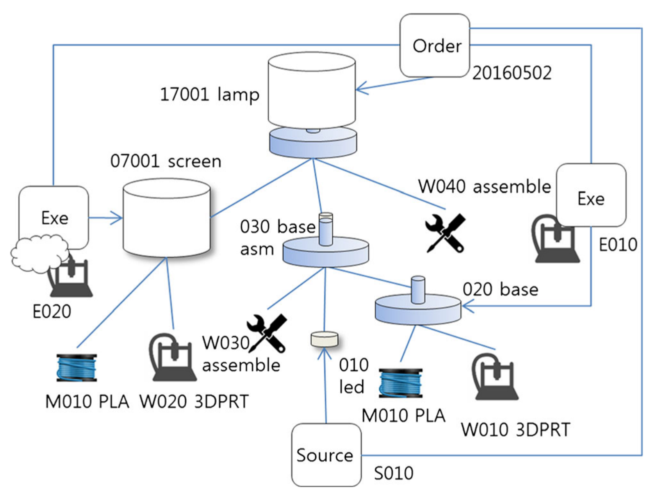


Fig. 5 An example product and associated work, order and operation objects

4.2 Integration of routing—bills of processes

To integrate CAPP with PDM, the product data model prepares the work object as a subclass of the item object (see the work object in Fig. 4). While engineering product structures (usually called engineering bills of material, EBOM) present only parts or materials for design specifications, the proposed model adds specifications of manufacturing processes (routings) with the related parts or material in their product structures using the work object.

In Fig. 5, 07001 and 020 parts printed with 3D printers have the work objects, W010 and W020, representing 3D printing in addition to their materials, M010 PLA, as their components. The sub product structures of 07001 and 020 specify all the necessary materials and component parts including routings to produce the parent parts. Usually, the work sequence consists of routings for the manufacturing process, and product structures with routings become manufacturing bills of material (MBOM).

Figure 6 shows the W010, W020, W030 and W040 work objects, which specify the 3D printings and assembly operation to produce the 17001 end product. This shows that the work objects also use the rel objects to link with other item objects (see the work and rel instances in Fig. 6).

4.3 Integration of operation—orders, sourcing, and execution

The operation group in Fig. 4 represents manufacturing data integrated with the item group through the generic object. The operation object has the order, execution and sourcing objects as its subclasses. In Fig. 5, when a personal manufacturer receives an order for the 17001 product, he or she can represent it with an order object linked to the 17001 part object (see 160502 object). Then, he or she purchases the 010 part and asks the 3D printing service provider to print the 07001 and 020 parts. All the manufacturing activities are represented with the order, sourcing, and execution objects (see instances of the order, sourcing, and execution objects in Figs. 5 and 6).

As a result, the proposed product data model has represented all product design and manufacturing data for product specifications, routing planning, material resource planning, and manufacturing execution in an integrated data model.

5 Implementation of the proposed model and its applications

To demonstrate the feasibility of the proposed data model, this study implemented the model as a prototype PDM system. To illustrate the supporting functions of the implemented PDM system, representative application examples of the PDM system for each design and manufacturing process were selected.

- Configuration control is an application during the product design phase, which illustrates using social media collaboration with outside experts.
- Cost estimation is an application during the process planning phase, which uses both data from product structures and bills of processes.
- Material resource planning is an application during the production planning phase, which calculates the amount of material from customer orders and product structure information.
- Remote monitoring and control of 3D printing illustrates the IoT technologies used during the manufacturing execution phase.

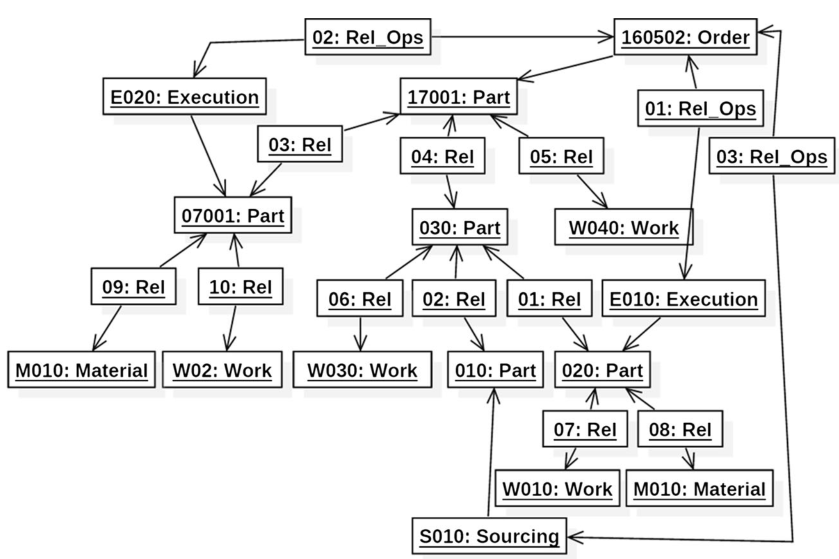


Fig. 6 An instance diagram for the example in Fig. 5 based on the data model in Fig. 4

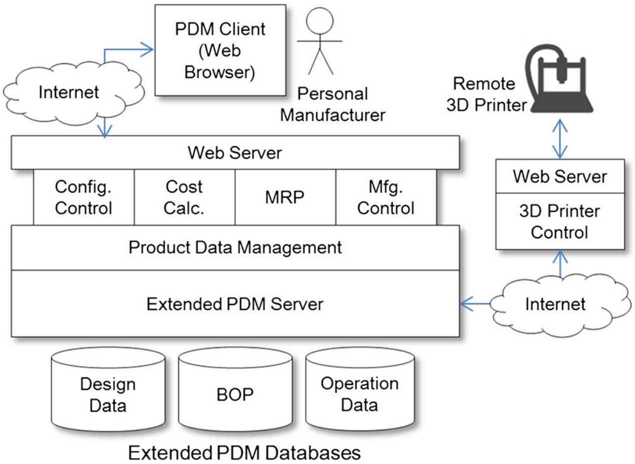


Fig. 7 System architecture of the implemented PDM system

Section 5.1 describes the system architecture for the implemented prototype system with connected 3D printing services. It also introduces an example product that will be used for application examples in the following sections. Sections 5.2 and 5.3 present illustrative applications of the implemented PDM system with a comprehensive product design and manufacturing example.

5.1 System architecture with connected 3D printing services and an example product

Figure 7 shows the system architecture of the implemented PDM system. The system has extended PDM databases, which consist of the design, BOP and operation data. The extended PDM server supports access to data objects in the PDM databases with basic input/output operation. Product data management provides core PDM operation such as management of the parts list, engineering documents, product structures and engineering changes. Based on the product data management functions, the system supports applications for design and manufacturing processes through a web-based user environment. The

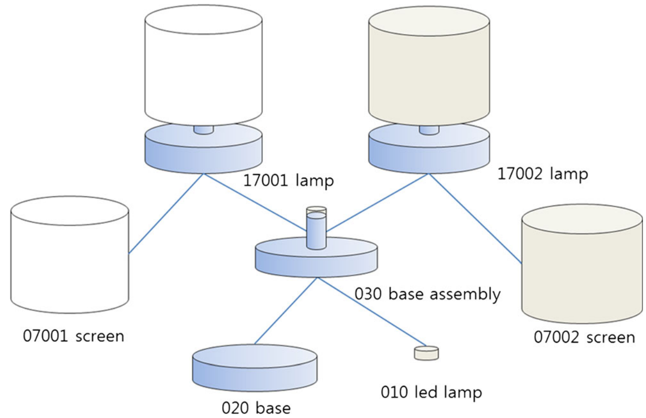


Fig. 9 Example product design and engineering changes

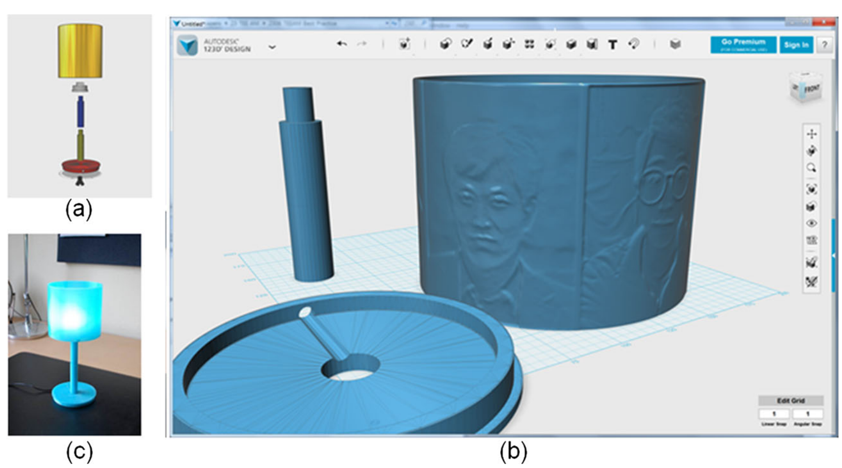
system is implemented with the MySQL database management system [31] and a Java-based web application development environment [32].

The extended PDM server connects remote 3D printers with control software that supports open hardware and software for 3D printers. The control software provides applications and APIs that allow remote control of dispersed 3D printers [21].

Figure 8 shows 3D CAD models and a completed product of the example used throughout this section. The lamp is a desktop stand with an LED light bulb powered by USB. The lamp was modeled using a 3D CAD system [18] freely downloaded through the Internet as Software-as-a-Service (see Fig. 8a). The screen of the lamp printed with specific images makes the product a highly personalized product (see Fig. 8b). The implemented PDM system supports various design and manufacturing data to realize the lamp using 3D printing services (see Fig. 8c).

Figure 9 shows a simplified version of product structures and an engineering change of example products (see Figs. 5 and 6 for product structures with their associated design and manufacturing objects). The engineering change is reviewed and approved through the configuration control process described in Section 5.2.

Fig. 8 Product data for the example products



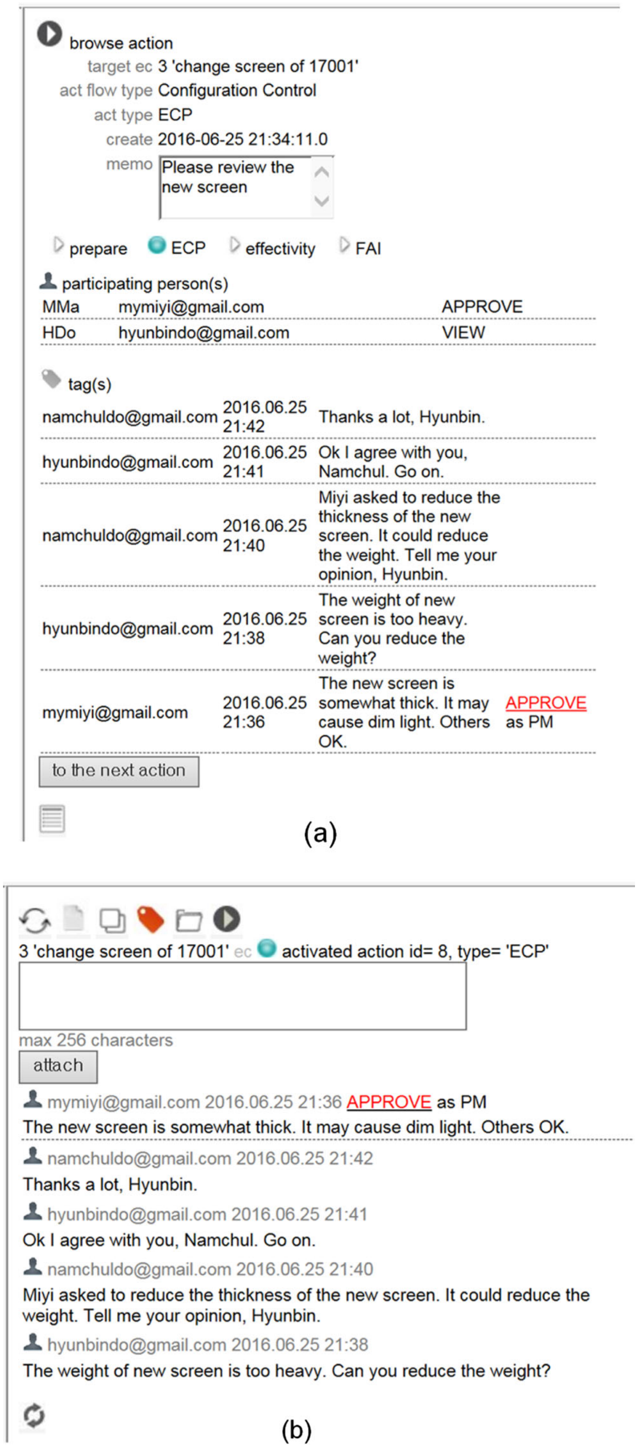
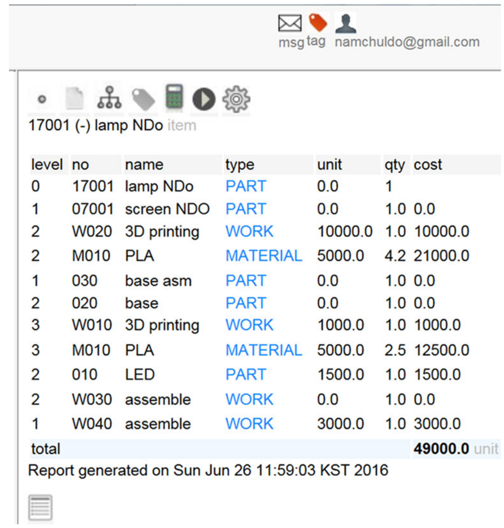


Fig. 10 The EC, action, and tags for configuration control process

5.2 Configuration control and process planning examples

Controlling product configurations checks the acceptance of stakeholders for an engineering change and decides on its application. The stakeholders for engineering changes usually include other design engineers, product managers, manufacturing engineers and inventory controllers. In the case of personal manufacturing, they could be outside experts who can advise on the changes.



level	no	name	type	unit	qty	cost
0	17001	lamp NDo	PART	0.0	1	
1	07001	screen NDO	PART	0.0	1.0	0.0
2	W020	3D printing	WORK	10000.0	1.0	10000.0
2	M010	PLA	MATERIAL	5000.0	4.2	21000.0
1	030	base asm	PART	0.0	1.0	0.0
2	020	base	PART	0.0	1.0	0.0
3	W010	3D printing	WORK	1000.0	1.0	1000.0
3	M010	PLA	MATERIAL	5000.0	2.5	12500.0
2	010	LED	PART	1500.0	1.0	1500.0
2	W030	assemble	WORK	0.0	1.0	0.0
1	W040	assemble	WORK	3000.0	1.0	3000.0
total						49000.0 unit

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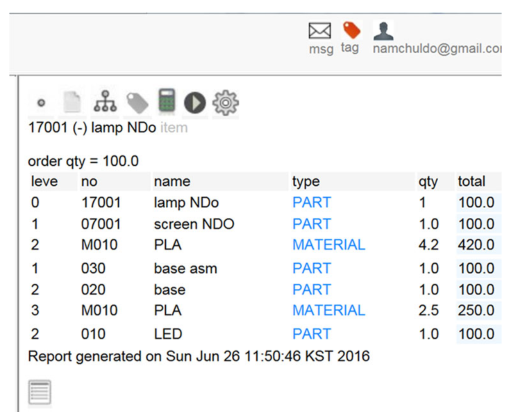
Fig. 11 Cost estimation from product design and process planning data

The implemented system provides the engineering change, action and note tag objects for configuration control (see Fig. 4). Figure 10a shows an action browse window to review an engineering change on the screen of the example lamp (see structure changes in Fig. 9). The window shows the action manages configuration control with the prepare, EC proposal (ECP), effectivity and Final Assurance Inspection (FAI) stages. Figure 10b shows exchanges of note tags among participating engineers or experts during the ECP stage of the target engineering change. The example application shows that SM in the extended PDM system can support collaboration among personal manufacturers and outside experts during configuration control processes.

The proposed model suggested BOP, which integrates manufacturing processes into product structures. Figure 11 shows the integrated product structures of both parts (including material) and processes represented with the work objects. For example, material M10 and work W010 as material and a 3D printing process for the 020 part indicate that the material



leve	no	name	type	qty	total
0	17001	lamp NDo	PART	1	100.0
1	07001	screen NDO	PART	1.0	100.0
2	M010	PLA	MATERIAL	4.2	420.0
1	030	base asm	PART	1.0	100.0
2	020	base	PART	1.0	100.0
3	M010	PLA	MATERIAL	2.5	250.0
2	010	LED	PART	1.0	100.0

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Fig. 12 Material resource planning

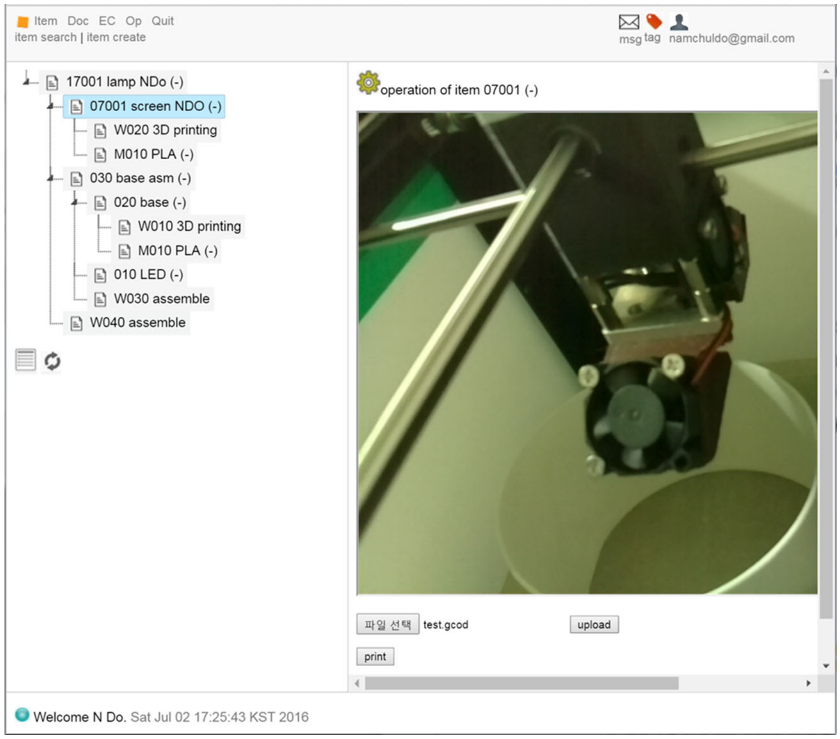

Fig. 13 Windows of the extended PDM to monitor 3D printing processes

and work objects should be prepared to produce the parent part. Using the integrated product structures and BOP, the implemented PDM system can estimate the cost of products.

Figure 11 shows the result of the cost estimation of products during the process planning phase. The window shows the estimated cost of the product from product structures with cost information from the participating parts, material and work objects.

5.3 Production planning and operation monitoring examples

During the production planning phase, to satisfy customer orders, personal manufacturers create operation objects that represent orders and plans for sourcing and manufacturing execution. During the production planning phase, personal manufacturers can calculate the necessary components and materials from customer orders and product structures of the ordered products. Figure 12 shows the result of the material resource planning to calculate the amount of necessary parts and material.

As a result of the production planning, personal manufacturers assign 3D printing services to specific parts with the execution objects. Different 3D printing services can be assigned to a part through its execution objects. One group is online 3D printing services provided by outside services, and the other is online 3D printing services connected to the PDM system. Figure 13 shows a window of the 3D printing service connected to the PDM system to upload 3D printing files, start 3D printing and monitor the 3D printing process during the production execution phase. The 3D printing functions are implemented using the REST (REpresentational State Transfer) APIs provided by the Octoprint control application [21].

6 Conclusion

This study proposed a product data model that can integrate design and manufacturing data for personal manufacturing based on 3D printing services. Application examples of the implemented PDM system based on the model show that it is a possible solution for personal manufacturers who are suffering from a lack of integrated information management tools for their product design and manufacturing. Its version and change management functions can also help personal manufacturers to reuse their product design for configuration management of highly customized products.

Since both personal manufacturing and 3D printing are at the initial stage of their development, and the integration of design and manufacturing data covers a large portion of product development and manufacturing processes, there are several limitations in our approach.

First, it requires comprehensive 3D printing services, which provide intelligent matching and scheduling functions. This study uses only remotely controllable 3D printers without management services. As Mai et al. [2] suggested, intelligent matching and scheduling services in the extended PDM system can help personal manufacturers produce their products using flexible and efficient 3D printing service networks.

Second, the framework or product data model should provide interfaces to other engineering or manufacturing cloud services for more competitive product design and manufacturing. A candidate solution is providing APIs that allow remote execution through the Internet. Several candidates such as REST technologies can be introduced to the framework for different cloud services to access data objects stored in extended PDM systems.

Third, as Bi et al. [33] indicated, combining IoT and cloud computing requires big data applications. To enhance the efficiency of the supporting information systems, the framework and data model should provide advanced data analytics tools for personal manufacturing. For example, in order to select relevant experts for existing product design or manufacturing problems, a personal manufacturer can apply data analytics tools to product data accumulated in the PDM system to receive suitable recommendations. The accumulated product design, manufacturing and SM data in the information system based on the framework can provide appropriate operational data for analysis.

Finally, the proposed framework, data models and application examples did not consider existing limitations of consumer 3D printers such as the low quality of 3D printed parts and limitations of material types for 3D printing. Since the framework is based on 3D printing services using low-cost consumer 3D printers, quality problems may require additional reworks or post-processing after remote-controlled 3D printing services. In addition, the current prototype system cannot support 3D printed parts containing specific materials such as metals, and associated 3D printing methods except for the fused deposit modeling method used in low-cost consumer 3D printers. These kinds of parts can limit open software-based remote 3D printing services supported by the prototype, and require different types of 3D printing services with additional pre- and post-processing.

As further research, the author plans to study advanced data analytics for groups of personal manufacturers and outside experts in a community to help their decision making during product design and manufacturing.

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